Development of a DEM-CFD coupled power model for vertical stirred mills

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Abstract

Vertical stirred mills are increasingly used for fine grinding applications in the mineral processing industry due to their high energy efficiency. Thus, modeling power draw is of great interest proven by the effort in previous work including analytical models. In this contribution the development of a DEM-CFD coupled model is presented to determine power draw under different operating conditions.

These include grinding media filling level, shaft speed and fluidization as well as changes in grinding compartment configuration. An extensive test program on an especially equipped test mill is initiated to validate the model.

Keywords

Discrete element method, mining, mineral processing, comminution, grinding, HIGmill

This content was first presented at 2026 SME Annual Conference & Expo, February 22-25, 2026 in Salt Lake City, UT and published in the proceedings (Denzel 2026).

Introduction

In the mineral processing industry comminution is the most energy-intensive process and accounts for a large part of operating costs for mineral concentrate production (Wills 2006). Approximately 50% of the electric energy at mine site and 4% of the global energy is consumed by comminution (Jeswiet 2016). This allows the mineral processing industry to significantly contribute to a sustainable future and a reduction of emissions by implementing more efficient comminution solutions. Tumbling mills are frequently used for comminution, especially for coarse grinding applications. In a tumbling mill different types of grinding media like steel balls, rods or pebbles are lifted together with the material in a rotating horizontal drum and particle breakage is achieved mainly by impacts. A significant share of the energy is hereby absorbed in low- impact contacts, which do not lead to particle breakage or further size reduction (Wills 2006).

Stirred media mills are an attractive alternative to tumbling mills, especially for fine and ultra-fine grinding applications due to the high induced shear energy. The specific breakage energy increases with decreasing initial particle size (Vogel 2003). Thus, more energy is required when grinding finer. Compared to ball mills, gravity induced tower mills are more energy efficient (Shi 2009) and are increasingly considered for applications previously performed by ball mills (Capstick 2012). Nowadays the vertical stirred wet milling technology is a well-recognized technology for tertiary, regrind and fine grinding applications.

Modeling comminution processes is of great interest because it allows to optimize and adjust to a large set of mutually influencing parameters. This is beneficial not only for research and development, but also in the aftermarket and service, allowing to properly react to changes in customer requirements and eventual failures. Especially, modeling power draw is of great interest, proven by extensive work in developing analytical power models based on measurement data for fine grinding vertical stirred mills (Heath 2016).

The Discrete Element Method (DEM) is a powerful tool for investigating phenomena occurring at the scale of particle diameter and simulating bulk behavior. Thus, DEM has become widely established as an efficient method addressing a variety of engineering problems with granular and discontinuous materials like granular flows, powder mechanics or comminution (Weerasekara 2013). Recent advances in discrete element modeling of rock fracture for next-generation comminution models are described in (Tojaga 2025).

Depending on particle size, number of particles, computational power and required accuracy different approaches have been developed to describe breakage embedded in DEM. In the Bonded Particle Model (BPM) progeny particles are resolved throughout the simulation, which is suitable for crushers (Quist 2016). In the Particle Replacement Method (PRM), the particles are replaced by several progeny particles when the criterion for failure is met.

Figure 1. Rendered HIGmill™

In some cases, especially when small particles are involved, the number of particles exceeds current computational limits and other numerical methods such as Computational Fluid Dynamics (CFD) or Smoothed Particle Hydrodynamics (SPH) may play a leading role in simulating some comminution processes. SPH is particularly useful for two-phase and free surface fluid flows, as occurring in tumbling mills, and can be coupled with DEM (Murariu 2024). CFD is ideal for single-phase flows including laminar and turbulent flows with various fluid rheologies and is able to describe particle-fluid interactions and media flow accurately when coupled with DEM (Carvalho 2023).

As DEM breakage models are more suitable for coarser comminution applications due to still limited computational power, Population Balance Models (PBM) are additionally used to predict product fineness in grinding applications and can speed up breakage simulations (Herbst 2014). The UFRJ mechanistic mill model (Carvalho 2013) was applied to describe comminution in a vertical stirred mill (Oliveira 2020). This approach was also used to simulate media and slurry motion in a continuous vertical stirred mill using a DEM-CFD coupled model assuming a Newtonian fluid with a viscosity exclusively depending on solids volume fraction (Carvalho 2023). This was further developed with an improved rheology model considering slurry concentration and particle size (Petit 2025).

A different approach for modeling a vertical stirred media mill is presented in (Larsson 2021) using the particle finite element method (PFEM) for the fluid including non Newtonian behavior, DEM for the grinding media and the Finite Element Method (FEM) for the mill structure.

Vertical arrangement leads to high grinding intensity in the bottom grinding chambers and uneven power distribution along the shaft. Thus, bottom rotors may wear out more than upper rotors, critically influencing service intervals and operational costs. In (Denzel 2025) a DEM model to determine the power distribution along the shaft in a vertical stirred mill is presented. Different rotor con- figurations were evaluated, whereby the rotors vary in diameter, alignment and spacing. An optimized rotor con- figuration with a combination of different rotors could be developed, which leads to a more even power distribution and a significant reduction of load on the bottom rotors, also reducing liner wear. Simulations also revealed particle dynamics, which explain field experience in terms of wear. Furthermore, this study shows that higher filling levels increase power draw following an exponential trend.

To support mill development and optimization of existing operational mills, a model is demanded to simulate and predict power draw of vertical stirred mills under different operating conditions. These include variations of shaft speed, grinding media filling level and fluidization as well as geometrical changes in grinding compartment configuration. Depending on process conditions and special requests, different rotor and liner configurations for the same mill type are in operation. Retrospective changes in operational conditions like feed material or power consumption require modified shaft configurations in some cases. Another reason for modified grinding compartment configurations is the intentional transfer of wear to parts which are more accessible for logistical reasons or changes in supply chains. Thus, this power model will provide a powerful tool for mill development, service and technical support in the aftermarket significantly reducing experimental costs and reaction time.

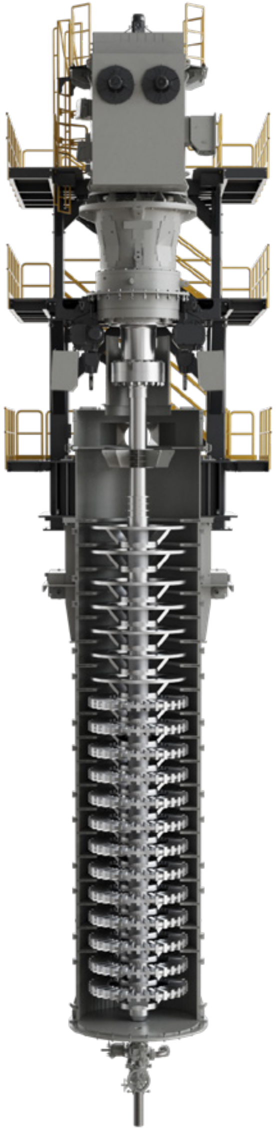


Figure 2. Rendered cross-sectional view of HIGmill™

HIGmill™ technology

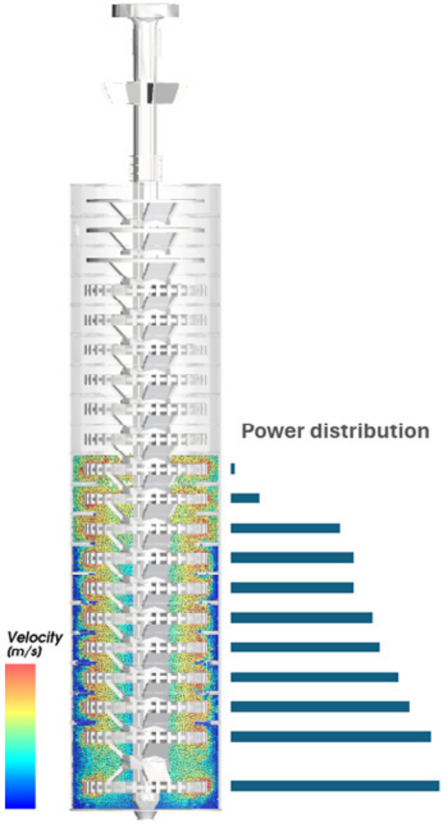
The HIGmill™ (High Intensity Grinding) is a high-speed vertical wet-stirred media mill, designed for efficient comminution targeting fine and ultrafine particle size distributions (Wang 2025) offered in sizes from 75kW and 200L to 7.15MW and 50,000L. Its configuration consists of a stationary shell with rotating grinding rotors on a shaft to stir the media charge against a series of stator rings (Figure 3).

Extensive studies were performed to optimize rotor design in terms of energy efficiency using DEM, laboratory, pilot scale and industrial size mills resulting in a castellated rotor design (Keikkala 2018). The castellations hold a layer of grinding beads, reducing slippage between beads and rotors compared to flat discs. This leads to reduced rotor wear (Letho 2016) due to increased bead-to-bead shear further away from the rotor, more inside the bulk of the bead volume (Heath 2017). The feed slurry is introduced from the mill bottom, travels upwards through a media bed and eventually discharges at the top. The process is typically a single pass with no external classification required.

Particle breakage in the HIGmill™ occurs primarily through attrition mechanism, combining compression and shear forces. The special design encourages attrition break- age, particularly in high intensity grinding zones. The rotating grinding rotors create centrifugal forces which push coarser particles and grinding media into the high intensity grinding zones on the periphery of the grinding chamber, while finer particles travel upwards closer to the mill shaft.

Figure 3. Rendered cross-sectional view of HIGmill™ with ceramic grinding media

This prevents over grinding and ensures the energy is applied mainly to coarser particles. Gravity and the vertical arrangement of the HIGmill™ ensure that the media is kept compact during operation, leading to intense inter- bead contacts, maximized energy transfer through the mill volume.



Source: Denzel 2025
Figure 4. Power distribution in a 50,000L HIGmill™ determined with DEM

Power distribution (Figure 4) can be optimized by modifying grinding compartment configurations (Denzel 2025). These effects lead to high grinding efficiency and minimize energy consumption. In combination with other process equipment, the HIGmill™ also contributes to minimizing water consumption, further reducing carbon footprint and OPEX (Wang 2024).

Development strategy

In Figure 5 the development strategy for the DEM-CFD coupled power model is depicted. Purpose of the model is to simulate and predict power draw of vertical stirred mills under different operating conditions including variations of shaft speed, grinding media filling level, fluidization and changes in grinding compartment configuration.

First a DEM model of the 25L test mill is created. In the DEM model only particle dynamics are considered. As fluidization has a significant influence on power draw, the DEM model is coupled with a CFD model to also consider fluid dynamics and its influences on particle dynamics including buoyancy and drag.

To validate the numerical model an extensive test program is performed at Metso's test center in Villach (Austria). A trial on a water-fluidized 25L test mill is used as baseline for parameter variations and scaling. Design of experiments is conducted whereby key parameters are varied systematically including shaft speed, flow rate, filling level, rotor diameter and grinding media size and density. In the next step water is replaced by ore slurry and solids content and viscosity are varied. This is challenging due to the non-Newtonian rheology of ore slurries, which have a shear-thinning behavior. Therefore, a viscosity model is required which needs to be implemented into the simulation model. In the following step scaling effects on a lab- scale are evaluated using a 5L and 200L test mill.

Further scale-up effects are determined using data from large operational mills. The large number of particles in these mills would require enormous computational effort. To simulate large mills within a reasonable time with contemporaneous computing power, coarse grain models are used.

Hereby the total number of particles in the simulation is reduced by replacing original particles with parcels which represent the collective behavior of the original particles. When scaling laws are considered, coarse grain models allow a balance between computational efficiency and physical accuracy (Di Renzo 2021).

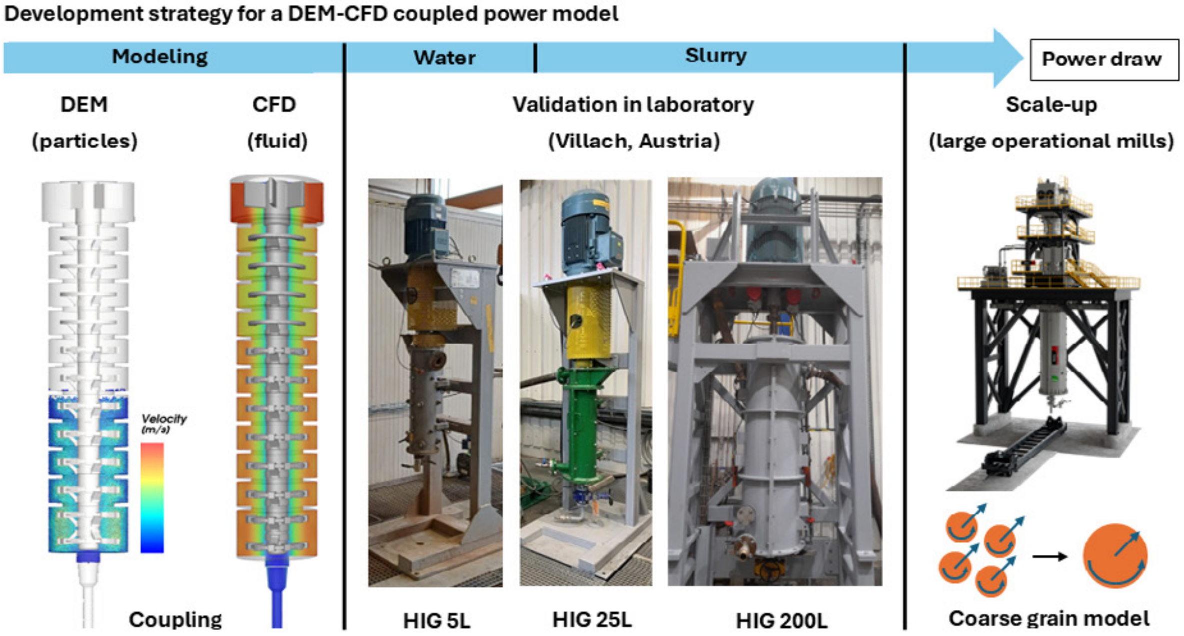


Figure 5. Development strategy for a DEM-CFD coupled model to determine power draw in vertical stirred mills

Modeling

In the first step a surface model is derived from a solid CAD model. Only surfaces in contact with particles or fluid are considered to reduce computational effort in the following meshing process. Then a fluid volume is derived from the surface model, inlets and outlets are defined and the geometry is divided into static and rotating walls. The same surface geometries are used for DEM and CFD models to ensure coupling capability.

In the DEM model (Figure 5) normal forces are calculated using the Hysteretic Linear Spring model. Initial material parameters from (Probst 2023) are used and are further adjusted by an extended material calibration procedure using static and dynamic angle of repose tests. In the simulation mono-sized particles are used representing the average grinding bead diameter. The mill is filled with a volumetric fill feature, which instantly fills a volume with particles around a seed considering boundary geometries. Due to high peaks during start-up, torques can only be evaluated after a quasi-steady state when initial oscillations are subsided. The required simulation time to reach this quasi-steady state depends on rotor configuration and increases with higher grinding media filling levels. The power is then calculated considering the rotational shaft speed.

The mesh for the CFD model (Figure 5) is created using Ansys' watertight workflow and is refined in areas where a higher resolution is required. The inlet is defined as mass-flow inlet and the outlet as outflow without restrictions.

The color scale in Figure 5 represents the particle translational velocity in the DEM. In the CFD model the color also represents the fluid velocity but with a different scaling. The CFD model confirms high circumferential fluid velocities in upper chambers, also with non-castellated discs. Resulting centrifugal forces prevent coarse particles from exiting the mill which contributes to a narrow particle size distribution in the product.

In Figure 6 the 1-way coupled DEM-CFD model is depicted whereby the fluid is visualized by a vector field.

The color scale represents particle and fluid velocity on the same scale. To create a 1-way coupled DEM-CFD model the constant fluid field from the CFD software is imported into the DEM software. 1-way coupling in this case means that particles are influenced by the fluid, but the fluid is not influenced by the particles. 2-way coupling would increase accuracy but also increases computational effort significantly as the fluid field needs to be recalculated after each particle movement.

Therefore, the data is transmitted between DEM and CFD software which increases computing times. 2-way coupled DEM-CFD simulations were performed for a water-fluidized 5L test mill (Probst 2023) on a high-end calculation server within several weeks. To simulate larger mills within a reasonable computing time and to provide an industry supportive model, 1-way coupling is pursued to simulate power draw.

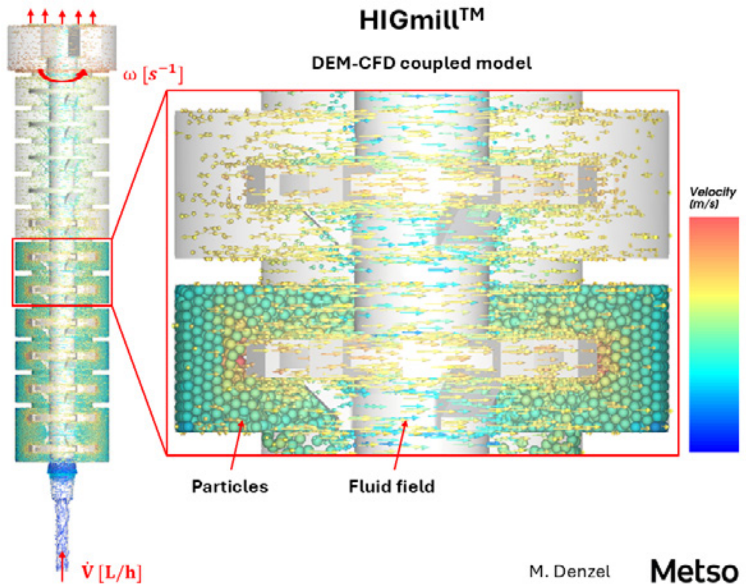


Figure 6. DEM-CFD coupled (1-way) model of 25L test mill with fluid visualized by a vector field

Experimental

To validate the model an extensive test program in Metso's test center in Villach (Austria) is initiated. The first trials are performed on a 25L test mill which is equipped with torque and rotational speed sensors at the top of the shaft (Figure 5). This test mill is further equipped with pressure sensors for each grinding chamber (Figure 8) and the feed pipe.

Four pressure sensors can be mounted per chamber which allows to validate the CFD model and evaluate pressure gradients between and within individual grinding chambers. The fluid is introduced with a hose pump through the bottom feed pipe.

Vibrations are measured manually at the mill shell. High vibrations are noticed around 600 rpm on this mill which varies with rotor con- figuration and grinding media filling level.

A standardized test procedure is applied whereby the shaft speed is stepwise increased for each test. Test parameters are varied individually according to the design of experiments. To ensure comparability of test results due to re-use of grinding media, the grinding media is screened before each trial.

Grinding media conditions significantly affect inter-particle friction coefficients and depend on surface roughness, wear, wetting and cohesion effects. A simple angle of repose test is performed before each trial to capture grinding media friction behavior and eventually adjust friction coefficients to increase simulation accuracy.

In Figure 7 torque data from a trial with three different flow rates is plotted against shaft speed and compared with DEM results.

Hereby the grinding media filling level is kept constant, and flow rate was incrementally increased. The results show that torque follows an exponential trend with shaft speed increase and that fluidization significantly decreases torque.

Torque data near resonance speeds at 600rpm is lower and was excluded for curve fitting. DEM results follow a similar exponential increase but with a higher incline as fluidization is not considered.

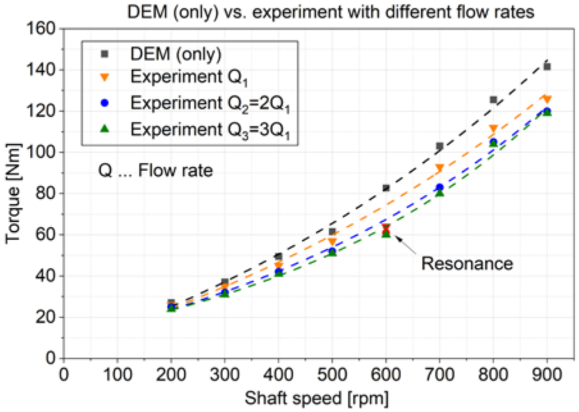


Figure 7. Comparison of DEM (only) and experimental results on a water-fluidized 25L test mill with various flow rates

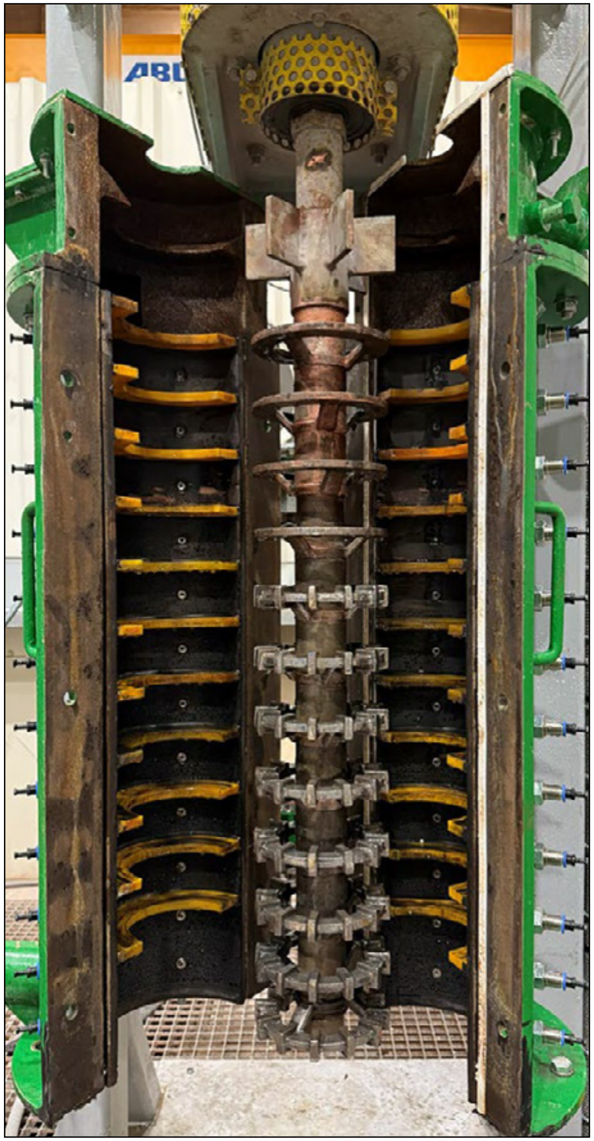


Figure 8. Special sensor-equipped 25L test mill in Metso's test center in Villach (Austria)

Conclusion and outlook

Comparison of DEM and experimental results in Figure 6 shows that DEM overestimates torque because fluidization is not considered. Fluidization significantly reduces torque, which matches field experience. This confirms the importance of coupling DEM with CFD to increase accuracy of the simulation model by considering fluidization effects.

Previous studies and initial simulation approaches showed that a 2-way coupled DEM-CFD model requires computing times which are too high for this use case to be applied as an industry supportive model. Thus, 1-way coupling is pursued to simulate power draw also for large mills in reasonable computing times. This provides an applicable balance between accuracy and computing time with current computing power.

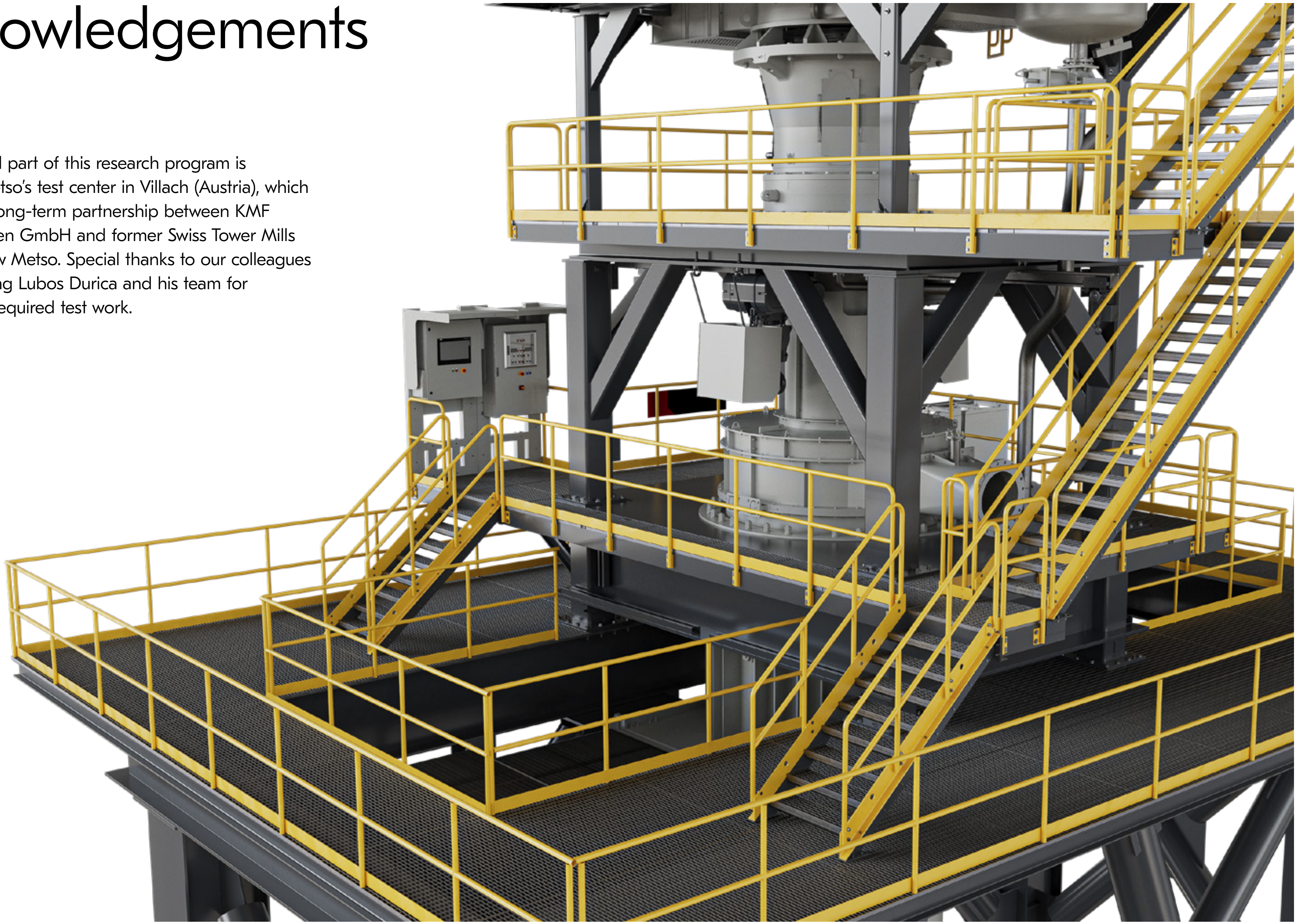
At the time of writing this contribution, first trials with a water-fluidized 25L test mill have been performed to create a reference for future parameter variation. In the next steps filling level, rotor configuration and grinding media size and density will be varied. These test conditions will then be simulated with the 1-way coupled DEM-CFD model and compared with experimental results.

Additionally, an extended material calibration procedure will be carried out using static and dynamic angle of repose tests to increase accuracy of the model. Furthermore, pressure measurements will be performed to validate the CFD model and evaluate pressure gradients between and within grinding chambers.

Figure 9. HIGmill process island rendering

Acknowledgements

The experimental part of this research program is conducted in Metso's test center in Villach (Austria), which resulted from a long-term partnership between KMF Maschinenfabriken GmbH and former Swiss Tower Mills Minerals AG, now Metso. Special thanks to our colleagues in Villach including Lubos Durica and his team for conducting the required test work.



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