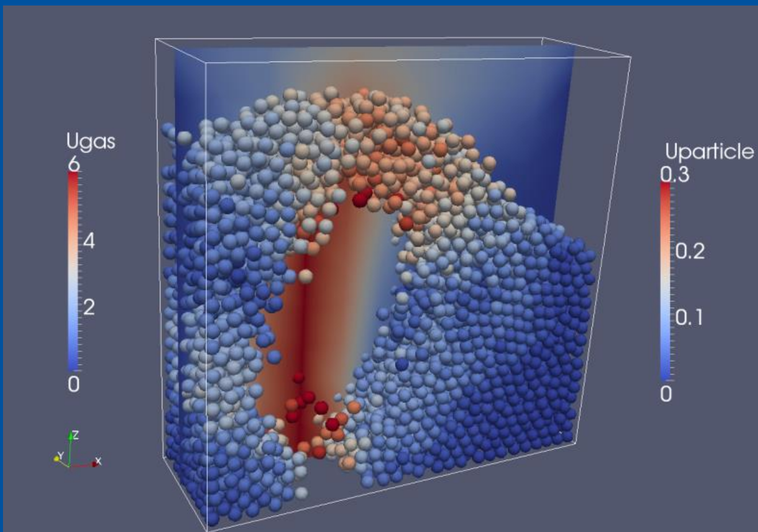

Christian-Doppler Laboratory on Particulate Flow Modelling

Volume I, 2009

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Front cover: Fluidized bed simulation as result of a Discrete Element Method (DEM) and Computational Fluid Dynamics (CFD) synthesis. This simulation is based on opensource software and runs fully parallel on a Linux cluster.

Editorial

Dear Readers,

with the beginning of this year the Christian-Doppler Laboratory on Particulate Flow embarked on a challenging journey to application driven fundamental research activities.

In this brochure you are invited to stroll through quite different particulate flow regimes - starting from small dust particles in an ambient gas flow to dense particle strands, rigorously inter-colliding coarse particles and finally to packed beds of nearly motionless particles. Reflecting this diversity a smart synthesis of dedicated particulate models might often lead to the best overall results.

All of these research activities are based on a two-phase strategy. In a first fundamental project phase the physical key phenomenon of the very particulate flow is analysed by analytical considerations, simplified experiments and corresponding numerical simulations. Once this validation activities have succeeded, in a second step the thus developed simulation tools are applied to real world applications. With this strategy the declared mission of the Christian-Doppler Association, the transfer of fundamental knowledge towards industrial partners, should be realized.

With these introducing words I wish you a pleasant reading. I hope you enjoy it as much as I enjoy accompanying these research efforts !

Sincerely,

Stefan Pirker
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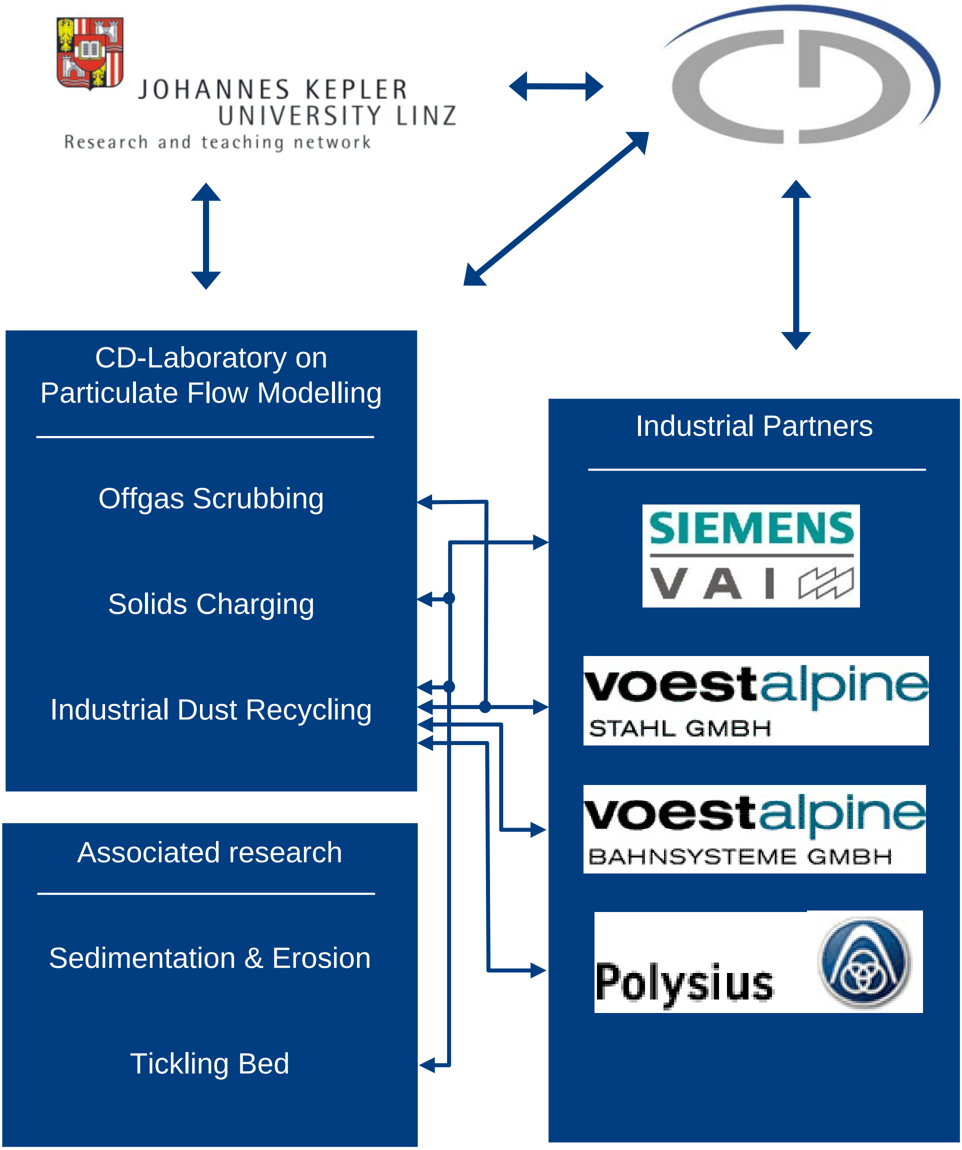
Contents

Organisation



Module I: Offgas scrubbing

In cooperation with voestalpine Stahl GmbH the cleaning of dust laden blast furnace off gas is investigated by means of numerical, analythical and experimental methods. In the existing wet scrubber plant, dust laden off gas is guided through a spray tower towards an annulus gap. Throughout the wet scrubber solid dust particles should be captured at the surface of the liquid droplets. After the scrubber the then dust laden droplets are readily separated by gravitation. Wet scrubbers are very robust and reliable cleaning devices. Their main draw back is a relatively high energy consumption in terms of pressure drop. Goal of this project is to optimize the wet scrubber by achieving better dust capturing efficiency.

From a physical point of view the scrubbing process comprises a whole set of phenomena starting from droplet break-up and coalescence to the behaviour of the wall film and the dust capturing mechanism itself.

Within this study these phenomena are addressed by dedicated sub-models and incorporated into a comprehensive simulation model within an Open Source CFD code. Thereby, representative droplets are traced in a Lagrangian frame of reference while the fine dust particles are treated as additional passive Eulerian phases. Nevertheless, these passive dust phases are allowed to drift with respect to the gas phase due to gravitational and centrifugal forces. For the computation of the dust phases' diffusivity a model considering the dust particle diameter and the local turbulence characteristics is used. Droplet break-up is considered by some droplet breakup model (e.g. the Taylor Analogy Breakup (TAB) model). Furthermore, dust capturing is triggered by impaction, interception and diffusion mechanism. In a further step the influence of a wall film is considered by a model extension solving the shallow water equations at wall boundaries. Sub-models for deposition of droplets to the film is implemented as well as droplet entrainment from the film due to film detachment and wave cresting.

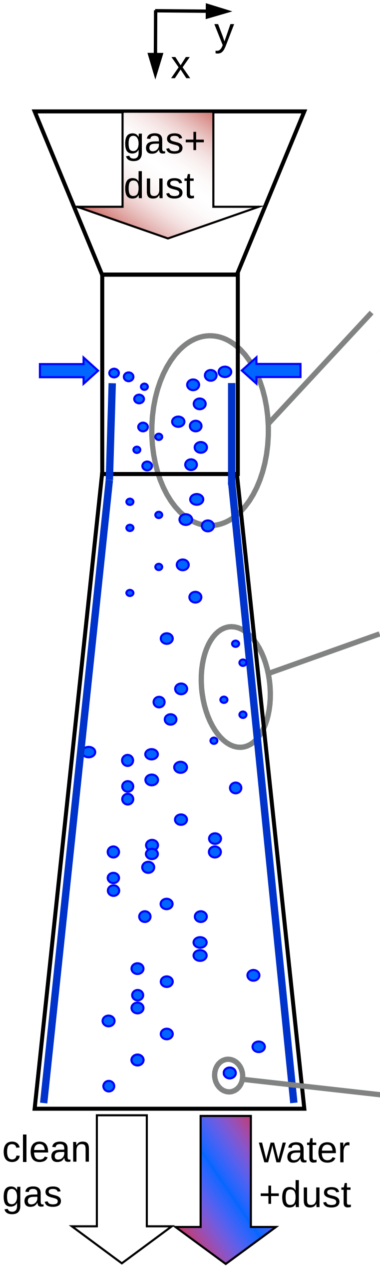


Fig.1: Principle sketch of a Venturi wet scrubber

droplet breakup

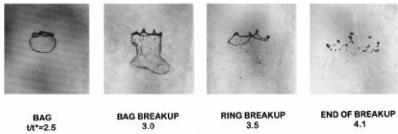


Fig. 2: Bag break-up of a liquid droplet

liquid film

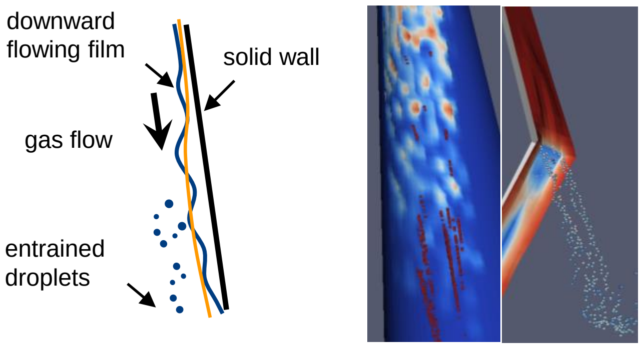


Fig. 3: (left) film droplet interaction, (right) wall film simulation

dust capture

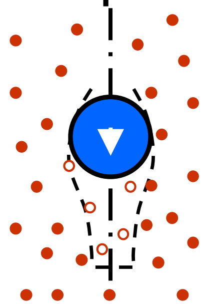


Fig. 4: dust capturing model

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Module II: Solids Charging

In module II, research effort together with Siemens VAI Metals Technologies GmbH (SVAI) are taken to investigate the charging of coal and direct reduced iron (DRI) into the melter gasifier (MG) of a COREX plant.

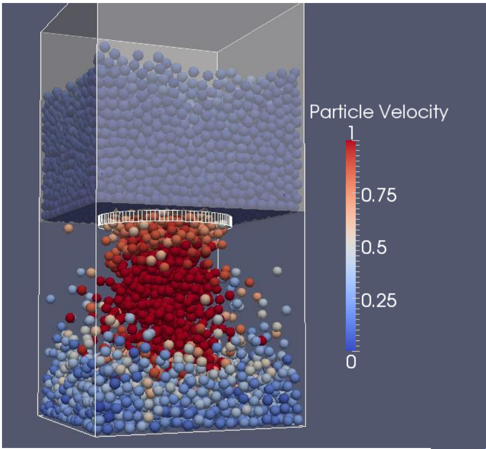
The goal of the project is to develop a comprehensive model to describe (a) the physics of the granular media involved and (b) the interaction of the granular media with the fluid phase, which is the gas injected into the MG.

Coal and DRI are charged into the melter gasifier, with variable chutes exerting influence on the direction of the particles. After a free-fall, the particles impact onto a granular bed, where they are subject to (a) inter-particle forces (b) forces exerted by the wall and (c) forces exerted by the fluid flow through the packed bed.

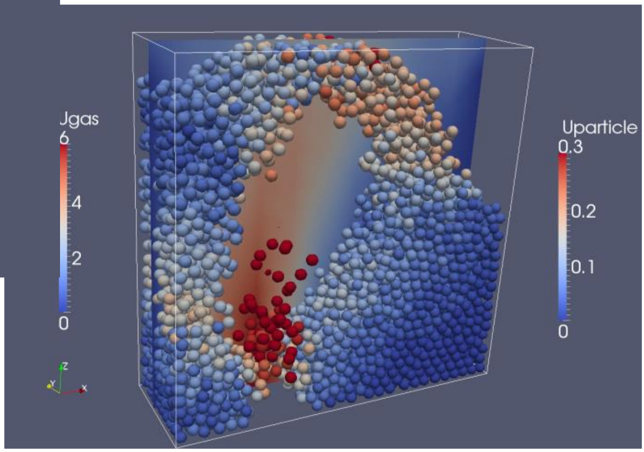
A granular charging facility was especially designed to conduct dedicated validation experiments. With the help of measurements and scaling considerations appropriate validations of the developed numerical models are going hand in hand with simulations.

Because this physics is extremely complex with different physical regimes in each stage of the charging/operation process and the scale of the industrial plants is large, we propose a problem-specific synthesis of the models best fit for the very problem seems to be the best trade-off between capturing the physics and computability. This is achieved by coupling the following approaches

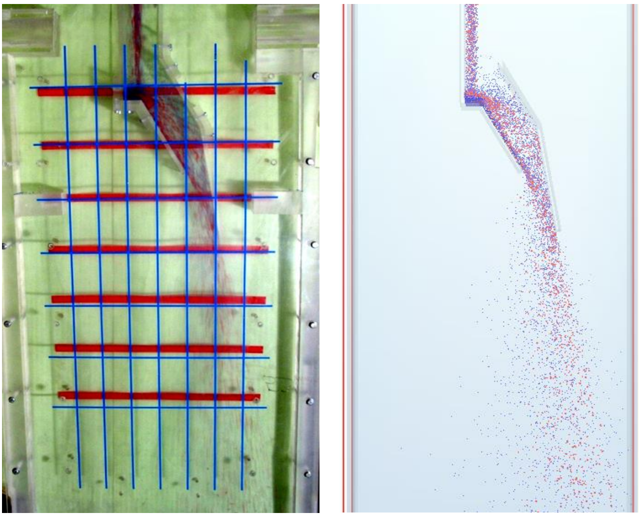
- The Discrete-Element-Method (DEM) to describe to particles' motion during the first part of charging and in the upper section of the bed
- A Discrete Phase Model (DPM) describing the free fall motion of the particles
- A Continuum Model for Slow Granular Flow in the lower part of the bed
- CFD for capturing the gas flow through the MG



Example of a DEM simulation:
Simulation of hopper discharge



Example of a coupled CFD-DEM simulation of a
mixed fluid-granular system: Simulation of fluidized bed



Example of a experimental simulation validation:
Lab-scale charging experiment (left) and
corresponding DEM simulation (right)

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Module III: Industrial Dust Recycling

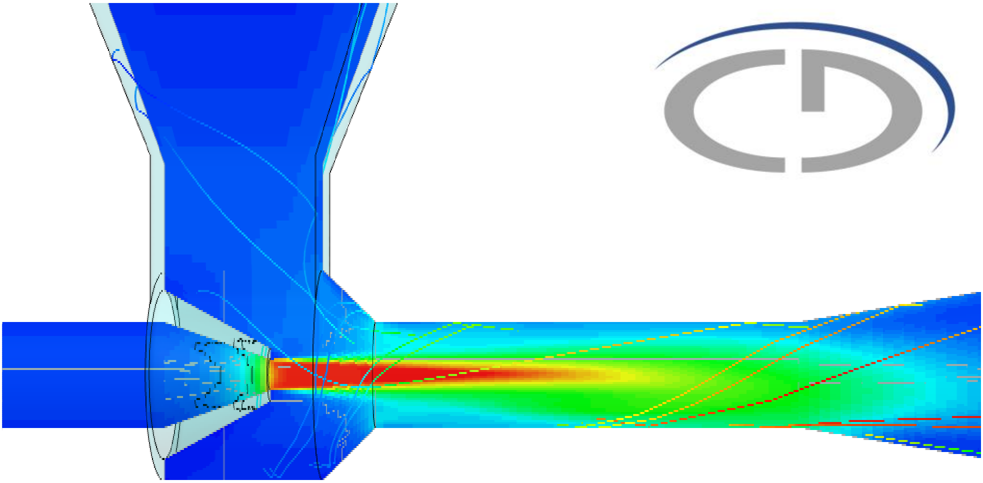
In a collaborate research effort with Siemens VAI Metals Technologies GmbH (SVAI), voestalpine Stahl GmbH (VAS) and voestalpine Donawitz GmbH (VASD) the handling of dust within metallurgical processes should be investigated.

This includes Pulverised Coal Injection (PCI) and particle movement inside the lance and the blowpipe of a blast furnace as well as particle separation in cyclones or the transportation of particles towards dust burners.

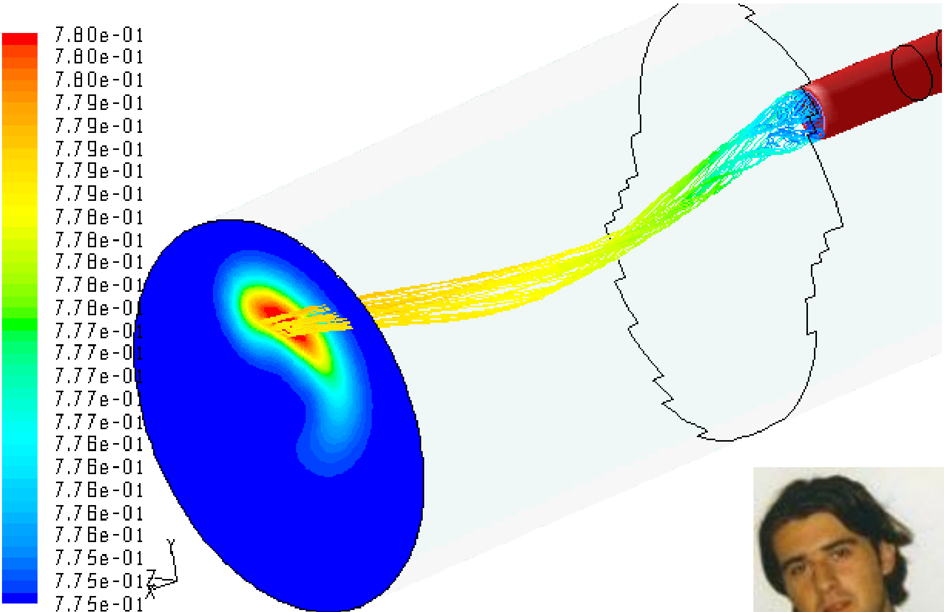
Above mentioned flow situations are studied by dedicated experiments at the CD Laboratory's test rig (see also page 18). Based on these measurements and scaling considerations an appropriate validations of the developed numerical models should be achieved.

Depending on the particulate flow regime specific physical phenomena govern the particle behaviour. While in case of high particle loadings inter-particle collisions and particle strand formation become important (see also page 12) the interaction between the particles and the fluid's turbulence has to be thoroughly addressed in case of dilute particle flows.

Different numerical models can be used for simulations and predictions in all of these applications. Besides of this, further improvements of numerical methods are needed in order to be able to simulate different phenomena appearing in multiphase flows. Some effects, such as particle-wall and particle-particle collisions or the effect of particle rotation and Magnus force, can be appropriately simulated only by including additional sub-models in the existing simulation routine. Further development and improvement of these sub-models is also planned in the frame of Module III.



Gas velocity distribution and particle trajectories in an injector



Mass fraction and path lines of the gas from the lance at the blowpipe outlet

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Module III: Industrial Dust Recycling

In cooperation with Polysius AG the separation of cement dust in cyclones or similar separation aggregates should be numerically studied by hybrid particle models.

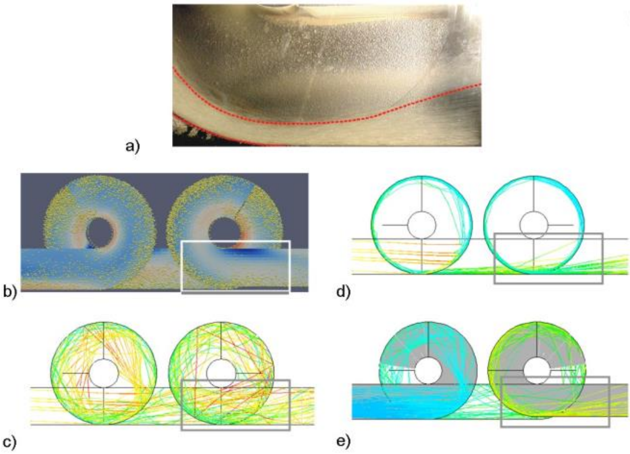
In preceding research activities it has been shown that at medium to high particle mass loadings a dominant particle strand formation can be observed at the inner wall of the cyclone. Actually, this particle strand formation is responsible for the enhanced overall separation efficiency at increased particle mass loadings.

In a first step a the key phenomenon – the particle strand formation and eventually dispersion – has been pictured by a simple experiment. In a pneumatic test facility the particle strand behaviour can be studied inside a curved channel.

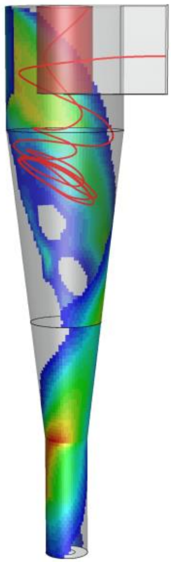
Corresponding to this fundamental experiment the particle strand behaviour can be represented by numerical simulations. Thereby, two main approaches – the Eulerian and the Lagrangian particle model – are readily available. While within the first approach the multitude of particles is considered at an artificial continuous particulate phase that can penetrate the interstitial gas phase, in the second case individual particle trajectories are traced through the computational domain. Linked to these fundamentally different concepts individual physical phenomena like inter-particle collisions, particle rotation and Magnus force or the effect of wall roughness can be more likely pictured by either a Eulerian or a Lagrangian model.

It has already been shown that a synthesis of Eulerian and Lagrangian models could improve the overall particulate flow simulation. Thereby, inter-particle collisions might be pictured by the Eulerian model while the effect of poly-dispersity is modelled by Lagrangian trajectories.

Thus, future research efforts should concentrate on further development and validation of these hybrid particle models.



Particle strand dispersion: (a) experiment, (b) Lagrangian Discrete Element Simulation, (c) standard Lagrangian model, (d) collisions Lagrangian model and (e) hybrid particulate model



Real world application of particle strand separation in cyclones; the particle strand is pictured by the meandering contour – in addition a trajectory of a very small particle is given

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Sedimentation and Erosion

Supported by a DOC-fellowship of the Austrian Academy of Sciences the numerically modelling erosion and sedimentation is studied. This can be organized into two main tasks. Firstly, the local erosion and sedimentation events have to be addressed by a proper mathematical model. Secondly, the effect of the changing topology on the fluid flow should be considered.

The first task is fulfilled by using an Eulerian multiphase model. The flow of the continuous fluid is considered only above the packed bed and the surface of the packed bed is assumed to be a rough wall. Single particle behaviour is not focused because this is restricted to very small geometries.

Modelling the changing topology of the packed bed is achieved by two main methodologies. In a first approach the surface of the packed bed is assumed to be inside a fixed global computational domain (Immersed Boundary Method). The packed bed is considered as artificial media incorporated by a penalty approach to the momentum equations. The penalty function is adjusted to the deformation of the surface accordingly. The second approach links the computational grid for the fluid flow modelling to the changing topology of the packed bed (Arbitrary Lagragian Eulerian Method). If the position of the packed beds surface changes due to erosion or sedimentation events the above grid has to be deformed accordingly. Typically, this can be done in a stationary way because the time scales of the fluid flow are far less than the time scales of the erosion and sedimentation process.

The above models already has been validated by an corresponding wind tunnel experiment. While the Arbitrary Lagrangian Eulerian approach is easier to implement and more accurate in case of moderate erosion patterns the Immersed Boundary approach is superior in case of massive erosion.

Finally, future research is focused on the model transfer to industrial applications as river bed erosion or snow drift.

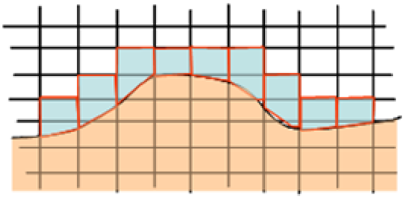
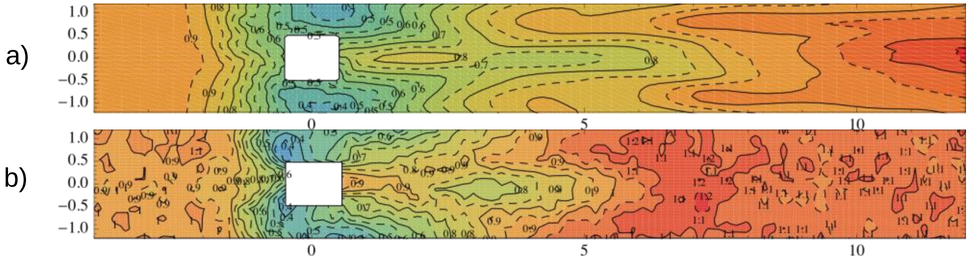
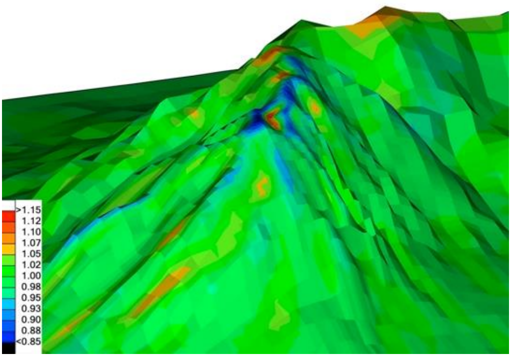


Illustration of the Immersed Boundary Method



Comparison of the dimensionless height of the packed bed:
a) Simulation, b) Measurement

Wind tunnel Experiment



Model transfer to snow drift simution

This work is funded by a DOC-fellowship of the Austrian Academy of Sciences

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Tickling Bed

The aim of this work is to develop a tool for modelling the liquid / gas / solid flow in the lower part of a melter gasifier as used in the COREX® or FINEX® process or of the blast furnace in order to increase the overall performance of the plants. A packed bed with particles and two liquids, slag and pig iron, and gas flowing through is simulated by means of CFD (Computational Fluid Dynamics).

While in a typical operation the reducing gas that is injected by a nozzle in the lower part of the gasifier rises through the packed bed to the surface, the solid material – coal and direct reduced iron particles – are heated up and eventually start to melt in a cohesive zone. Once melting occurs the thus produced liquids – metal and slag – drip in opposite direction of the gas phase towards the bottom of the gasifier. Furthermore, the packed bed itself is slowly lowered due to the continuous melting. Thus, in stationary operation particles have to be charged continuously at the bed's surface.

The comprehensive simulation of the trickle bed behaviour comprises four phases – liquid metal and slag as well as gas and the moving bed of solid particles – and furthermore, links this flow situation to thermal considerations. As a simplification individual droplets or liquid films are not resolved. Rather, interaction between the phases is realised by momentum sources. These sources are defined so that the dynamic holdup agrees with empirical data found in literature. As a result the melting and dripping behaviour of iron and slag is visualized showing static and dynamic holdup, pressure drop and velocities of the individual phases.

This work has been financially supported within the Austrian competence centre programme COMET by the BMVIT; by the BMWFJ; by the provinces of Upper Austria, Styria and Tyrol; by the SFG and by the Tiroler Zukunftsstiftung.

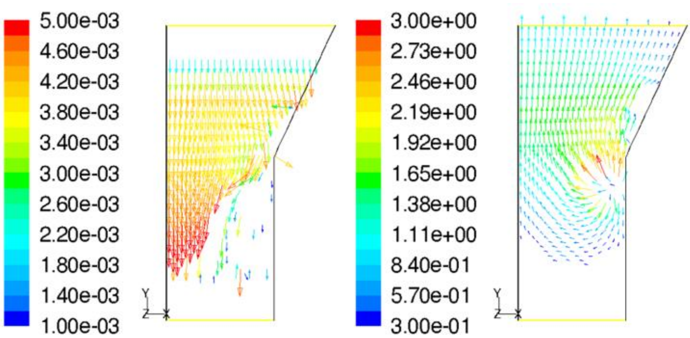

Fig.1: Flow field of the tickling slag phase and the rising gas phase

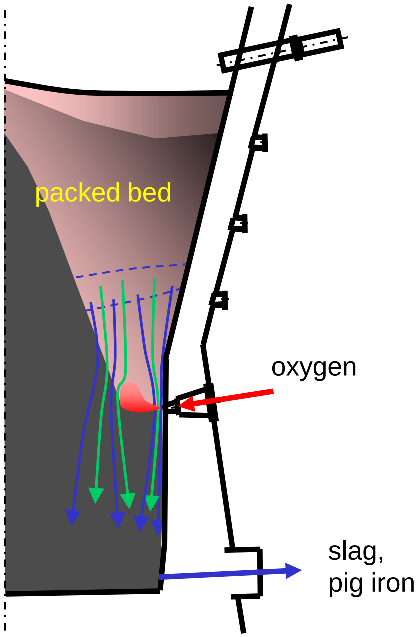

Fig.2: Sketch of the flow situation in a melting gasifier; while gas is flowing upward two liquid phases – slag and metal – are tickling downward, in addition the packed bed itself is slowly moving downward, © J. Wurm

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Experiments

In order to validate numerical models or to calibrate model constants, fundamental experiments are necessary. In order to be not dependent on experimental data from literature a pneumatic test rig was designed. In a modular concept we are able to conduct various experiments in a particle laden gas flow. A fan provides gas velocities up to 25m/s. According to application particles of different size and mass can be feed in by a vibrating chute or an injector lance. After passing the experimental modules in the channel gas and particle flows are separated by a cyclone (Fig.1). The basic operating conditions of the test rig (fluid velocity, pressure losses, temperature, particle loading etc.) are controlled by an I/O system based on a PLC.

Various equipment is available for investigating fluid and particle flows. The available measurement methods are covering:

- Particle image velocimetry (PIV):
  System with two cameras for stereo PIV or combined PIV/LIF (laser induced fluorescence) measurements.
- Online particle sizing and counting:
  The system based on white light diffraction has two sensors and is therefore able to measure e.g. before and after a cyclone quasi-simultaneously to investigate separation efficiency.
- High speed camera:
  B/w camera with 2.000 fps at full resolution and up to 10.000 fps at reduced resolution.
- Constant temperature anemometry (CTA):
  System with two channels an various wire and film probes for measurements in gases and liquids.

Focus for future research will be light diffraction for particle sizing in low laden flows and optical image analysis for highly laden particle flows.

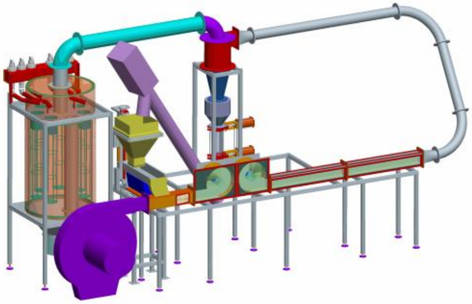
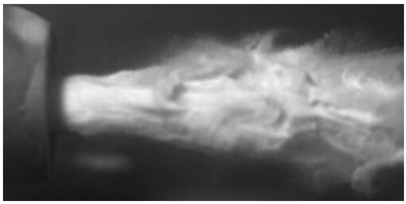
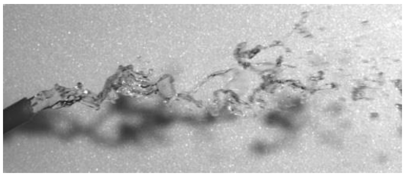


Fig.1: One possible outline of the pneumatic test facility. The configuration shows the double looping experiment also depicted on page 11.

Fig.2: a) Glas powder (D50 approx. 50 µm) ejecting from a nozzle in a surrounding gas flow. Freeze frame from a movie taken with high speed camera at 10.000 fps. b) Breakup of a water jet in dominating gas flow. High speed movie at 2.000 fps.



a)



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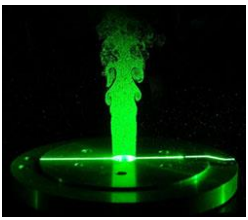

Fig.3: Free stream turbulence of a jet ejecting from a nozzle illuminated by PIV laser.

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Industrial Partners

A huge amount of particulate rawmaterials - ore, coal and additives - is charged to a COREX® or FINEX® plant for the production of hot metal. Particles tend to segregate with regard to size, density and shape especially during charging. Siemens VAI wants to take control and advantage of such behavior to reduce rawmaterial consumption even further. Also dust recycling from low to high gas pressure is in focus.

Industrial plants are no place for experiments and yet continuous innovations are expected. Therefore we need the development und concurrent validation of fundamental models for the simulation of particulate flows. While simulations of single phase gas and liquid flows are state of the art, the simulation of particulate flows requires new techniques in experimental, analytical, mathematical and computer matters. For this purpose we rely on this CD-Lab as our scientific partner.

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In blast furnace pulverised coal injection the individual coal particles pass the raceway in not more than some milliseconds. Even in that short period of time the combustion behaviour of the particles is influenced by the local flow situation. Aim of our cooperation with the CD-Lab is a mathematical modelling of coal dispersion directly at the lance tip. Furthermore, these numerical simulations should be validated by dedicated experiments.

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In the long run these investigations should lead to a better understanding of the process of pulverised coal injection. Based on this knowledge we hope to improve our operating conditions in order to improve the efficiency of the process.

We experience the cooperation with this CD-Lab as a very smooth joint effort in studying applied particulate flow phenomena. Thanks to the top quality of the Lab's staff, we get quick and sound answers to questions that occur in our research and development environment. Furthermore, Dr. Pirker really seems to be a playing captain rather than a purely administrative head of the group.

Since the CD-Lab always tries to combine numerical simulations with accompanying dedicated experiments, we have confidence in the thus obtained results. With respect to particulate flows I have the feeling that this CD-Lab is 'one step ahead' of other groups.

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Our goal is to be better than the commercially available state of the art. For us the cooperation with the CD-Lab on particulate flow modelling seems to be the key to the actual state of scientific research.

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Selected Publications

PIRKER S. and KAHRIMANOVIC D. (2009), Modelling Mass Loading Effects in Industrial Cyclones by a Combined Eulerian-Lagrangian Approach, Acta Mechanica, Vol. 204, No.2-3, pp. 203-16.

KAHRIMANOVIC D., KLOSS C. and PIRKER S. (2009): Numerical Study and Experimental Validation of Particle Strand Formation, Progress in Computational Fluid Dynamics, Vol. 9, pp. 383-392.

GONIVA C., PIRKER S., TUKOVOC C., FEILMAYR C. and BÜRGLER T. (2009): Simulation of Wet Scrubbing by a Combined Eulerian-Lagrangian Model, Proc. Open Source CFD International Conference, Barcelona, Spain.

SCHNEIDERBAUER S., FISCHER P. and PIRKER S. (2009): Online NWP-Model Data as Boundary Conditions for Snow Drift, International Snow Science Workshop 2009, Davos, Switzerland.

GONIVA C., KLOSS C. and PIRKER S. (2009): Towards fast parallel CFD-DEM: An Open-Source Perspective, Proc. Open Source CFD International Conference, Barcelona, Spain.

KLOSS C., AICHINGER G. and PIRKER S. (2009): Multi-scale Modelling of Particle Motion by Means of DEM and DPM, Multi-Scale Modelling Symposium - A CSIRO cutting edge symposium, 7-8 December 2009, Melbourne, Australia.

KLOSS C., GONIVA C., AICHINGER G. and PIRKER S. (2009), Comprehensive DEM-DPM-CFD Simulations – Model Synthesis, Experimental Validation and Scalability, CFD 2009 conference, Melbourne, Australia, 7 pages.

HAUZENBERGER F. and PIRKER S. (2009): Simulation of Gas / Liquid Flowing through a Packed Bed, Steelsim 2009, Ed. A. Ludwig, ISBN 3-901384-23-5, 6 Pages.

PIRKER S. and EGGER M. (2009): Modelling steel de-sulphurization by lime powder injection, Steelsim 2009, Ed. A. Ludwig, ISBN 3-901384-23-5, 6 Pages.

PUTTINGER S., MEHRLE A., MEILE W. and GITTLER P. (2009): Numerical optimization and experimental investigations on the principle of the vortex diffuser" , 27th AIAA Appl. Aerodyn. Conf., US.

Imprint:

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