Real-World Application of Core Simulation for Process Optimization

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The making of cores still creates surprises for tool and corebox makers. Core related defects are a significant cost factor of casting production. The layout of coreboxes traditionally follows an experienced-based trial and error process until a satisfactory core quality is achieved. The ramp-up of new tools for production usually requires several time and cost intensive optimization loops, including the final approval under production conditions. Each trial run leads to more or less extensive tool changes, without the assurance for the foundry engineer that the chosen modifications actually lead to the desired success. Only the end-result is seen, so decisions are not based on a clear cause-effect-principle, which would confirm which change causes what effect.

The simulation of core production processes is a relatively new methodology, introduced more than 20 years after the introduction of casting process simulation to fundamentally change the corebox and process layout by providing insight into core shooting and curing processes. The complex interactions during the fluidization, the transport, and the subsequent compaction of the sand/binder mixture in a corebox, as well as the gassing, curing, and drying process of cores, cannot be comprehended by traditional “linear“ thought processes. The simulation of core making processes enables the engineer to find and quantify the essential parameters with the biggest impact on core quality prior to cutting the steel for a new corebox. Right at the beginning of the design process, core production and its processes can be displayed - virtually. The entire process and its relevant physical parameters become transparent. This allows engineers to apply goal oriented procedures based on physical laws and clear facts. The technical and economical feasibility of cores becomes, thereby, quantifiable. Additionally, process understanding and the realization of quality improving actions are made easier. Tool makers get 3-dimensional insights into the core making process and are enabled to efficiently develop the coreboxes towards the requirements of production.

Core shooting simulation model evaluation

Modeling the core shooting process is an extremely complicated process, as the flow of sand particles and air continuously changes. The flow process of sand-air mixtures is completely different than the one of melt flow because the local properties of the “fluid” constantly change. The interactions between air and sand between each other and with their surroundings (shot cylinder, nozzles, corebox) require the additional consideration of technological boundary conditions and the integration of specific knowledge **[1, 2 ,3]**.

Choosing the right simulation model required the evaluation of several modeling approaches and their validation in cooperation with development partners. In example, one development partner tested a “mixture model” in direct comparison to the finally realized model, in which the sand and air mixture phases are calculated **[4]**. The characteristic dynamics of the core shooting process, where sand and air are typically flowing with drastically different velocities in different directions, could not be described in a satisfactory manner for all application cases using that “mixture model”.

Therefore, the simulation program MAGMA C+M is using a model for the description of the dynamics of the air-sand mixtures, which is based on treating air and sand, as well as sand-binder mixtures, as two separate phases **[5, 6, 7]**. Besides the dominant momentum transfer between air and sand, it is also considered how the sand grains interact with each other.

Process modeling also requires the consideration of equipment related parameters, i.e. the way how the pressure build-up is accomplished inside the shot cylinder. The nozzles literally connect the core shooting equipment with the core making tool. In the reality of core making processes a multitude of nozzle geometries is utilized. Their properties are modeled using pressure-loss laws. For the venting of core boxes, vents of different designs and sizes are used. The small vent openings are containing the sand inside the corebox and allow the air to escape. Experimentally calibrated flow laws assure the realistic simulation of the pressure-loss at the vents.

During the setup of a core shooting simulation, it needs to be decided if the entire core making equipment of i.e. hopper and corebox need to be modeled or if it is sufficient to apply a boundary condition to the nozzles only. Considering the entire machine naturally leads to longer simulation times, but sometimes only this way all parameters impacting the core shooting process can be considered. This is especially true for multi-cavity tools, where all cores need to be filled equally and in a similar manner. The consideration of the hopper becomes important especially when a low fill grade can lead to “through shots” at some nozzles, impacting the entire filling process.

Application of core shooting simulation

Simulation displays a detailed view of the core shooting process. Results and criteria are provided at any point in time of the process. It is beneficial to position the nozzles during the tool making phase. Effects that are driven by nozzle variations can be considered and evaluated.

The visual analysis of the filling process provides an efficient comparative evaluation of different nozzle configurations. Small changes in the nozzle locations can have a significant impact on the dynamics of the core shooting process and the expected core quality.

In order to achieve clear assistance during the core shooting process optimization, it is not only desirable to have an accurate analysis of complex cores beyond just the final result, but o all kind of cores. Therefore, additional results like the local air and sand velocities, sand distribution from each nozzle throughout the corebox, as well as meaningful curves for sand and air volumes, velocities and pressures throughout the core or inside nozzles and vents are provided.

Case study: optimization of a coldbox core for a turbocharger housing

Turbochargers have high inner surface quality requirements due to the required gas flow efficiency in their application. Sand core derived surface defects, therefore, immediately lead to the rejection of the casting. This leads to specific quality challenges in the core making process. The layout of coreboxes is often restricted by customer’s requirements regarding the location of nozzles and vents.

Prototype cores from an initial corebox layout showed reproducible voids in PUR Cold-Box cores **[8]**, especially in the critical volute, **figure 1.** The initial core making simulation, which was based on this configuration, matched the defect distribution very well, **figure 2.**

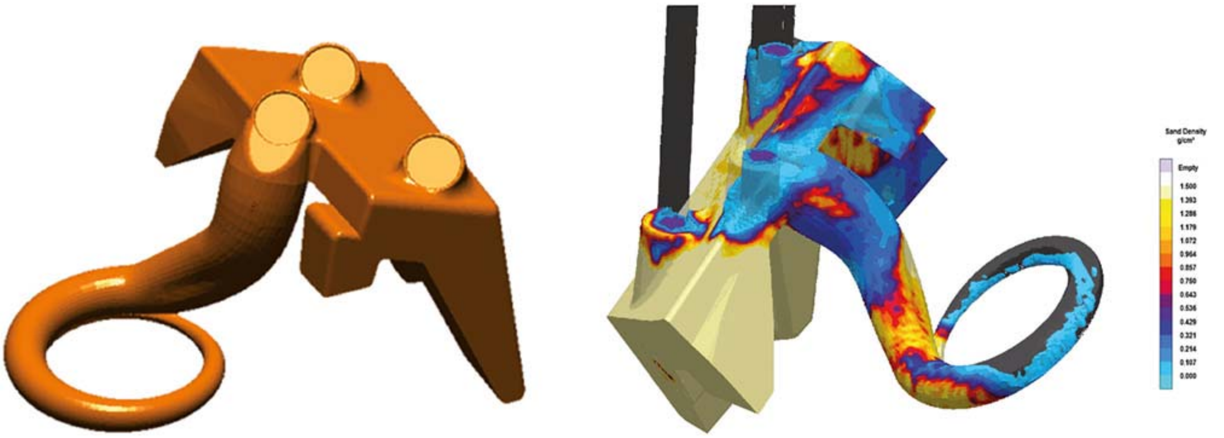

Figure 1: Turbocharger core geometry **(a)** and sand/binder mixture density distribution during the core shooting process **(b)**.

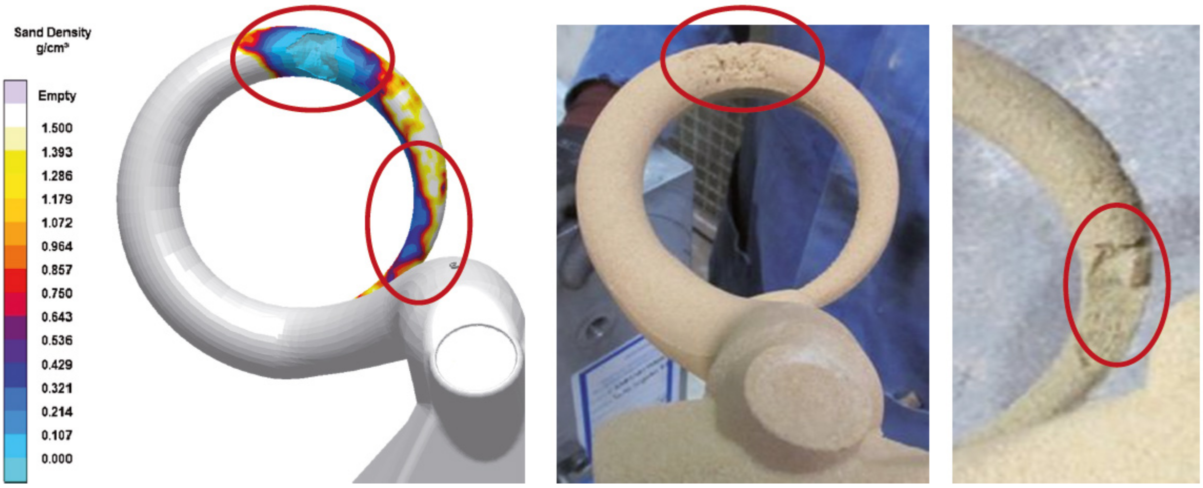

Figure 2: Predicted density distribution in the volute of the core **(a)** and real defects in prototype core of the initial corebox layout **(b)** und **(c)**.

After this positive experience with the results of MAGMA C+M the foundry accepted and applied core simulation as predictive tool for the concurrent optimization of the corebox. The proposals for the optimization of the core shooting process were evaluated by the foundry’s experts through using core simulation.

Initially, it was assumed that the voids in the volute were created by a venting issue. Therefore, the first step was to add more vents in the volute area, which was evaluated by the core simulation. Opposite to the expectation of the experts, the version with 6 vents didn’t show a significant improvement over the initial 4 vent setup, **figure 3.**

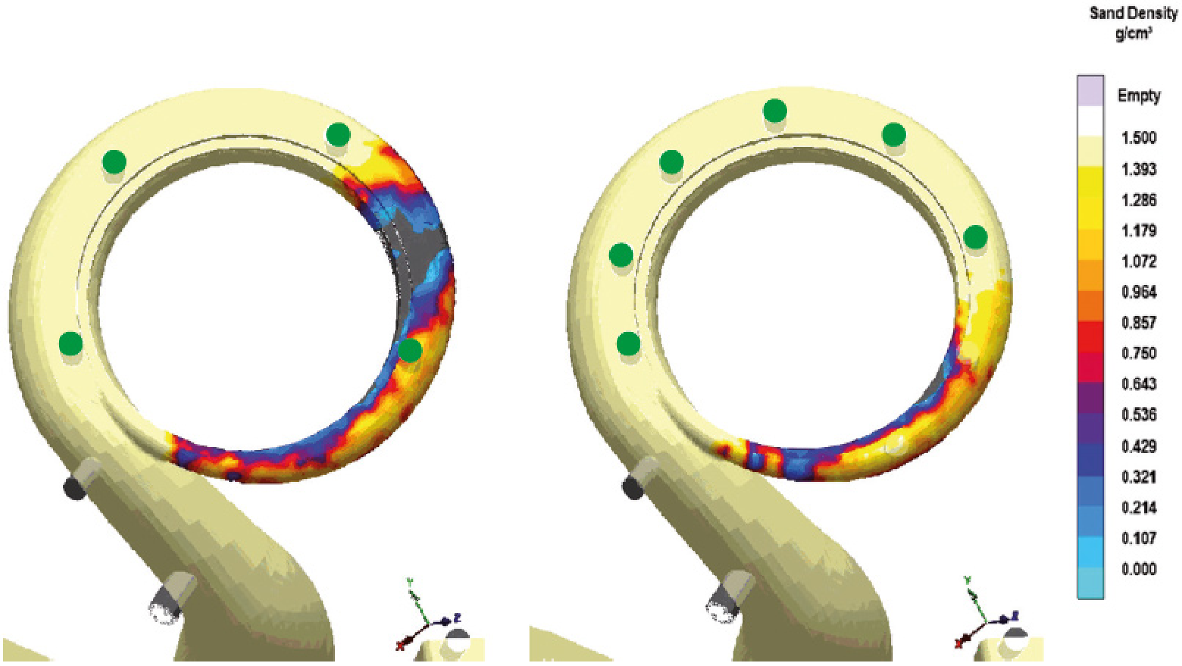

Figure 3: Simulated result for different vent configurations **(a)** 4 vents **(b)** 6 vents

A detailed analysis of the core shooting process showed the root-cause for the compaction problem: The vents near the entry of the volute let the air, which is the carrier medium for the sand/binder mixture, escape too early. This leads to a flow velocity reduction of the air and the sand before the sand can fill the entire core cavity, **figure 4**. The evaluation of the air flow velocity distribution shows a substantial reduction in velocities near the two marked vents (from more than 5 m/s to approx. 2 m/s). This results in a loss of carrier air and subsequently into a reduced kinetic energy and insufficient compaction.

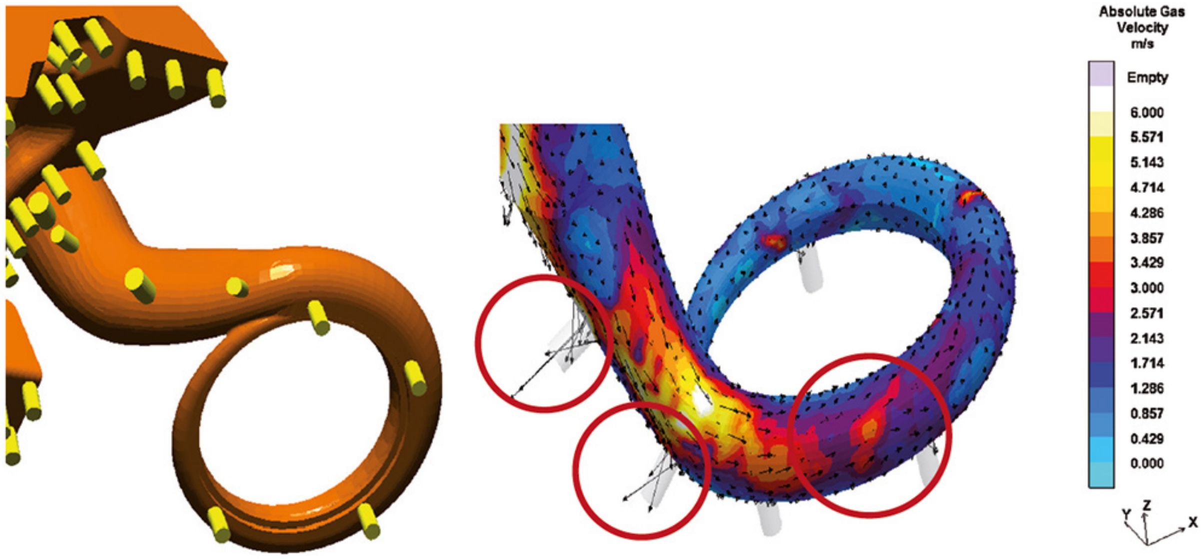

Figure 4: Configuration of vents in initial setup **(a)** and air velocity profile **(b)**.

The final configuration combining an improved venting with the elimination of the two vents near the volute's entry was evaluated using MAGMA C+M, **figure 5.** The air velocity result clearly shows that the velocity in the entry of the volute is increased due to reduced venting, but then the velocity decreases rapidly inside the volute, which leads to a large local pressure loss. A large pressure loss in the last-filled areas is a good indicator for the good compactability of the sand. The fast flowing sand looses speed very quickly and can, due to its kinetics, be compacted very well. At the same time, the quickly degrading air velocities show that the air can escape very well.

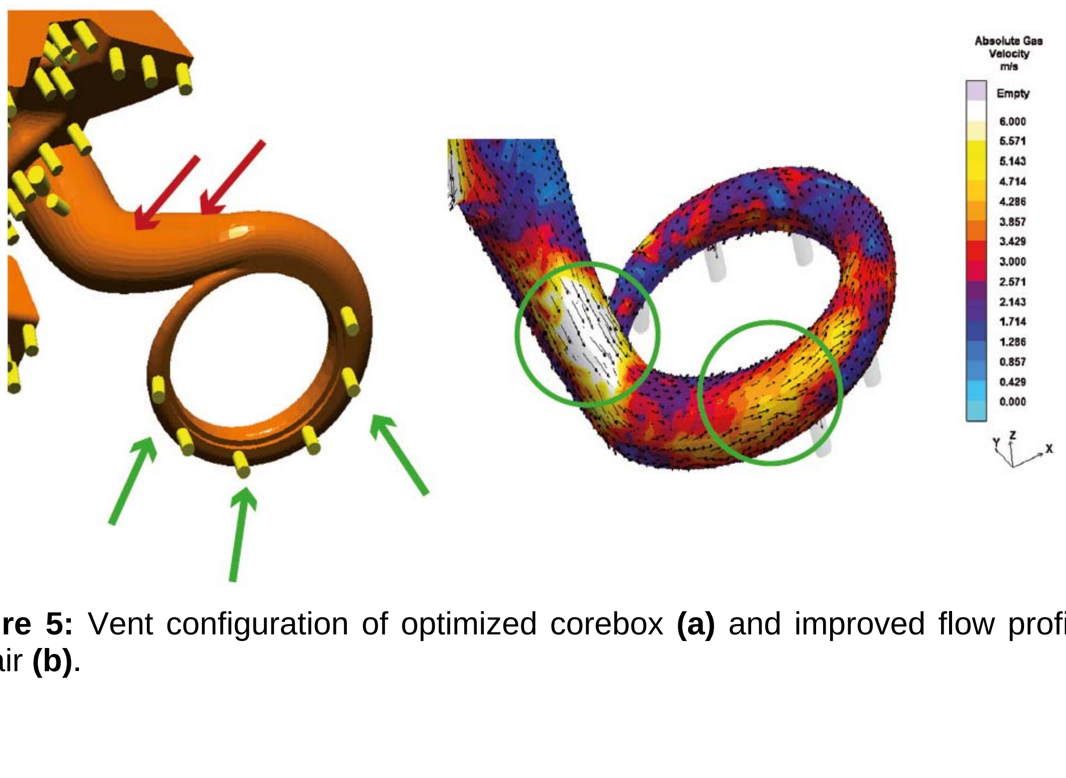

Figure 5: Vent configuration of optimized corebox **(a)** and improved flow profile of the air **(b)**.

The progress of the core shooting simulation shows this process very clearly using sand density distribution results, **figure 6.** The optimized version leads to reproducible defect-free cores in the real world.

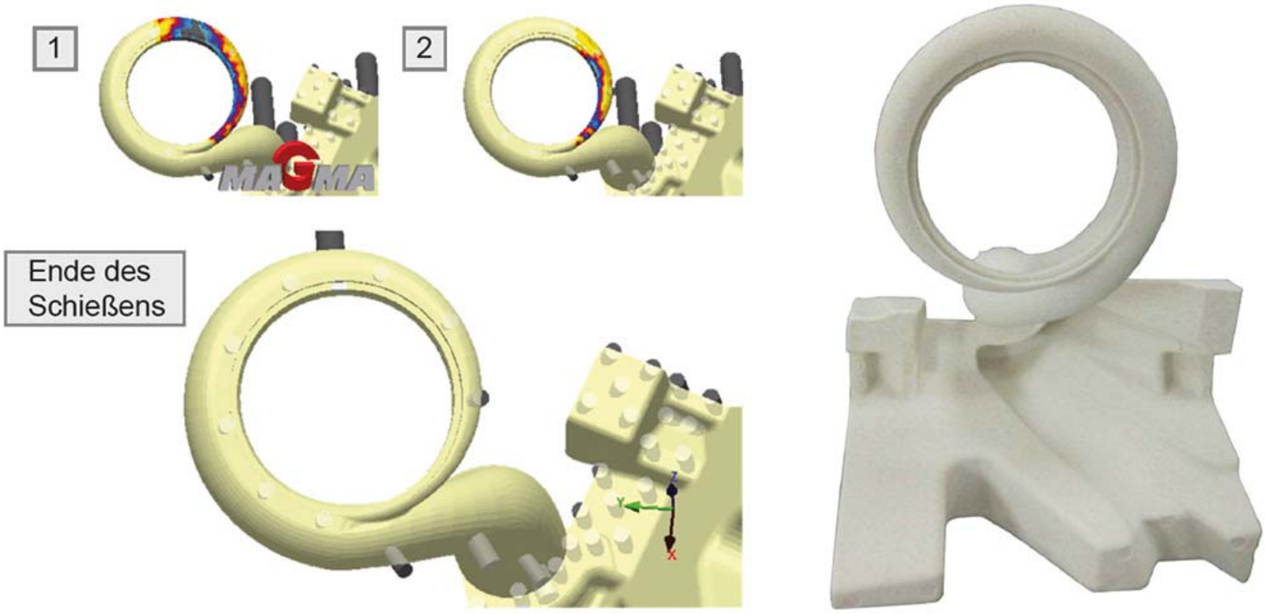

Figure 6: Compaction progress the volute at the end of the core shooting process (left) and optimally shot core (right).

Geometry dependent functionality of nozzles

The core making department utilizes a variety of nozzle geometries. In their most simplistic form, holes in the shot head plate act as nozzles. The variation of the hole-diameter is then the only option to impact the shot behavior from the nozzle's perspective. This is often an economical option for very simple cores. However, usually real nozzles are used connecting the shot head with the corebox. Typically, cylindrical, conical or stepped nozzles are used.

Different nozzle geometries lead to different flow characteristics. Laws of fluid mechanics cannot be applied to air-sand flows in core shooting processes. In example, a stepped nozzle versus a cylindrical one leads, at a given pressure boundary condition, to an increased velocity (due to continuity laws). During core shooting, the sand will agglomerate at the point where the nozzle is narrowed and the sand velocity will decrease, **figure 7**. Besides the sand velocity, also the mass flow changes depending on the nozzle geometry.

The requirements on the selection process of nozzles increases with increasing core complexity. So far nozzle geometries have been chosen based on experience and trial and error - even for difficult cases. The flow behavior inside nozzles is still largely unknown. Experiments describing the sand flow out of nozzles show that just the geometrical modification of nozzles can lead to either continuous sand flows with almost constant velocities or lead to discontinuous, pulsing sand flow, **figure 8**. The flow processes leading to such characteristic flow behaviors are currently not observable or evaluable through experiments. Simulation now permits a differentiating look into the flow processes inside nozzles. The physical phenomena can now be fundamentally understood and quantitatively evaluated. It is important to the core maker to have the knowledge of nozzle geometry related impacts on the core shooting result. Sand velocities and effectively shot sand masses can be very different dependent on the chosen nozzle configuration. Dependent on the core geometry, this also has an impact on the local compaction of the core, **figure 9**. The insights gained through simulation can be used to choose the correct nozzles to achieve an even filling of complex cores. Based on evaluations using simulation, systematic rules can be derived for what nozzle should be used with which type of core.

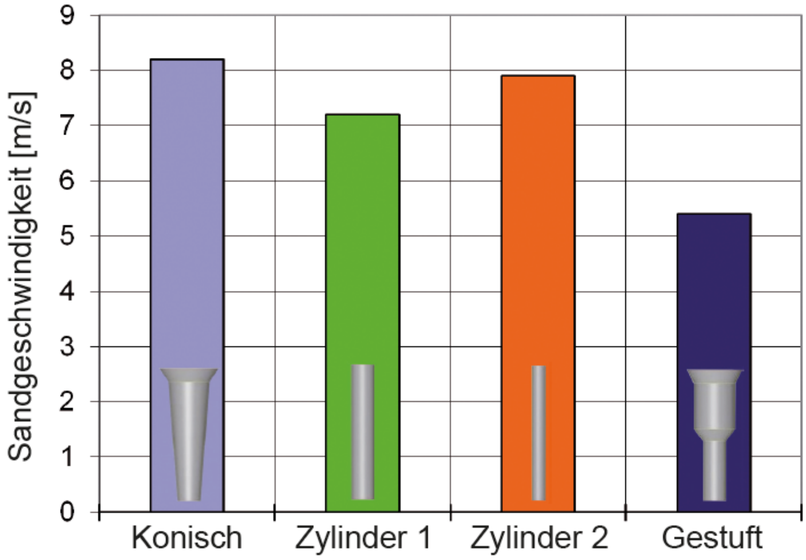

Figure 7: Measured velocities at exit of several different nozzles. The velocity is highly dependent on the nozzle geometry (at a given equal boundary condition). The same exit diameter of a cylindrical nozzle "Zylinder 1" and a stepped nozzle "Gestuft" lead to drastically different velocities.

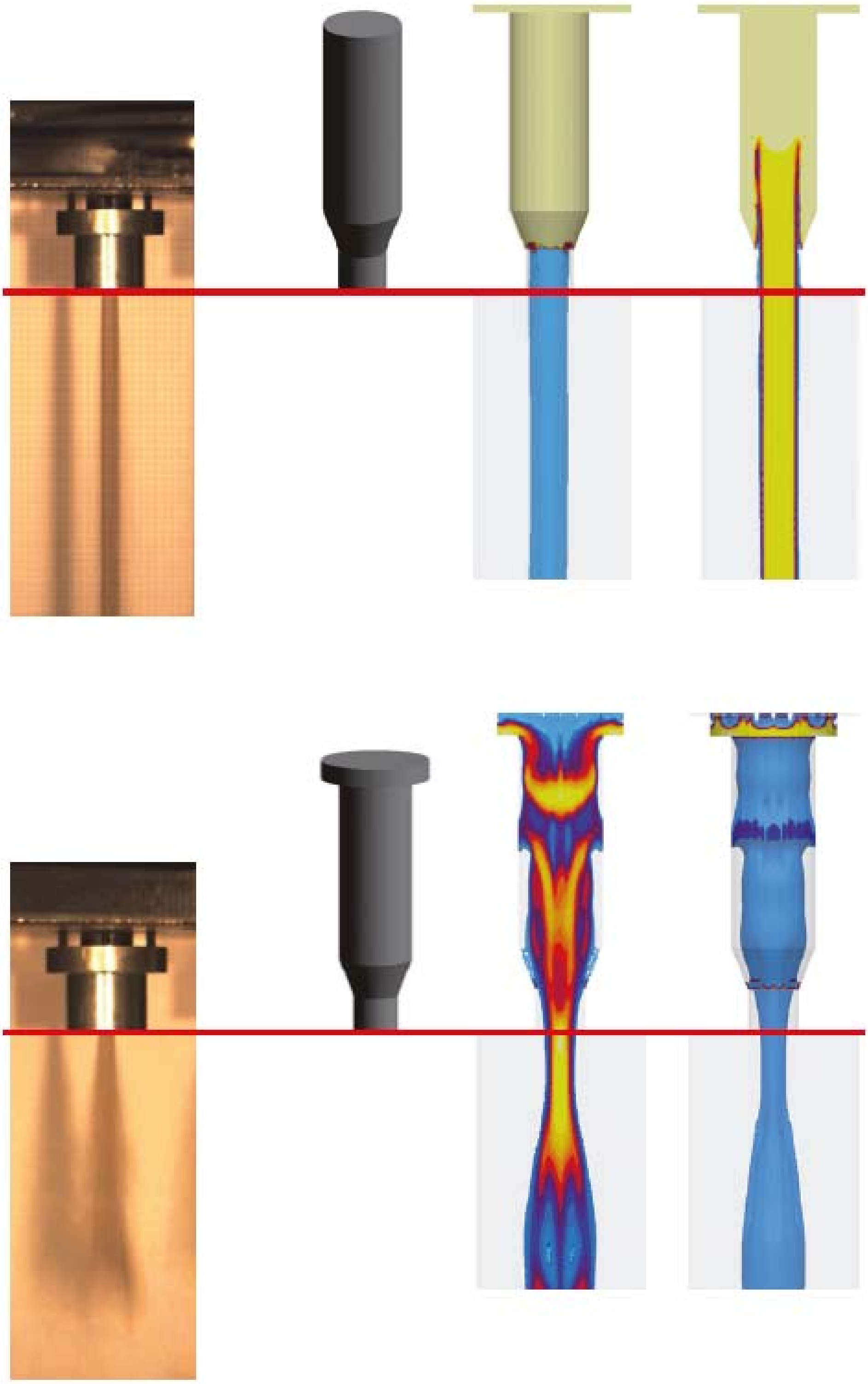

Figure 8: Comparison between real and simulated sand flows for different nozzle geometries. The sand typically flows as continuous stream out of the nozzle **(a)**. A geometrical change can change the sand flow into a discontinuous, pulsing flow **(b)**, where the stream widens. Depending on the core geometry, this can lead to a better core quality. Simulation permits for the differentiated evaluation of flow processes in nozzles **(c)** and **(d)**.

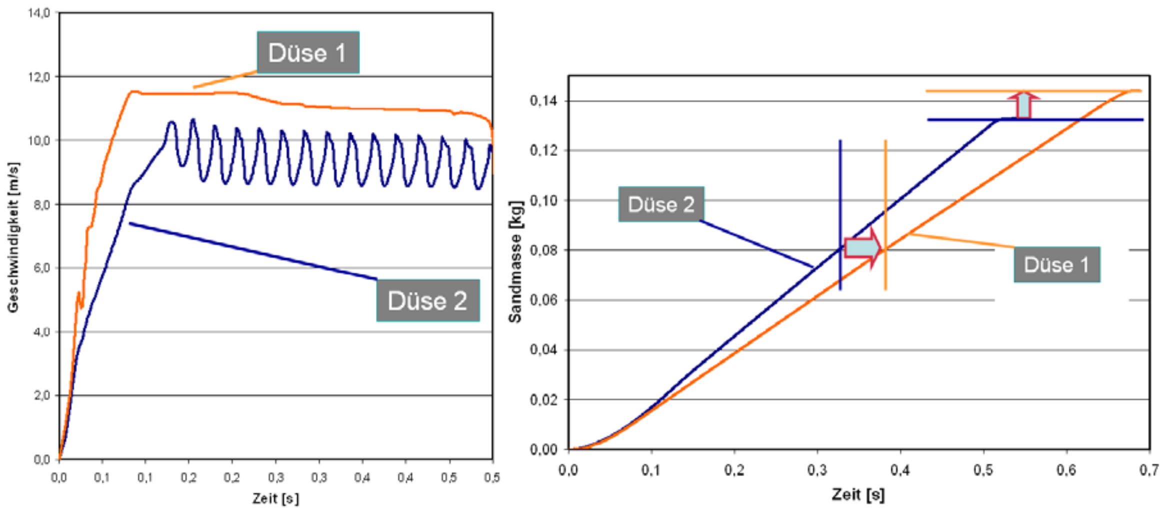

Figure 9: Sand velocities and amount of sand as function of time for two different nozzle geometries. The velocity **(a)** and the amount of sand as well differ for nozzles with equal nozzle diameter dependent on their geometry. The resulting sand amounts leads (dependent on the core geometry) to different compaction grades **(b)**. Here: "Düse 2" fills the corebox faster, but the total amount of sand is smaller. The core is, therefore, a little less compacted.

Modeling of core curing with gas

When gas is used during the curing of cores, a heated gas is funneled into a previously shot core. The usual curing mechanisms for gas curing, i.e. for PUR-coldbox (this is also true for dry curing processes of inorganic binders cured with heated air in heated coreboxes) can be simulated **[6]**. The transport of gas through the open pore space of sand cores characterizes the flow process during the curing process. For PUR-coldbox curing a catalytic acting tertiary amine needs to be transported throughout the entire core. The curing success is dependent on many factors, i.e. binder (composition and amount), solution agent (kind and amount), and the grade of wetting of sand grains by the binder film, amine type, as well as sand and gas temperature **[9]**. The gas flow through the core sand is primarily dependent on the core geometry, the nozzle configuration, the gas pressure, and the gas permeability of the sand mixture.

Normally, a nozzle configuration beneficial for the shooting process of the core is not optimal for the gassing process. In example, a lot of amine is lost when the gas has to traverse only short distances from the nozzles to the vents, while other areas require higher pressures and equivalently higher amine amounts to be reached.

Initially, it is the goal of simulation to reproduce the amine flow correctly over the entire gassing and curing process. Right at the beginning of the corebox design and layout process it can be evaluated if all areas of the core are sufficiently flooded by the curing gas. Simulation provides a realistic description of the gassing and purging processes with air. Thereby a root-cause analysis can be performed early and defect eliminating measures can be applied.

Case study: optimization of coldbox core for a gearbox cover

It is an essential job of the core maker to assure the shortest possible cycle time for the sufficient curing of a core. Curing problems are often only found after apparently good cores have been shot and the nozzle configuration has been established for the shooting process, **figure 10**. The simulation of the amine gassing process for the insufficiently cured core shows that the amine is not reaching the critical areas of the core during the production cycle, **figure 11**.

Figure 10: Defective core after curing. The marked areas shows the insufficiently cured regions of the core.

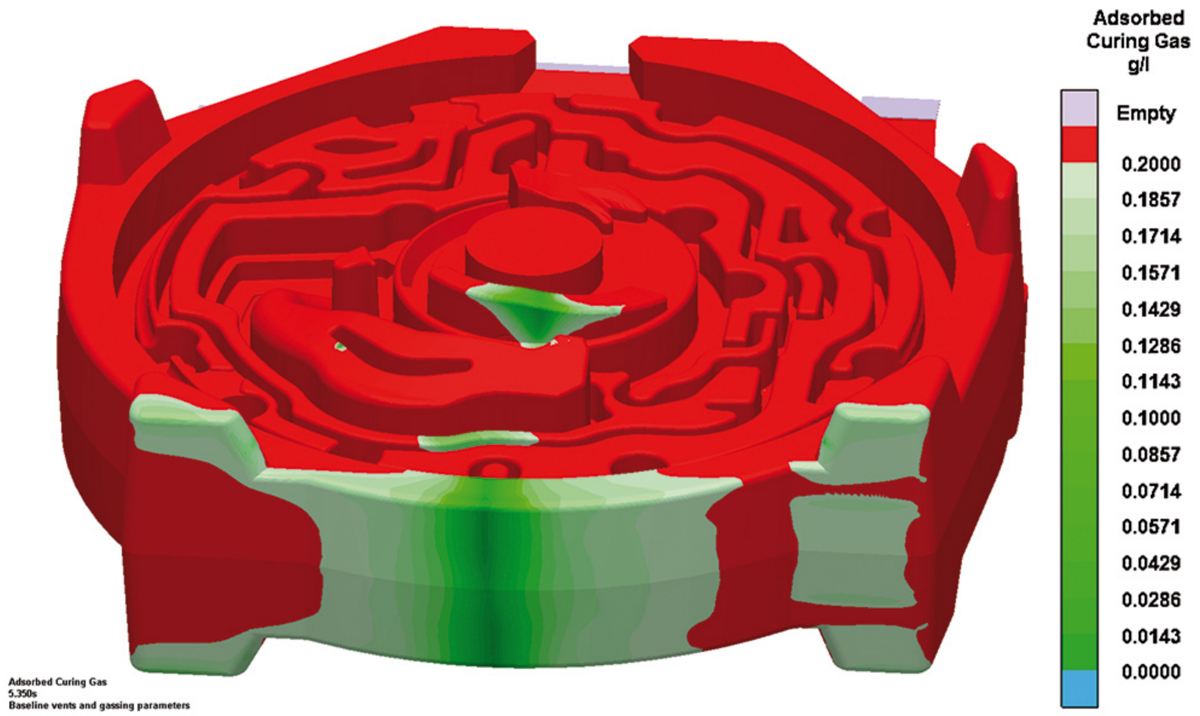

Figure 11: Amine gassing simulation. The concentration of absorbed amine is shown indicating the degree of curing. Completely cured areas are shown in red, incompletely cured areas in green (the darker the green, the less cured).

Usual actions to eliminate curing related defects are often the increase of the amine amount, of the gas pressure, of the gas temperature or, additionally, of the gassing time. The variation of these process parameters is, unfortunately, only applicable in a small range and limited by the requirement of an economical core production. As the core maker cannot recognize the causes for the defect (as they can already be caused by the corebox layout), the mentioned measures are usually just fighting the symptoms, but are not eliminating the root-causes of the defects. Very often, the true cause for curing related defects is funded on a “flow problem” due to an unfavorable nozzle and vent configuration. Even small changes in the position of vents can have a huge impact on a successful core production, **figure 12**. In complex core geometries and nozzle configurations it is almost impossible to “guess” the flow behavior of the curing gas. Simulation now delivers a detailed and objective flow analysis. The pressure distribution in the core, local flow velocities and the display of temporarily changing amine flows are important results to evaluate the gassing efficiency.

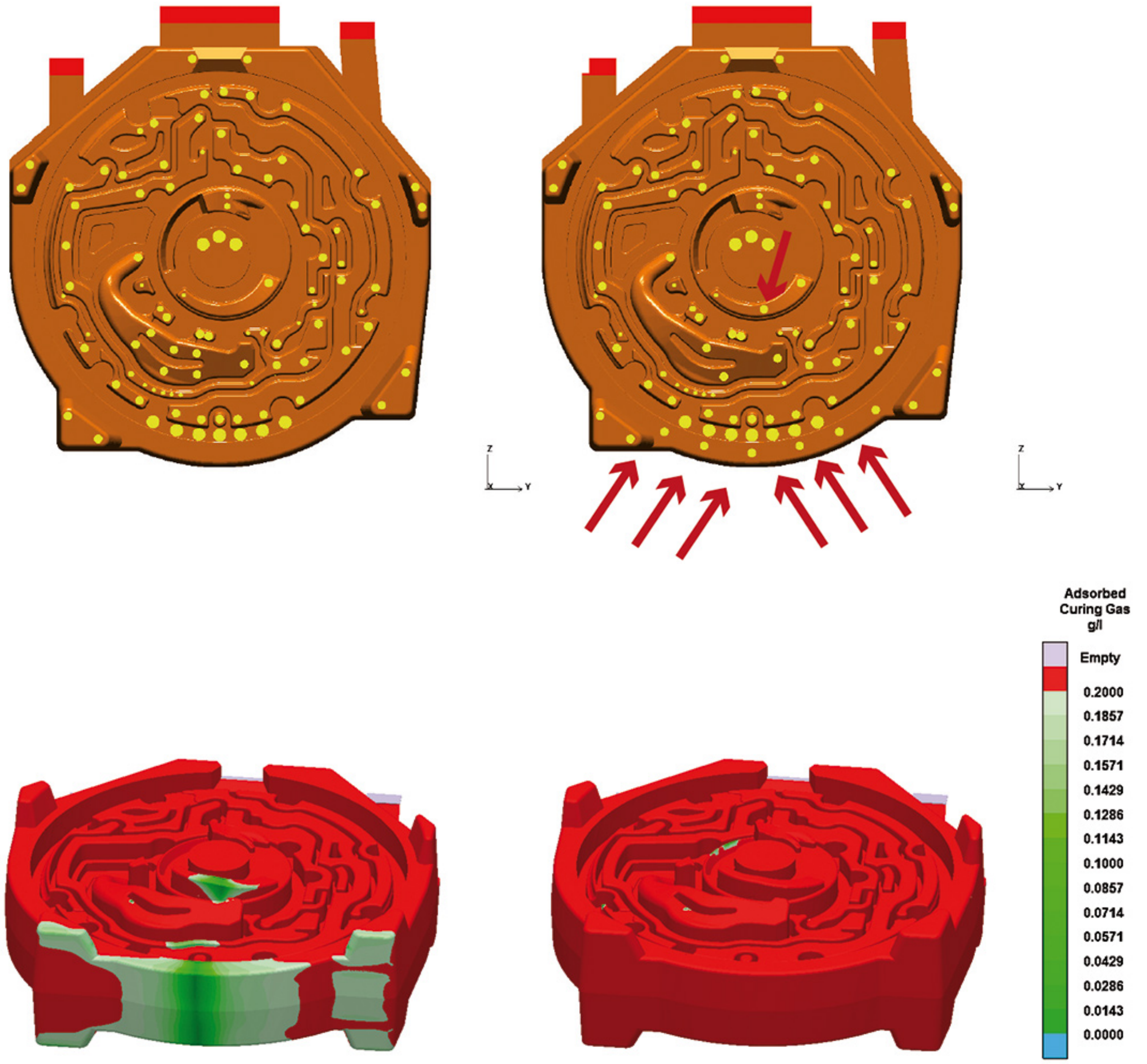

Figure 12: Comparison of gassing efficiency between the original **(a)** and the improved venting configuration **(b)**. The manipulation of the gas flow leads to the sufficient flooding of the entire core.

Simulation, therefore, enables the core maker to optimize the nozzle and vent configuration for the shooting as well as the curing process already in the design phase of a corebox. The trial and error process of varying corebox layouts and process parameters on the shop floor can be significantly reduced or even eliminated.

Summary and outlook

With MAGMA C+M a virtual tool to simulate the core making process is presented, which is designed for the requirements of production. Core simulation is a technologically valuable tool placing the analysis of the entire core making process chain of shooting and curing on a scientific fundament. The core maker is thereby efficiently supported to making decisions throughout all relevant process steps covering corebox design through quality control.

Simulation makes complicated physical processes transparent and understandable. Defect tendencies can be exposed to a root-cause analysis and counter measures can be effectively implemented. Tool design changes can be evaluated without expensive real-world trial runs. The early optimization of coreboxes is shortened and provides a significant cost savings potential.

Literature:

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Key Words:

Core making process simulation, core shooting, 2-phase flow, nozzle, vent, sand-air mixture, core shooting equipment, optimization

Core making simulation is a new technology to assist core and tool makers to improve their core box designs and core making processes. Core making simulation as offered with MAGMA C+M is more as a replacement of unnecessary trials and physical experimentation. It offers a new methodology to assess a complex 2-phase flow of sand/binder and air and reveals the “black box” core box. In this paper real industrial cases are presented, how MAGMA C+M helped optimizing the core shooting and curing process of complex cores as well as offers insights to the flow situation of nozzles.