15th IFK
Proc. of the 15th International Fluid Power Conference <Symposium/Conference>
<DOI>

Downsizing of hydraulic power units by accurate prediction of disperse flows

Dr.-Ing. Mark-Patrick Mühlhausen*

Dr.-Ing. Markus Perschall*

M.Sc. Alexander Huber*

**Bosch Rexroth AG, Zum Eisengießer 1, 97816 Lohr am Main*

Corresponding author: mark-patrick.muehlhausen@boschrexroth.de

Abstract.

Downsizing of hydraulic power units means installing the same hydraulic power within a smaller footprint or increasing hydraulic power within the same footprint.

To achieve this, knowledge and influencing the condition of the hydraulic fluid and the tank flow are crucial. The condition of the hydraulic fluid depends primarily on dispersed contaminations by air bubbles, water droplets, and dirt particles. All of these should be separated in the reservoir, which can be significantly improved through suitable flow guidance. The resulting improved fluid condition contributes to significant resource savings over the entire product life cycle, thus generating tangible economic and technological advantages.

The difficulties in implementation lie, on the practical side, mainly in the strong influence of the system's operating conditions, such as pressure and flow rate curves, and on the modeling side, due to the complex properties of hydraulic fluids, which also vary across the entire spectrum of fluid classes. Both challenges often prevent generally valid statements and therefore require a multitude of CFD simulations for various systems and even the same systems under different load situations.

We combine the solution to the resulting high demands on the model quality and the performance of the numerical method in bTrack, our in-house solver for dispersed flows. In this presentation, we provide an overview of the physical and numerical fundamentals of bTrack. We start with simple equations of motion and extend these continuously with algorithms capturing more complex phenomena like collision, breakup and coalescence. We also present and discuss coupling strategies between the disperse and continuous phase implemented in bTrack. The performance and efficiency of the models are presented and discussed using various application examples for bubble, particle, and droplet flows in tanks.

bTrack has thus been an essential component of the myCro Downsizing toolbox from Bosch Rexroth for more than a decade.

Keywords. downsizing, air bubbles, mycro, cfd, simulation

1. INTRODUCTION

The hydraulic industry faces increasing pressure to reduce the footprint and weight of hydraulic power units while maintaining or increasing performance. This downsizing trend is driven by demands for improved energy efficiency, reduced material costs, and enhanced system integration in mobile and industrial applications. A critical component is the hydraulic reservoir, which traditionally has been sized conservatively to ensure adequate fluid conditioning, heat dissipation, and contaminant settling. Significant reservoir size reduction is only feasible if fluid quality can be maintained despite reduced residence times and settling volumes. Hydraulic fluid condition is strongly determined by three types of dispersed contaminations: entrained air bubbles, emulsified water droplets, and solid dirt particles. Air enters through turbulent mixing at free surfaces, and suction-side leakage; water through condensation and seal leakage; and particles through external ingress and internal wear.

These dispersed contaminants cause numerous detrimental effects on hydraulic system performance and durability. Entrained air reduces the effective bulk modulus, leading to spongy system response, reduced positioning accuracy, and increased noise and vibration as well as oxidation and Diesel effect. Water contamination accelerates fluid degradation through hydrolysis, promotes corrosion of metallic components, reduces lubrication effectiveness, and catalyzes oxidation processes. Solid particles cause abrasive wear on precision surfaces, leading to internal leakage, reduced efficiency, and component failure.

The extent of air and water contamination strongly depends on both fluid properties and operating conditions. Air solubility in hydraulic fluids follows Henry's law, making gas absorption and release pressure-dependent phenomena. This can be illustrated by a carbonated mineral water bottle: when sealed under pressure, carbon dioxide remains dissolved; upon opening, pressure drops and gas bubbles form and rise. Similarly, hydraulic fluid returning from high-pressure zones to the atmospheric reservoir experiences pressure reduction, causing dissolved air to nucleate into bubbles requiring separation. Water solubility and emulsion stability are likewise influenced by temperature, pressure, and fluid additive packages, with mineral oils, synthetic esters, and water-glycol fluids exhibiting drastically different behaviors.

Successful reservoir downsizing through improved contamination control offers substantial lifecycle benefits. Reduced reservoir volume directly translates to lower fluid inventory, decreased system weight, and smaller footprints – critical advantages in mobile hydraulics where space and weight constraints are severe. Improved fluid quality extends component life by reducing wear rates, increase maintenance intervals by slowing fluid degradation, and enhances system reliability through consistent performance. Economically, these improvements reduce both initial investment and total cost of ownership. Environmental benefits include reduced fluid consumption and lower energy requirements from improved system efficiency. Furthermore, high fluid quality enables tighter manufacturing tolerances in hydraulic components, permitting higher operating pressures and power densities – reinforcing downsizing objectives.

Effective downsizing requires accurate prediction of fluid flow patterns and contaminant separation efficiency within reservoirs. The reservoir must facilitate air bubble and solid particle separation while providing adequate deaeration surface, appropriate flow velocities to prevent particle resuspension, and sufficient residence time for settling. Computational Fluid Dynamics (CFD) enables optimization of reservoir designs, flow guidance structures, baffle arrangements, and inlet/outlet configurations without costly prototyping. However, reservoir flows present significant modeling challenges. The flow is inherently three-dimensional and highly unsteady, driven by turbulent structures and time-varying boundary conditions reflecting realistic operation. During typical operation, volume flow rates entering the reservoir vary by orders of magnitude depending on actuator movements, valve switching, and pump displacement changes. These transient conditions continuously alter the flow field, affecting particle trajectories and separation efficiency in ways not captured by steady-state simulations. Additionally, the wide range of hydraulic fluid types – from mineral oils to water-based fluids – each with distinct density, viscosity, surface tension, and foaming characteristics, prevents universal design rules.

Several numerical approaches exist for modeling dispersed multiphase flows. The Euler-Euler approach treats both phases as interpenetrating continua, solving conservation equations for each with interphase exchange terms. This method is computationally efficient at high volume fractions but requires closure models for interfacial forces and cannot easily track individual particle characteristics. The Euler-Lagrange approach treats the continuous phase as a continuum while tracking individual particles or bubbles as discrete entities moving according to Newton's equations. This method naturally accommodates polydisperse size distributions, enables direct implementation of collision, breakup, and coalescence models, and provides detailed particle trajectory statistics. For dilute to moderately dense dispersed flows – typical of hydraulic reservoirs where volume fractions generally remain below 10% – Euler-Lagrange offers optimal balance between physical fidelity and computational efficiency.

We employ a three-dimensional CFD approach combining Eulerian description of the continuous phase with Lagrangian tracking of dispersed contaminants. This framework captures complex, transient three-dimensional reservoir flow structures while resolving trajectories of individual air bubbles, water droplets, and solid particles. Lagrangian tracking naturally accounts for size-dependent separation, enables physically sound particle-particle and particle-wall interaction models, and facilitates bubble coalescence and breakup submodels. Two-way coupling ensures dispersed contaminants appropriately modify continuous phase momentum and turbulence fields, essential for accurate prediction at higher concentrations. This methodology is implemented in our in-house solver bTrack, developed and validated specifically for dispersed flows in hydraulic systems. bTrack is well matured and has been used in the analysis and optimization of hydraulic power units of Bosch Rexroth since more than a decade. Since the

Figure 1: mycro logo

beginning, it has been an essential part of the myCro Downsizing toolbox [1] and is today a further growing key factor of its success contributing to both customer-specific ETO applications as well as Bosch Rexroth Standard HPU solutions.

2. METHODOLOGY

The continuous fluid phase is described by the incompressible Navier-Stokes equations for mass and momentum conservation:

$$\nabla \cdot \mathbf{u} = 0$$

$$\frac{\partial}{\partial t}\rho\boldsymbol{u} + \boldsymbol{\nabla}\cdot(\rho\boldsymbol{u}\boldsymbol{u}) = -\boldsymbol{\nabla}\mathrm{p} + \boldsymbol{\nabla}\cdot\left(2\mu_{eff}\boldsymbol{S}\right) + \rho\,\boldsymbol{g} + \boldsymbol{S}_{b,mom}$$

with $\boldsymbol{u}$ the fluid velocity, p the pressure on the Euler grid, $\boldsymbol{S} = \frac{1}{2}[\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T]$ the deformation rate tensor. The momentum source term $\boldsymbol{S}_{b,mom}$ are caused from the bubbles and it is nonzero only in case of two-way coupling. The density is the pure liquid density $\rho = \rho_l$ and assumed constant, throughout. The viscosity is the liquid viscosity $\mu_{eff} = \mu_l$ in case of a laminar flow. These equations are solved on a 3D domain with Cartesian coordinates. Turbulence is modeled using RANS or LES approaches.

The bubble velocity is computed by solving an ordinary differential equation for the linear momentum considering different forces on the bubble. Generally, these forces may be divided into fluid dynamic forces (e.g. drag, pressure, virtual mass, and Saffman forces) and field forces (gravity, electrostatic forces, etc.). The new bubble position is then obtained in each Lagrange time step by integrating the bubble velocity so that the equations read

$$\frac{d\boldsymbol{x}_b}{dt} = \boldsymbol{u}_b$$

$$m_b\frac{d\boldsymbol{u}_b}{dt} = \boldsymbol{F}_D + \boldsymbol{F}_L + \boldsymbol{F}_{vm} + \boldsymbol{F}_p + \boldsymbol{F}_g + \boldsymbol{F}_{coll}$$

where $\boldsymbol{x}_b$ is the bubble position vector, m_b the bubble mass and $\boldsymbol{u}_b$ the bubble velocity vector. The forces on the right-hand side are drag force, lift force, virtual mass force, pressure gradient force, and gravity, respectively. For solid particles, it may be required to account for their rotation by additionally solving an equation of the angular momentum. Due to the extremely small mass of bubbles and their behavior during collisions, this is typically not considered.

The drag force results from the flow around the particle and can be expressed with the following equation

$$F_D = \frac{3}{4}m_b\frac{\rho_l}{\rho_b}\frac{C_D}{D_b}(\boldsymbol{u} - \boldsymbol{u}_b)|\boldsymbol{u} - \boldsymbol{u}_b|$$

where C_D is the empirical drag coefficient, and D_b is the bubble diameter. Because the drag force is one of the most important forces for disperse flows the right choice of the drag coefficient is crucial. There are several correlations proposed in literature, e.g. [2].

The lift force is caused by a shear flow around the bubble. It acts perpendicularly to the direction of the flow and can be expressed as proposed by [3].

$$F_L = C_L m_b \frac{\rho_l}{\rho_b} [(\boldsymbol{u} - \boldsymbol{u}_b) \times (\nabla \times \boldsymbol{u})]$$

where the lift force coefficient depends on the deformation of the bubble or droplet and can be expressed by the correlation of [4].

The virtual mass force accounts for the additional work that the bubble performs to accelerate or decelerate the surrounding fluid and can be written

$$\boldsymbol{F}_{vm} = C_{vm} m_b \frac{\rho_l}{\rho_b} \left(\frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} - \frac{d\boldsymbol{u}_b}{dt} \right)$$

like proposed by [5]. The virtual mass force coefficient is typically modeled constant.

The sum of the pressure force and the gravity force can be expressed as [6]

$$\boldsymbol{F}_p + \boldsymbol{F}_g = m_b \frac{\rho_l}{\rho_b} \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} + m_b \boldsymbol{g} \left(1 - \frac{\rho_l}{\rho_b} \right).$$

The collision force can be incorporated using hard-sphere or soft-sphere collision paradigm. All given equations are relying on choosing the respective coefficients carefully. Most of the coefficients from literature assumes ideal isolated lab conditions or deal with water or purified fluids. Due to the strong influence of the fluid properties and the deviation to hydraulic fluids an arbitrary error in prediction is introduced. To avoid these, the used relevant coefficients are based on experiments with hydraulic fluids.

Numerical Framework

The bTrack solver is an in-house tool designed for disperse multiphase flows in hydraulic systems, operating standalone or two-way coupled with ANSYS Fluent using first and second-order time integration. The solver is fully parallelized using MPI and written in Python and C, leading to both great flexibility and high performance. The software architecture is modular and designed to intercept and influence the operation at all relevant points during simulation to maximize flexibility during model development. Setup, monitoring and output files follow common open-source standards. Setup creation is simplified via a simple UI reducing input errors. The output format is also chosen to work seamlessly with Paraview. bTrack can be fully controlled via a command line interface, which makes it very suitable for parameter studies and automation.

In case of two-way coupling interpolation schemes from disperse to continuous phase and vice-versa are required. Besides robust and well validated schemes for interpolation of volume fraction to the Cartesian grid and undisturbed liquid velocity to each Lagrangian particle we also developed and validated interpolation schemes reducing computational effort.

Modelling turbulence in multiphase flows can be computational expensive due to the interplay between the turbulent continuous flow and the disperse phase, because it could demand a fully two-way coupled approach. To limit the effort while retaining the accuracy carefully modelling the effects is important. bTrack incorporates models for bubble induced turbulence to modify turbulent characteristics of the continuous phase and an advanced random walk model to take turbulent fluctuations into account for bubble motion calculation. bTrack relies on local fluid and flow properties by default, so that multiphase flows with spatial and/or temporal varying properties like density, temperature, viscosity, etc. can also be simulated. Based on local flow properties bTrack can simulate bubble coalescence, deformation and breakup. As a foundation of coalescence and collision an efficient detection kernel based on Sweep-and-prune algorithm is implemented. An overview about the features can be found here [7, 8].

3. RESULTS

Within this chapter we present several reservoir flows where the capabilities of bTrack can be shown. Figure 2 shows a typical reservoir flow. The flow inside is highly transient caused by two aspects: boundary conditions and flow instabilities. The typical load cycle of an application leads to a time dependent flow and pressure profile at each inlet or outlet of the reservoir. Unsteadiness and magnitude of flow rate and pressure lead then to flow instabilities inside the reservoir. Our experience has shown that capturing these effects is crucial in many applications. mycro optimized reservoirs are intended to work even with large oil volume changes, so called working or pendulum volume, inside the reservoir. To capture all relevant effects a multiphase simulation is often necessary. In figure 2 bTrack is used to calculate bubble motion and behaviour of different sizes within the oil volume, while the oil and air phase and their interface are simulated via a Volume-of-Fluid approach. bTrack can not only output all raw data but can compute many relevant characteristics and statistics during simulation. This saves disk space and speeds up post processing.

Figure 2: Transient multiphase flow

In figure 3 a bTrack water droplet simulation is shown. The droplets enter the reservoir through one of the pipes mounted from the top. The flow in this example is from the top to the bottom. Of main interest here is the accumulation of water droplets leading to puddle depending on the different vertical reservoir sections. Due to the Lagrangian approach of bTrack the motion and position of each droplet can be calculated in detail. Using statistical methods, the locations and extensions of puddles can be predicted. These predictions were in good agreement with experimental

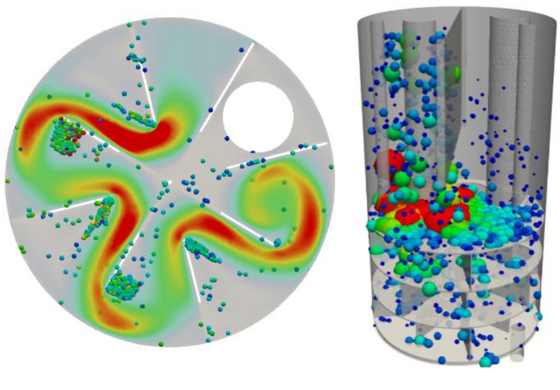

Figure 3: bTrack droplet simulation

investigations. The knowledge of the motion and position of disperse pollutions, like droplets, bubbles or particles are used in application dependent reservoir design.

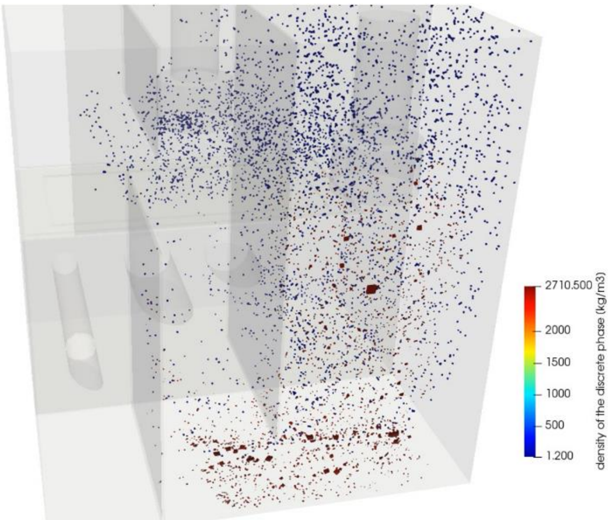

Figure 4: bTrack calculates multiple disperse phases

Figure 4 demonstrates how bTrack can handle multiple disperse phases at the same time, which enables for multi objective optimization of contaminant separation. In the given application metal particles in red are settling at the bottom, while air bubbles in blue rise to the oil surface. Both phases are influencing the velocity of continuous phase, the oil flow. This fact impacts the settling and rising times and are important for reservoir design and sizing. Each disperse phase can be described with their own properties, their own physical models and model constants. This allows for very accurate predictions and saves time.

Although the separation and settling takes place in the reservoir the flow inside is heavily depending on the application. One of these applications is shown in figure 5. If necessary bTrack is not limited to flows inside the reservoir. Disperse flows in suction and return lines can also be regarded in the same simulation, because disperse phase models, e.g. for bubble size, are taking local flow properties like pressure, temperature, density, volume fraction, etc. and numerical parameters like CFL number into account. This means that one description of a disperse phase can be valid for a wide range of flow conditions.

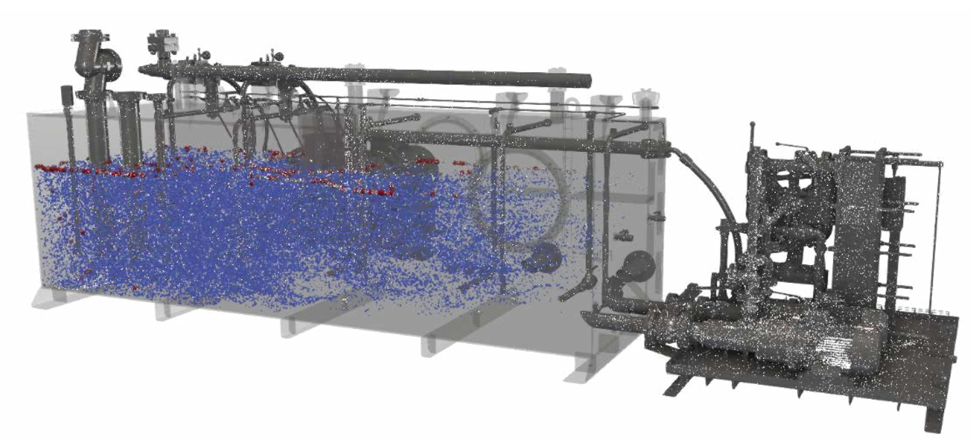

Figure 5: bTrack can capture flow in return and suction lines

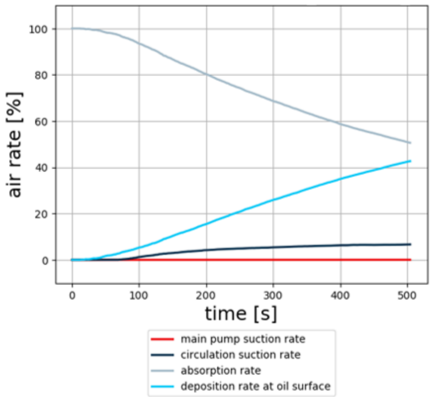

Figure 6: Air rate statistics

Detailed statistics like the air rates shown in figure 6 are calculated by default in bTrack and used for competitive design studies as well as in the analysis how robust a design is under changing fluid, ambient or operating conditions. These statistics are done for test bubble size spectra derived from several inhouse air release experiments for different hydraulic fluids. Application specific bubble size spectra are the foundation of reliable prediction.

Mycro reservoirs must fulfill highest standards and pass bTrack simulations with most conservative bubble size spectra.

4. Conclusion and outlook

In this work we presented the capabilities of our three-dimensional in-house solver bTrack for simulation of disperse multiphase flows. bTrack is used since more than one decade in analysis and optimization of hydraulic power units and is integral part of mycro, the downsizing toolbox of Bosch Rexroth. The huge amount of implemented models, the modular architecture and robust and performant numeric schemes makes it suitable for a wide range of applications. Experimental campaigns to derive new models, integrate new fluids and improve numerics are continuously carried out, to improve accuracy and reduce computational effort.

5. References

[1] "Bosch Rexroth," 21 01 2026. [Online]. Available: https://www.boschrexroth.com/de/de/produkte/industrielle-loesungen/industriehydraulik/aggregate/mycro/.

[2] A. K. I. Z. I. S. T. Tomiyama, "Drag coefficients of single bubbles under normal and micro gravity conditions," *JSME Int. J. Ser.,* vol. 41, no. 2, p. 472–479, 1998.

[3] P. Saffman, "The lift on a small sphere in a slow shear flow," *J. Fluid Mech.,* vol. 22, no. 2, pp. 385-400, 1965.

[4] A. T. H. Z. I. H. S. Tomiyama, "Transverse migration of single bubbles in simple shear flows," *Chem. Eng. Sci.,* vol. 57, no. 11, p. 1849–1858, 2002.

[5] C. Crowe, Multiphase Flow Handbook. Mechanical and Aerospace Engineering Series, CRC Press, 2005.

[6] S. B. D. S. M. G. M. Laín, “Modelling hydrodynamics and turbulence in a bubble column using the Euler-Lagrange procedure,” *Int. J. Multiph. Flow,* vol. 28, no. 8, p. 1381–1407, 2002.

[7] X. &. M. M.-P. &. F. J. Yang, “Interpolation methods for two-way coupled Euler-Lagrange simulation of finite-size bubbles,” *Chemical Engineering Science,* vol. 238, 2021.

[8] X. &. M. M.-P. &. F. J. Yang, “Efficient simulation of bubble dispersion and resulting interaction,” *Experimental and Computational Multiphase Flow,* vol. 3, pp. 1-19, 2020.

Biographies

Mark-Patrick Mühlhausen received his Diploma degree in mechanical engineering from Karlsruhe Institute of Technology in 2009 and Ph.D. in Mechanical Engineering from Karlsruhe Institute of Technology in 2012, respectively. He is currently working at Bosch Rexroth in the Engineering Domain Virtual Engineering and Verification Centre. He focusses on model and tool development.