Multiphase flow modelling for sustainable deep-sea mining

Suharto Saha [1,*], *Manuel* Münsch[1], *Aliena* Bösl[1], *Matthias* Semel[2], *Stefan* Wegerer[2] and *Andreas* Wierschem[1]

[1]Institute of Fluid Mechanics, Friedrich Alexander University Erlangen Nürnberg (FAU), 91054 Erlangen, Germany
[2]Bauer Group AG, 86529 Schrobenhausen, Germany

Abstract. Deep-sea mining extracts polymetallic sulphides at extreme depths, requiring sustainable approaches to minimize environmental impact. Seabed milling, particle transport, and a hydrocyclone based containment system are modelled in CFD-DEM simulations to support the development of efficient and sustainable deep-sea mining operations. For instance, turbulent material transport can be enhanced with shielded counter-rotating trench cutter wheels while mitigating turbidity plumes. Furthermore, with parametric studies on hydrocyclone pressure drop and separation efficiency, we designed the separator unit.

1 Introduction

The increasing demand for critical minerals such as copper, zinc, and cobalt has driven interest in deep-sea mining as a viable alternative to terrestrial extraction. Polymetallic sulphide deposits, located at depths of 3,000–5,000 meters, offer a high concentration of valuable resources. However, the harsh deep-sea environment, characterized by high pressures, low temperatures, and fragile ecosystems, presents significant engineering and environmental challenges. One of the primary concerns is sediment plume formation, where fine particulate matter disperses over large areas, potentially disrupting benthic habitats and marine ecosystems [1]. Efficient material separation and transport mechanisms are therefore essential for minimizing ecological impact while ensuring sustainable resource recovery.

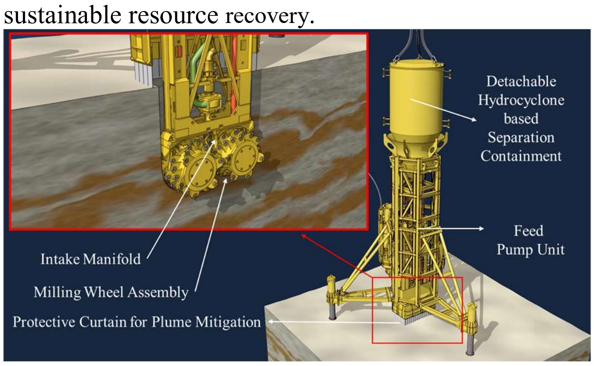

Fig. 1. Geometrical setup of the Deep Sea Sampling device.

The Deep Sea Sampling (DSS) project is a joint collaboration amongst various industrial and university partners in Germany addressing these challenges by adapting a trench cutter system for underwater use (Fig. 1). This system employs counter-rotating cutting wheels to fragment seabed material, which is transported via a pump to a hydrocyclone-like separator for solid-liquid separation, which is complemented by filters (Fig. 2). By implementing a closed-loop water recirculation system, the design minimizes sediment resuspension and reduces turbidity plumes, mitigating environmental risks. However, optimizing this process requires a detailed understanding of multiphase flows, particle transport, and turbulent interactions [2].

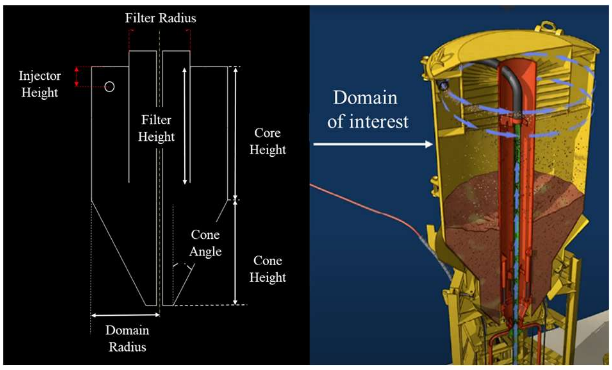

Fig. 2. Hydrocyclone-like containment device for DSS

2 Numerical Methodology

We employ Computational Fluid Dynamics (CFD) and Discrete Element Method (DEM) in Siemens Simcenter Star-CCM+ to model a diverse range of turbulent length scales. The study aims to investigate seabed milling, granular transport, and the performance of the containment system. Parametric studies help identifying key geometric factors of the custom hydrocyclone efficiency. Water at deep-sea condition (4°C) and corresponding density and viscosity has been used as transport medium for all simulations. The Reynolds number (*Re*) for the hydrocyclone simulation is dependent on the core diameter and inlet velocity ranges from $1*10^6 – 8*10^7$, indicating a highly turbulent

* Corresponding author: suharto.saha@fau.de

flow regime influenced by inlet velocity and diameter variations. For milling wheels, the *Re* ranges from 1-7*10⁶, confirming turbulence-driven particle transport around the rotating cutters. To account for this, numerical simulations of the flow within the hydrocyclone are performed using Reynolds-Averaged Navier-Stokes (RANS) and Unsteady Reynolds-Averaged Navier-Stokes (URANS) approaches [6]. To understand the generation of smaller turbulent structures and their interaction with solid particles, the milling wheels have been studied using Large Eddy Simulations (LES) using the Wall-Adapting Local Eddy-viscosity (WALE) model. The Stokes number (*St*) is a dimensionless parameter to characterize the behaviour of particles in a flow, particularly their ability to follow the streamlines or to deviate due to inertia. It is defined as the ratio of the particle relaxation time to the characteristic flow time. Particle density ranging from 2500 to 3700 kg/m³, and particle diameter (d_p) ranging from 1 µm to 5 cm have been studied. For the milling wheel, the characteristic velocity is based on the 1.25 m diameter of the wheel and its rotating speed of 15-25 RPM. For the hydrocyclone, it is based on inlet velocity (6 m/s). The cutoff diameter for *St* = 1, marking the transition between particle adherence and detachment to streamlines, is found to be 1.7 mm to 2.5 mm, depending on particle density. Based on *St*, various simulation strategies are adopted to model particle flow.

2.1 Geometric Parametrization for Design of Experiments (DoE)

The hydrocyclone geometry is parametrized to enable design space exploration. The geometry sets itself apart from the traditional hydrocyclones due to the presence of a central core for feed transport (Fig. 2). Key structural components including the cylindrical section, conical section, vortex finder, and inlet region—is constrained to maintain geometric consistency. Five primary design parameters have been selected for systematic variation viz. the cone angle, cone height, core height, filter height, and domain radius. These parameters are constrained within predefined limits (Table 1) to prevent unintended geometric inconsistencies while preserving the functional integrity of the hydrocyclone.

Table 1. Parameter Range for the Design Space Exploration

Parameter	Min	Max	Discrete/ Continuous
Cone Angle (-)	5°	40°	Discrete
Cone Height (m)	0.4	4	Continuous
Core Height (m)	0.2	3	Continuous
Filter Height (m)	0.3	3.5	Continuous
Domain Radius (m)	0.5	3	Continuous

The inlet positioning is constrained by linking it to the midpoint between the cylinder and vortex finder edges, ensuring spatial consistency and avoiding potential meshing errors. This structured parametrization framework provided a robust foundation for downstream computational modelling by maintaining geometric fidelity and ensuring smooth mesh generation without numerical artefacts. A Design of Experiments (DoE) study is carried out to systematically evaluate the influence of various geometric parameters on the performance of the hydrocyclone, with pressure drop selected as the primary objective function. Investigation on pressure drop is essential and indicates efficiency [3]. A custom pseudo-random sampling strategy is implemented via a StarCCM+ Java macro, generating input parameters within defined bounds. Although, inspired by Latin Hypercube Sampling, it avoids full LHS to maintain some manual control over parameter selection and geometric constraints..

2.2 Grid Generation and Turbulence Modelling

The computational domain is discretized using a hexahedral trimmed mesh with prism layers, ensuring boundary layer resolution (maintaining local y+ < 1) while maintaining computational efficiency. Grid resolution ranges from 1-300*10⁶ cells with varied parameters. A mesh independence study performed on five selected configurations shows that solution fluctuations remain below 2%, ensuring numerical stability and reliability. In addition to the refined mesh in the inlet region, resolution of counter-rotating Dean vortices have been used as one of the refinement criteria. To model swirling and separation accurately, a steady-state solution without curvature correction is first computed, followed by an unsteady solution, both using the k-ω SST turbulence model [5]. This captures turbulence anisotropy, near-wall effects, and flow separation. An incompressible segregated flow solver with SIMPLE-based pressure-velocity coupling ensures stability and steady convergence. A second-order implicit time discretisation improves temporal accuracy for unsteady features [8]. For the Euler-Lagrange multiphase simulations, particle injection is implemented near the hydrocyclone inlet, with d_p ranging from 1 µm to 1 cm, following a normal size distribution (mean d_p of 1 mm and standard deviation of 0.1 mm). The turbulent dispersion model is activated to account for stochastic fluctuations in particle trajectories due to local turbulence intensities.

Additionally, the Discrete Phase Model (DPM) is used to incorporate drag, lift, pressure gradient, and turbulent dispersion forces, enabling the assessment of particle rebound, sedimentation, and separation efficiency. To ensure accurate resolution of turbulent structures near the seabed, the initial simulations for the milling wheel simulations are performed using RANS on a grid-independent case, followed by URANS to capture transient effects, and ultimately LES to resolve finer turbulent eddies. The LES grid is refined in the core flow region to a resolution of approximately 30–60 times the Kolmogorov length scale, ensuring an optimal balance between turbulence resolution and computational feasibility. To mimic the drilling process, a particle bed is injected at the bottom with d_p of 1 μm-2 cm at an injection rate of 10 cm/s. For larger particles in seabed, $St << 1$ held, indicating that particle motion is dominated by the surrounding fluid, making them highly sensitive to flow fluctuations. This eventually led to the injection of over $50*10^6$ particles within the computational domain making it computationally expensive without particle depletion. Meshfree DEM simulations are used with a force-compensated approach to model buoyancy, reducing gravitational pull via a custom function for efficient and accurate particle interaction. DEM particle beds have been generated using 1-5 cm spherical particles, ensuring realistic representation of the seabed. Given $St >> 1$, these particles are largely inertial, i.e. their movement is primarily governed by the milling wheel impact rather than fluid flow. To study this, spherical particles are injected to analyse their response to wheel-induced forces, including movement, resuspension, and erosion.

3 Results and Discussions

A comprehensive design space exploration has been performed to evaluate the influence of five key geometric parameters—cone angle, cone height, core height, filter height, and domain radius—on the pressure drop across the filtration system of the concept (Fig. 3). The corresponding correlation coefficients quantifying these relationships are plotted (Fig. 4).

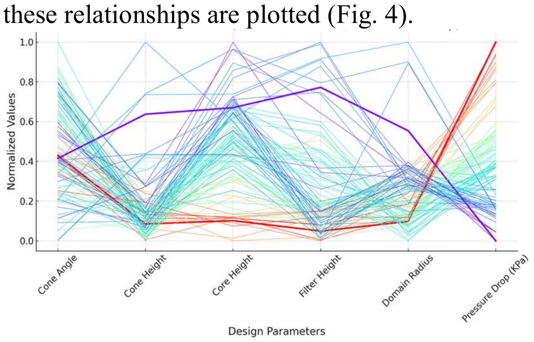

Fig. 3. Parallel coordinate plot of 93 designs illustrating normalised design parameters across all configurations coloured by pressure drop.

The analysis reveals that core height is the most dominant factor affecting pressure drop, followed by domain radius and filter height. Cone height exhibits a moderate impact, while cone angle contributes the least. Notably, the negative correlation signs observed for most parameters suggest an inverse relationship with pressure drop, implying that increases in these parameters generally lead to lower pressure losses. These findings highlight the importance of optimising core height, domain radius, and filter height to minimise resistance, whereas cone angle can be deprioritised in future design iterations. Investigations on hydrocyclone performance often emphasize the role of vortex finder geometry, cone shape, and inlet velocity in determining efficiency and pressure drop. Literature suggests [2,3,7] that increasing the core height generally leads to higher pressure drops due to increased flow resistance in the separation zone, which aligns with our findings (Fig. 5).

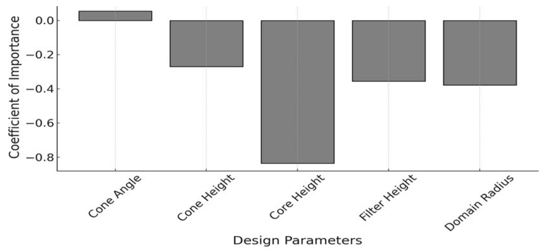

Fig. 4. Correlation based importance of design parameters.

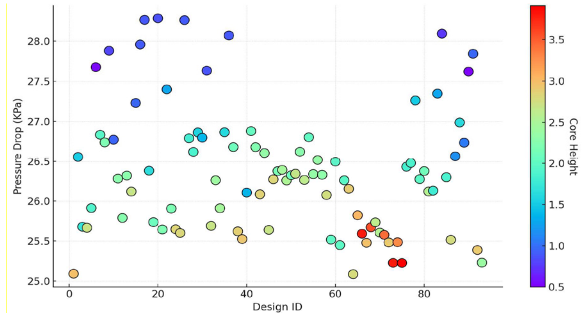

Fig. 5. Scatter Plot of Design Id vs. Pressure Drop (KPa) coloured by core height.

However, some research highlights [9] the influence of inflow diameter and underflow diameter as additional key contributors, which are considered in this dataset. Additionally, while many studies focus on the effect of cone angle on separation efficiency, its impact on pressure drop is considered secondary, which is consistent with our results. The separation diameter of the hydrocyclone-based device is further evaluated. Due to the large number of particles with smaller d_p, the particles are injected near the filters as tracers with mass and zero initial velocity to analyse their trajectories and interaction with the flow field.

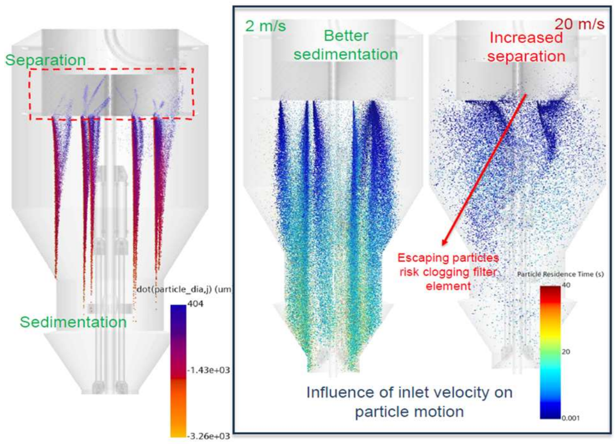

Fig. 6. Particle injection for separation and sedimentation

Preliminary results indicate that a wide range of particle diameters tend to exit through the filters at higher inlet velocities, leading to inefficient fine particle separation and an increased risk of filter clogging. At lower inlet velocities, enhanced sedimentation is observed, demonstrating the functional effectiveness of the separation container and highlighting the need for supplemental filtration systems (Fig. 6). An analysis of separation diameter across varying velocities shows that it increases with inlet velocity (Fig. 7). Notably, the separation diameter rises sharply at lower velocities, but the rate of increase diminishes at higher velocities, indicating asymptotic behaviour governed by inertial effects and flow saturation..

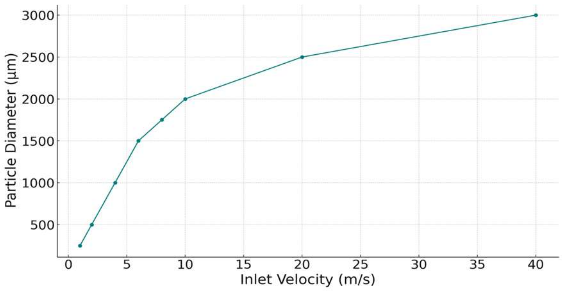

Fig. 7. Particle separation diameter vs. inlet velocity in hydrocyclone-based separation containment (m/s).

Further, the simulations for the milling wheels focus on the flow field, particle transport, and turbulence generated by the counter-rotating cutters operating at the seabed. A Rigid Body Motion approach is used to model the rotating wheels. Turbulent structures are analysed to evaluate their formation and influence on particle entrainment. Visualisation of the flow field (Fig. 8) reveals the development of small-scale turbulent structures in the inter-wheel region, with zones of high vorticity highlighting intense turbulent interactions and higher velocities, which drive particle transport to the hydrocyclone.

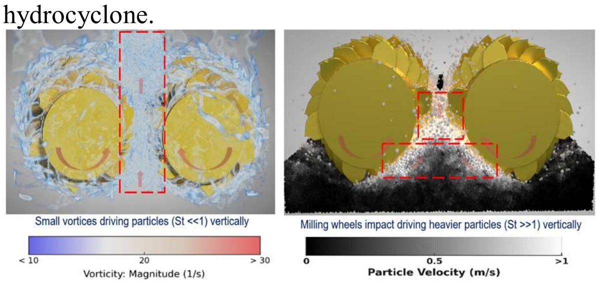

Fig. 8. CFD(left)-DEM(right) simulation of milling process.

The rotation induces a lift force, creating strong recirculation and turbulent interaction that play a significant role in particle entrainment and transport. The Euler-Lagrange coupled multiphase simulations captured the behaviour of inertia-driven particles at *St* >> 1, ensuring a detailed representation of solid-fluid interactions. The DEM simulations additionally modelled the seabed as a fixed particle bed, incorporating varying d_p (1-10 cm). Cohesion forces and bond strengths have been included to simulate a wide range of seabed conditions, from loosely packed sandy beds to solid rock formations. The particle transport and the milled profile is in qualitative agreement to the on-shore tests using the trench cutter. The DEM approach, along with flow simulations, confirms that particles are transported in the central section toward the intake manifold due to both the lifting force (*St* << 1) of the fluid and the direct mechanical impact (*St* >>1) of the cutting wheels. Fluid management strategies ensure that sucked-up water with minimal turbidity is returned to the site. While full-scale validation is not yet feasible due to the conceptual nature of the mining system, pilot-scale testing is planned in future. The current study serves as a conceptual design, and results show qualitative agreement with established trends in hydrocyclone and trench cutter behaviour. The numerical setup, including mesh resolution and modelling strategy, follows state-of-the-art practices in industrial simulations, ensuring methodological reliability.

4 Conclusions

This study presents a CFD-DEM framework for modelling key deep-sea mining processes, including seabed milling, particle transport, and hydrocyclone separation. Core height and domain radius are identified as key design factors influencing pressure drop and separation efficiency. Using RANS, URANS, LES, and DEM, the approach captures fluid-particle interactions across scales, aiding performance optimisation and reduced environmental impact, laying the groundwork for low-impact, robust extraction systems.

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