Sand Core Engineering & Process Modeling

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ABSTRACT

Computer process models have been used in the foundry industry for many years. They are widely used by all types of foundries, from jobber shops to high-volume casting producers. During recent years, the computational fluid dynamics (CFD) industry has turned its attention to creating process models for the core blowing operation and the new set of mathematical, physical and engineering problems have to be solved numerically. This paper describes the work that has gone into validating a math-based tool, and the practical application of the math-based tool to the core-making process.

INTRODUCTION

Traditionally, process models have been available to the foundry engineer to enable verification of mold filling and feeding systems for metal flow and solidification analysis. Now that a commercially available solution to process simulation is available to the core-box tooling designer, the door is open for a more scientific approach to tooling design, and less reliance on customary practice and local knowledge. The trial and error stage of tooling development is a costly and time consuming process. Any modifications made to the blowing and venting method will inevitably lead to time delays and increased costs. The end result can be a sub-optimal box before the tool has even been commissioned. The ability to make these design changes on a computer rather than at the tool makers will result in increased productivity and capacity for the toolmaker and the foundry.

In addition to the tangible benefits of shortening lead times and reducing re-work, the potential to really understand the core blowing process is enormous. There are many publications and technical papers that attempt to explain the process requirements for blowing cores[1], but research and experimentation to validate the process models demonstrate that customary process constraints are not robust enough to design every tool by the same set of rules.

The computer will never replace the tooling engineer. Computer models in all applications, though capable of making realistic predictions, are not able to consider every possible variable that exists within a foundry environment. However, it is anticipated that computational modeling for core blowing will become widely accepted and utilized to develop the processes and assist the engineers in making better design decisions. Using the computational models will not only help the engineers understand the physics that influence the core making process but also provide meaningful data on the process that will assist in equipment selection and comparative process improvements.

DIFFERENT APROACHES TO SIMULATING THE PROCESS

There are several computational approaches which may be used to model the filling cores and molds with sand. All start with basic conservation laws such as the conservation of mass and momentum. The formulation of these equations can be classified broadly as continuous or discrete.

A continuous approach uses an Eulerian frame of reference and subdivides the domain of interest into a finite number of control volumes. All material entering or leaving each volume is tabulated and the flow fields are solved at various locations within the domain. This is a very natural approach for modeling fluids.

A discrete approach uses a Lagrangian frame of reference and subdivides the material of interest into a finite number of control masses. The forces acting on each control mass are tabulated and the motion is solved. This is a very natural approach for modeling particles.

The challenge in accurately modeling the filling of sand cores and molds patterns is that the motion of both air and sand is important to the filling behavior. Aerodynamic drag often initiates the sand motion; however as the sand densely packs a region the air must be displaced and flows through vents as well as ejector pin and parting line clearances. Since neither the air nor the sand can be neglected, neither a purely continuous nor a purely discrete modeling approach would be able to accurately capture the multiphase physics. A single-phase, continuous approach would either neglect the sand entirely, or model the air-sand mixture as a heavy liquid. A single-phase, discrete approach would neglect the air field entirely.

To capture both fields multiphase approaches have been attempted[2,3]. The most common multiphase method for modeling sand core filling is referred to as "Eulerian – Eulerian" or "continuous – continuous." This means that there are two distinct phases in the model, both utilizing a continuous, Eulerian formulation of the equation sets resulting in separate fields for the air and sand. Both phases are effectively treated as liquids with different densities and viscosities.

The largest problem with the continuous, Eulerian – Eulerian approach is the underlying assumption that sand is a fluid. Put simply, sand is not a fluid. A granular material such as sand will not deform under any applied stress as would a fluid. Granular materials support their weight through inter-particle contact forces, not a hydrostatic pressure gradient as a fluid would. A granular material is quantized in nature and cannot be infinitely subdivided as a fluid. Additionally, sand has a size distribution. In spite of these shortcomings, continuous, Eulerian – Eulerian methods are still available as an extension to existing metal flow and solidification software packages.

This paper discusses validation of an "Eulerian – Lagrangian" or "continuous – discrete" formulation for computing multiphase sand core blowing. The air is continuous in an Eulerian frame of reference while the particles are discrete in a Lagrangian frame of reference. Particles are not modeled with incorrect, continuous assumptions.

All results presented herein were created using Arena-flow®, a Computational Particle Fluid Dynamics (CPFD) program based on the Multi-Phase, Particle-In-Cell (MP-PIC) numeric method which is formulated specifically for the coupled fluid-solid motion inherent within dense particle flows [4-8]. The governing equations of the fluid phase are treated with a continuum model on an Eulerian grid, while the sand particles are treated as discrete entities, or discrete groupings thereof, using a Lagrangian representation. The two distinct phases are fully coupled through a volume fraction relation and particle-to-fluid momentum transfer. The fluid phase is air and the particles are sand. The flow is incompressible and isothermal. An isotropic particle normal stress model is used to describe collisions between particles. At solid walls (tooling, blow tubes, etc.) particle behavior is dictated by a particle-wall interaction model which allows for general combinations of specular and diffuse particle reflection, depending on the incident velocity and angle of impact.

The MP-PIC code[8] is a transient, three-dimensional solver utilizing a finite-volume formulation for the Eulerian phase. Particles, or particle groups, are modeled using a Lagrangian approach. Coupling between the phases is treated implicitly and three-dimensional, conservative interpolation operators are used. To ensure conservation of the fluid, a pressure-velocity error equation is formed from the fluid continuity and momentum equations and a SIMPLE type of solution is used to solve this equation.

Additionally, the code contains specialized, proprietary, sand core engineering models to aid the foundry engineer. These include a density model which captures local density variations in a filled core, a transient curing model which tracks the transport of catalyst (amine) and the progression of the curing front through a cold-box core, and a sand flowability model which captures restricted flowability due to binder and shape effects as well as tool wear and resin wipe-off models.

FUNDEMENTAL VALIDATION

Due to the fundamental approach utilized by the MP-PIC code[8], it captures a variety of fundamental granular flow physics phenomena as well as the more complex physics associated with sand core engineering. In order to validate the fundamental physics, a series of experiments were conducted that, at first glance, appear very simple. In terms of experimental complexity, every foundry man will be familiar with the physics being demonstrated. The complexity only becomes apparent when a process model is attempted and the computed output from the various modeling approaches is studied and compared. Two such experiments follow.

U-Tube experiment

The "U-Tube" is a geometrically simple experiment used to evaluate granular flow. Sand falls under gravity around a "U" shaped bend constructed from square section clear polycarbonate tube with internal dimensions of 22mm x 22mm. A measured amount of sand was permitted to drop from one side of the tube and high-speed video data was collected as the sand stacked up around the bottom.

Figure 1 compares the actual result with various calculation results. Figure 1a shows the measured sand inside the U-Tube after it comes to rest. Figure 1b shows the final output from the MP-PIC calculation. Figure 1c shows the final output from a process model using the single phase fluid approach. It is observed that the MP-PIC code (ref 8) calculation is able to accurately predict the final sand shape whereas a fluid cannot due to the hydrostatic behavior observed in Fig. 1c.

Figure 1a: Experimental result b: MP-PIC calculated result c: Single phase fluid calculation result

Figure 2 shows the calculated sequential motion of the sand particles filling the tube at 0.1 second intervals using the MP-PIC approach. The calculation begins with stagnant sand at the top of the left arm, and continues until the sand particles come to rest. Both the volume fraction variations during the drop, as well as the timing agree with the experiment and are captured well by the MP-PIC code[8].

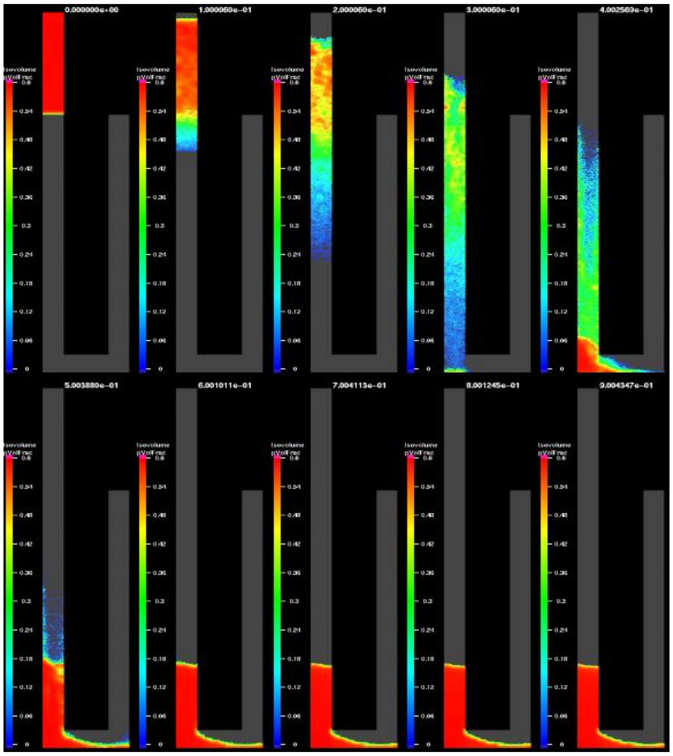


Figure 2: MP-PIC calculation of sand dropping in the U-Tube

Hour glass experiment

The hour glass is a familiar object, and the behavior of the sand particles flowing in an hour glass is comparable to the sand flow from storage hoppers or silos in any foundry. Two experiments were conducted using simple hour glass geometry.

Figure 3 shows the MP-PIC code[8] calculated sand flow for sand falling in a vertical hour glass. Sand is initially densely packed at the top and is permitted to fall under the influence of gravity.   The air at the bottom is displaced and flows up to fill the void created by the falling sand.

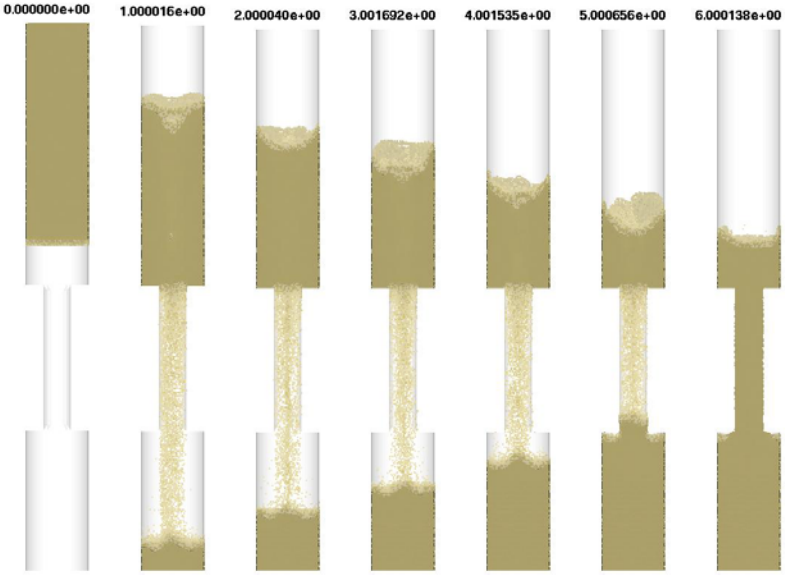


Figure 3: MP-PIC calculation of sand falling under gravity in a vertical hour glass

Although the visualization of the sand flow is very familiar, the physics involved can be challenging to calculate. Hour glasses have been used for millennia as time keeping devices because the mass flow of sand through the neck is linear in time. A fluid flowing through the same geometry would yield a quadratic mass flow, thus if one were to model the sand flow using a traditional CFD software package, the incorrect result would be obtained. The MP-PIC results shown in Fig. 3, however, agree well with experiments for both the final sand shape, as well as the time-evolution of the solution.

The second hour glass experiment also demonstrates the value of calculating the correct fundamental physics. In this case the geometry was rotated 45 degrees and the experiment was repeated. A subsequent MP-PIC code[8] calculation was also performed. Figure 4 shows the calculated results which agree well with the experiment. The sand flow is more complex than in the vertical case and the granular nature of the flow is strongly evident. Notice that non-horizontal sand surface angles are supported by inter-particle contact. This is typical of a granular material, and is not a stationary solution for a fluid in the same geometry.

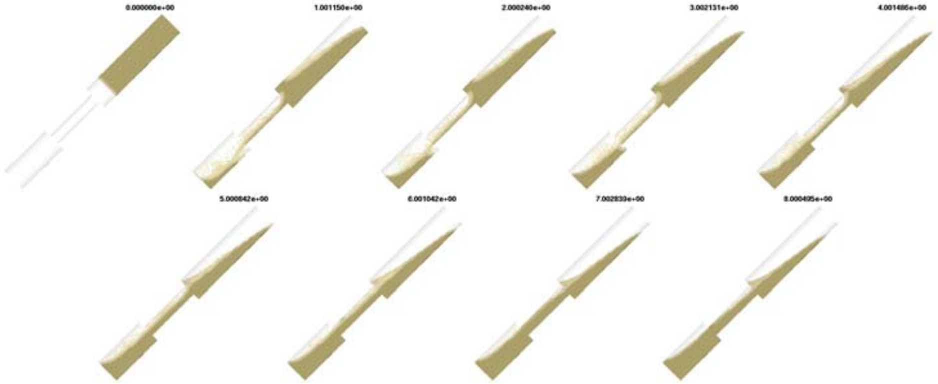


Figure 4: MP-PIC calculation of sand falling under gravity in an angled hour glass

PRACTICAL APPLICATION OF THE MP-PIC CODE

The application of the MP-PIC code[8] to real-world scenarios provides the opportunity to carry out further validation and development of the code. In addition to the validation opportunities, a comparison to the core blowing process demonstrates the potential for fully understanding the process and making improvements based on scientific data rather than trial and error or historical methods.

Defining the model

General Motors Powertrain at Defiance, Ohio, USA, provided the unique opportunity of evaluating core blowing by recording data on production tooling for a block water jacket and slab assembly[9]. Previously published results of the study by Williams, et. al., are summarized[9-11]. Figure 5a shows the cores as they are ejected from the machine at the end of the cycle. The technique used to model the process involved reducing the model down to one water jacket core and a small section of the sand magazine as shown in Fig. 5b. By reducing the problem to one core this created a much more manageable model size in terms of memory and runtime. The unfortunate trend with process modeling has typically been to build more and more variables into the model without necessarily trying to control the variables in the real-world process. By using sound engineering judgment when constructing the model and interpreting the results, the process can be reduced to variables that can be controlled and a robust solution to core making problems can be achieved. Figure 6 shows the comparison between the recorded pressure data and the computed pressure data when comparing the actual process with the model as defined in Fig. 5. The correlation of data justifies the modeling approach and demonstrates the validity of only modeling the parts of the process that are really necessary.

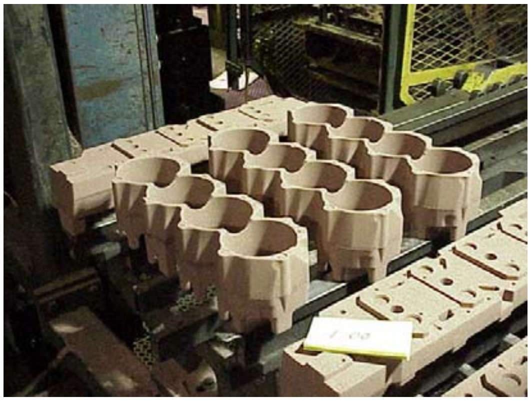
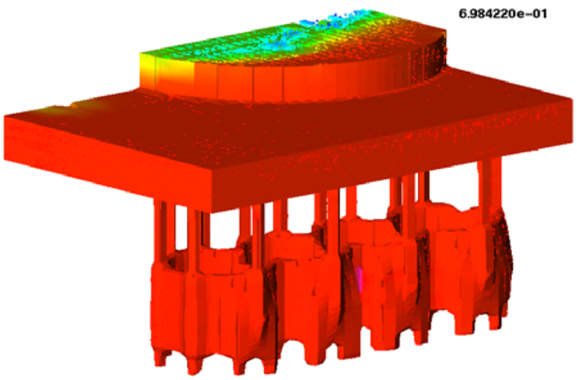


Figure 5a: Production cores



b: MP-PIC computational model

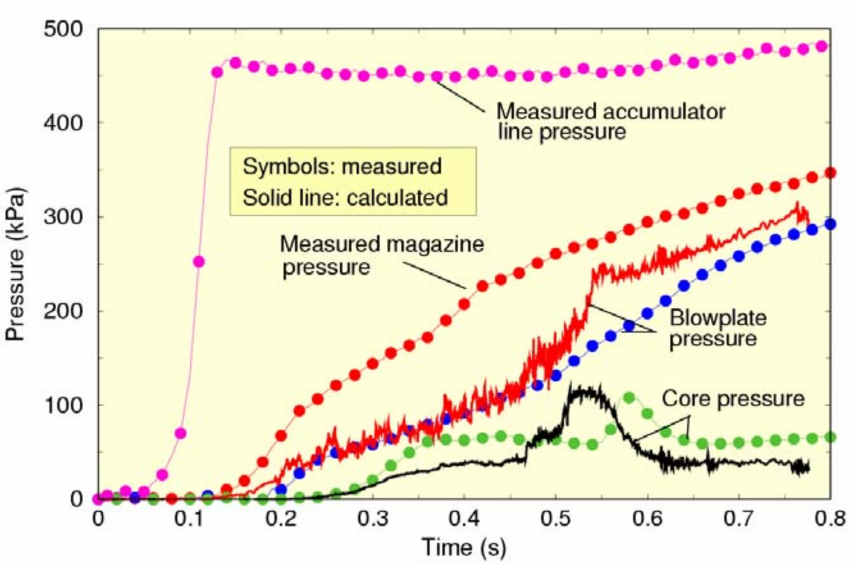


Figure 6: Measured and calculated pressures in the magazine, blow plate and cores[8]

MGG Flue-way core

Figure 7 shows a flue-way core from M.G.G. Telegen[12] in The Netherlands. This core was modified in a manner such that it could be produced with a repeatable defect for sand core simulation evaluation purposes. A MP-PIC model of the core process was constructed to identify this defect on the core during the blowing cycle. This defect took the form of an incomplete fill condition, however it should be noted that information regarding the presence and nature of the defect was only made available to the computational engineer after the numeric study was complete.

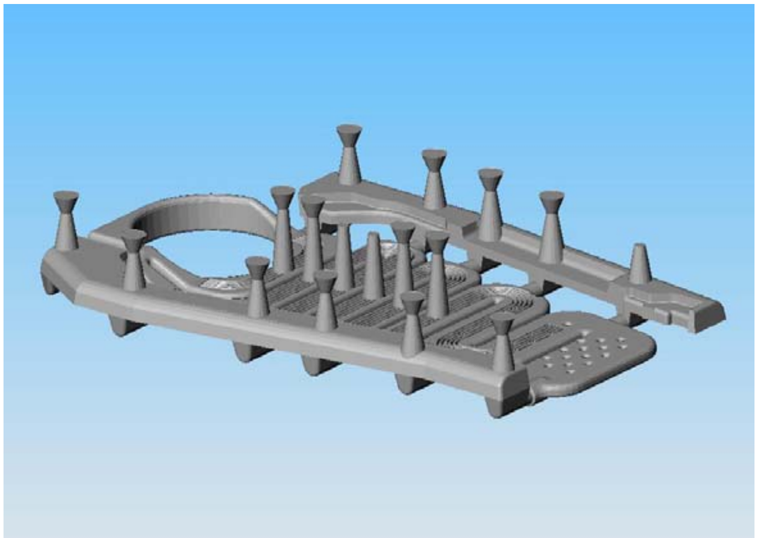


Figure 7: Flue-way core and blow tube geometry

To produce the defect, the blow tubes seen in the center and far right of the geometry (Fig. 7) were present on the core box but not connected through the blow plate so that sand would not be delivered to the core cavity in these regions. As with the previous, GM water jacket example, when constructing the computational model for this core, the scope of the model was limited in complexity as outlined below. The entire sand magazine and core geometry was first modeled to predict air flow through a packed bed of sand using a porous media to represent the filled magazine cavity. This approach is computationally inexpensive because the particles are not calculated as moving entities within the calculation. This technique represents the "worst-case scenario" with maximum sand in the magazine and is valid in cases where the magazine is not under suspicion as the weakest link in the process. The output from the air flow calculation reveals the pressure gradients within the magazine and the data can then be applied in the particle flow calculation. Figure 8 shows the CAD data for the core and sand magazine on the left (Fig. 8a), the computational mesh in the center (Fig. 8b) and the initial condition of the model on the right (Fig. 8c).

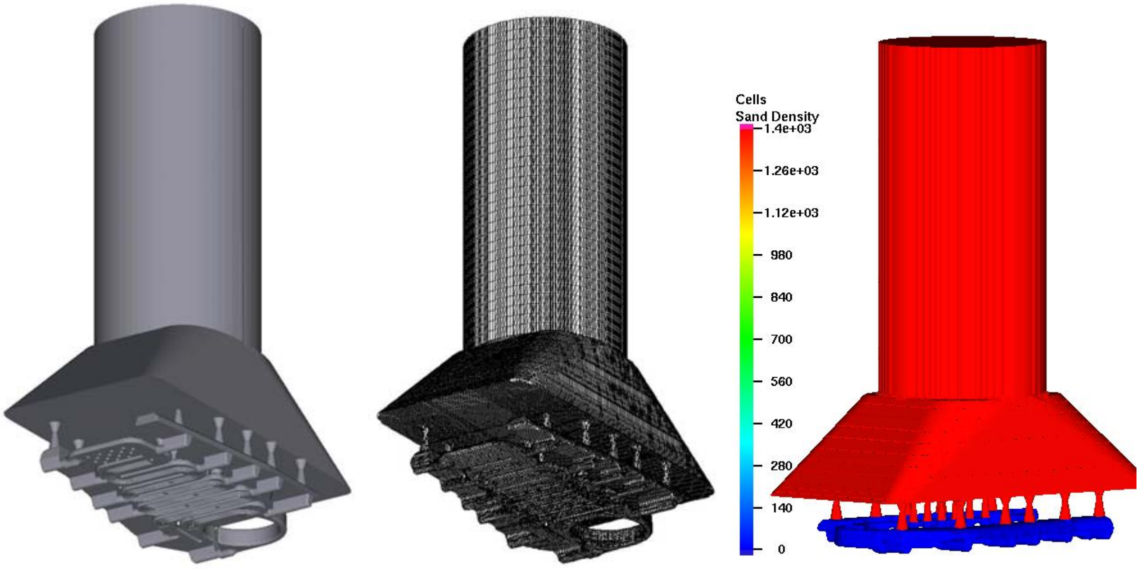


Figure 8a: CAD model b: Computational mesh c: Initial computational sand location (red)

A boundary condition with a pressure of 500,000 Pa was applied to the top of the magazine to represent the blow pressure applied during the process and the core box vents were allowed to exhaust to atmosphere. The pressure in the lower regions of the magazine was monitored during the calculation and a pressure of 463,000 Pa was reached 50mm above the blow plate (as shown in Fig. 9a). This pressure was then applied as a boundary condition to a smaller, detailed model of the core box and blow plate area as indicated in Fig. 9b.

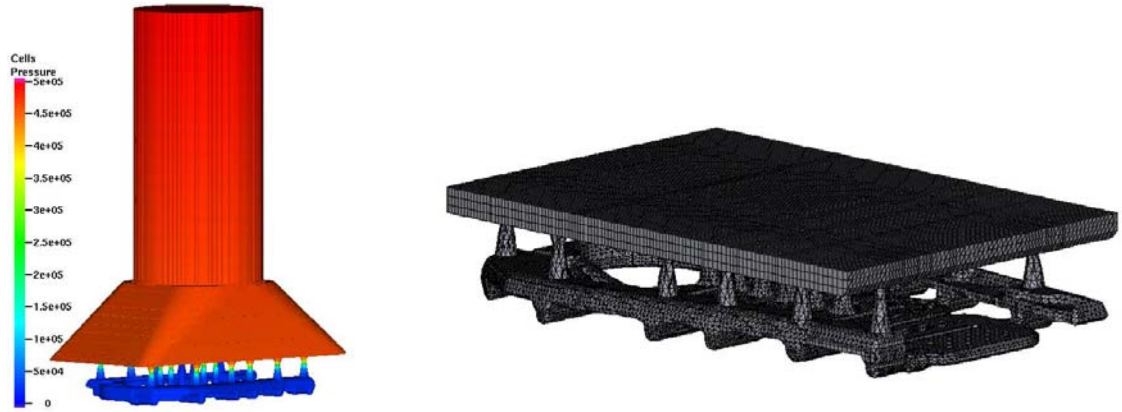


Figure 9a: Pressure result of full-scope model b: Smaller, detailed model of the core box and blow plate

The MP-PIC calculation incorporated the core and blow plate geometry along with a localized section of the sand magazine as shown in Fig. 10. Particles were taken randomly from the sand size distribution as specified in Fig. 11 and allowed to enter the calculation domain at the pressure boundary location at the top of the blow plate.

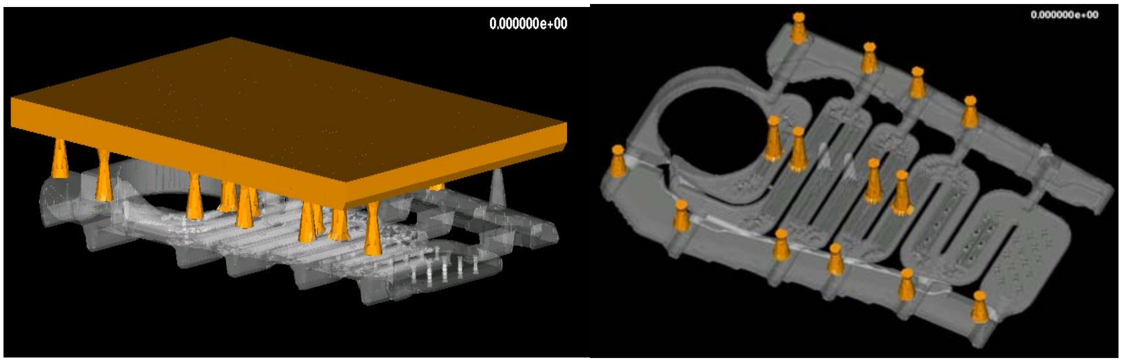


Figure 10: Initial location of sand in the smaller, detailed model

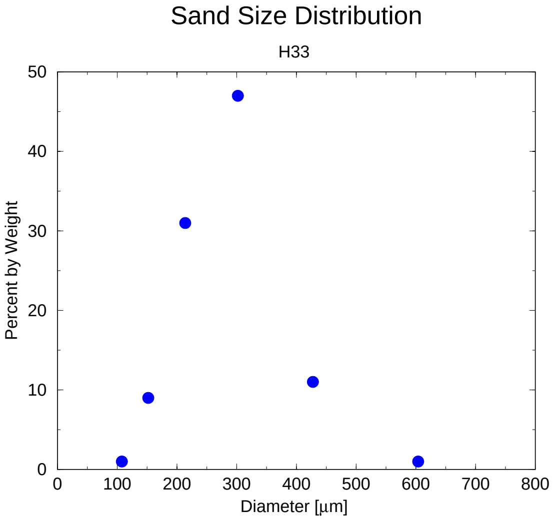


Figure 11: Sand Size Distribution

The computation was further simplified by making certain assumptions about the process: the process is assumed to be isothermal, the airflow is assumed to be incompressible and there are no leaks in the tooling. The particle normal stress model allows the sand particles to pack to a maximum, pre-defined density of 1400 kg/m^3 and the proprietary density model allows variation in close pack density based on local transient conditions.

These assumptions certainly influence the outcome of the calculation and engineering judgment is used to evaluate the effects of these assumptions. The assumption that there are no air leaks in the tooling means that air can only escape through the vents, in reality some air may escape from the joint line and this can result in the tooling filling slightly faster than predicted and the actual fill patterns may vary from the calculated fill. The issue of filling time is of little consequence when typical core filling times are under one second and the response time of mechanical valves in conjunction with the de-pressurization time will not normally allow for blow times to be fine tuned to within a few tenths of a second. The compressibility of the air would result in a volumetric expansion through the blow tubes which is not being modeled. The air is assumed to be at a density and viscosity that is equivalent to 300,000 Pa which is an estimate of the pressure in the blow tube region. It could be argued that the volumetric expansion would benefit the process in terms of air velocities and therefore the model is again representing the worst case scenario. However, modeling the process without a full magazine is of great benefit in reducing the overall size and run time of the problem. These reductions result in faster answers and the possibility of performing many more parametric calculations within a given period of time. Any influence from piping or rat-holing in the magazine will not be modeled and the assumption is valid where large magazine-to-core volume ratios exist.

Calculation Results

Local Density Variation

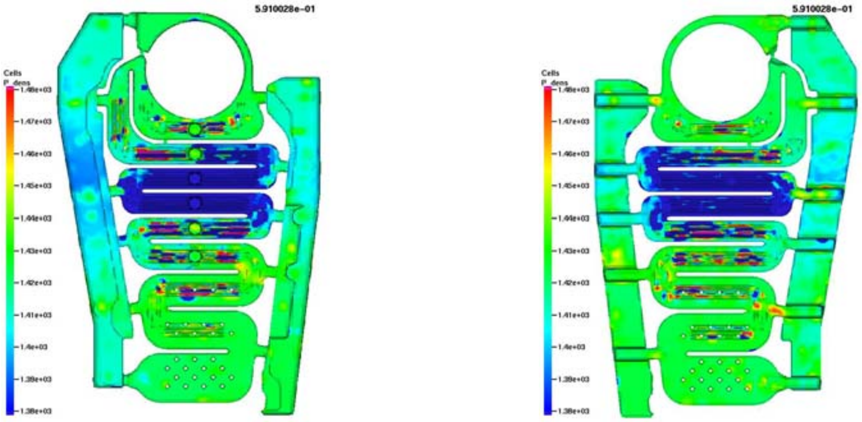


Figure 12 a: Cope side local density variation b: Drag side local density variation

Figure 12 shows the calculated output on local density variation in the cope (left) and drag (right) parts of the core. Low-density regions of less than 1380 kg/m3 are predicted in the regions where the two blow tubes were not connected in the center of the core. The majority of the core is calculated to be in the region of 1420 – 1430 kg/m^3.

The density increase associated with core filling through the blowing process can be seen in Fig. 13 at approximate time intervals of 0.1 seconds. The last image shows a non-fill condition in the central region of the flue-way.

Air Pressure

Due to the combined continuous – discrete nature of the MP-PIC approach, not only is the correct filling of the core computed, but the cause of mis-fills is revealed as well. Figure 14 shows the transient pressure history of the core at several snapshots in time, indicating the possible cause of the non-fill condition. The air pressure distribution is shown at time intervals of 0.1 seconds, beginning at 0 Pa (gauge) at time 0 through 0.4 seconds. The frames indicate a high-pressure region in the area that did not fill at 0.2, 0.3 and 0.4 seconds. Due to the lack of a pressure gradient in this region, no significant air flow is detected, resulting in a stagnant region. Since aerodynamic drag is the primary mechanism for moving sand into this region of the core, the lack of air flow results in the incomplete sand filling here.

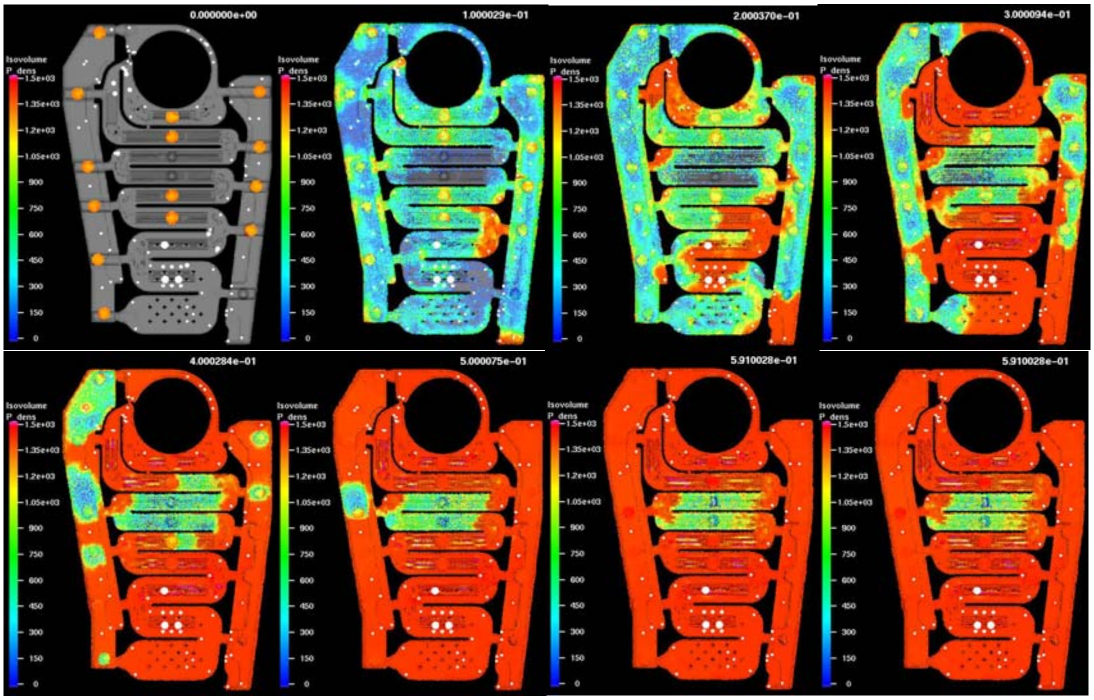


Figure 13: Transient filling of the core

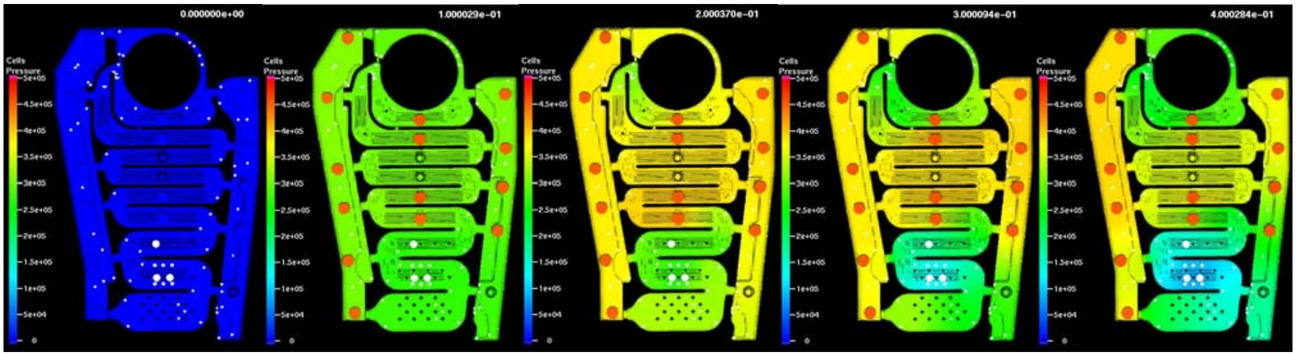


Figure 14: Transient pressure in the core

The chart in Fig. 15 compares the transient pressure in the well vented sections of the core versus the boundary condition (blow pressure). Pressure in the core increases as the blow pressure increases and sand begins to cover the process vents. As the nearby blow tubes fill with sand, a large pressure drop develops through the packed sand resulting in a pressure reduction in the core cavity. This does not occur in the problematic region.

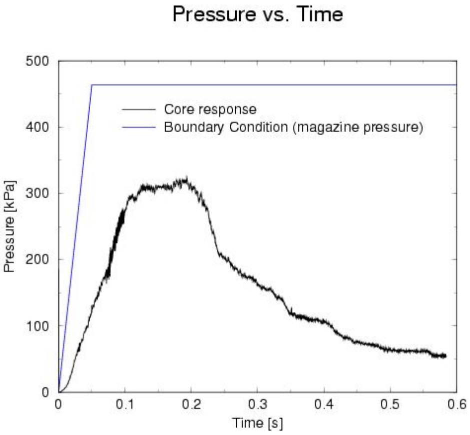


Figure 15: Transient pressure response

Sand Compaction

The sequences of events in Fig. 16 show the flow of the sand particles into the flue-way section. The images on the left are taken from the area defined as “Area 1” in Fig. 17; the images on the right are of “Area 2.” The blow tubes seen in the center on the left hand images are not connected to the blow plate and remain empty during the process.

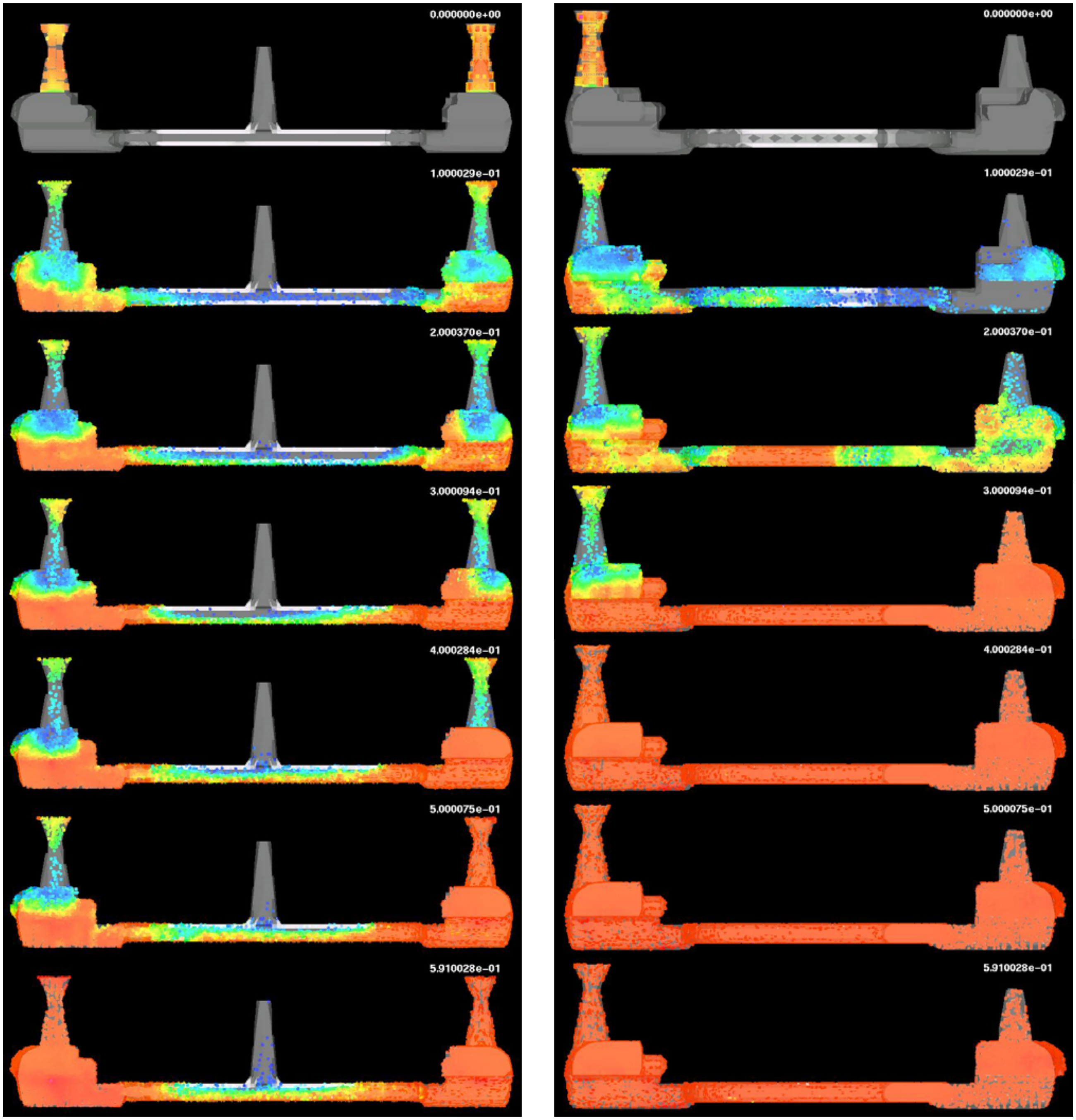


Figure 16a: Problematic regions (Area 1) b: Well packed region (Area 2)

The sand in Area 1 begins to fill the flue but stops flowing when the initial momentum is lost. By contrast, the sand in Area 2 continues to flow until a high degree of compaction is achieved. The core filling behavior is governed by the flow of air within the tooling. Both the sand and air fields are extremely important in capturing this phenomenon.

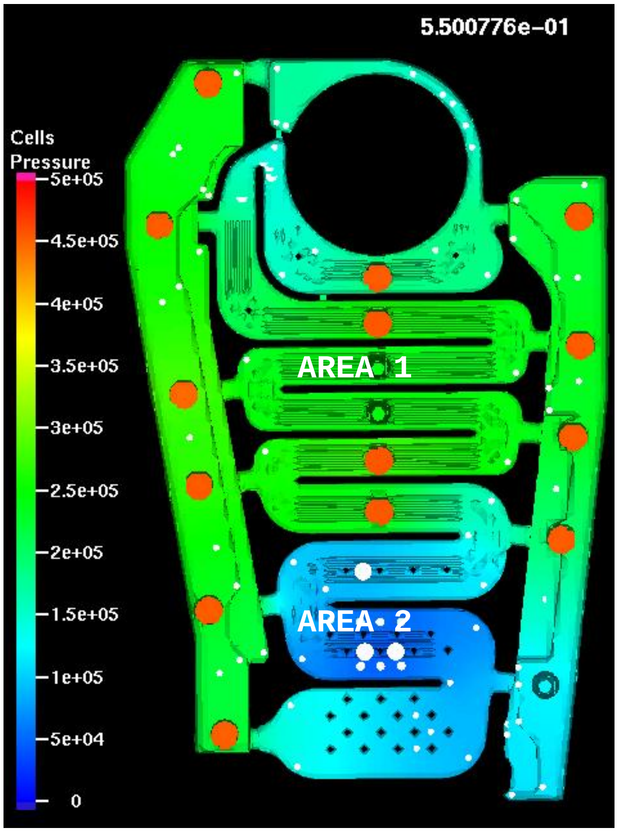


Figure 17: Identifications of “Area 1” and “Area 2” in the core

Conclusion

The results of the MP-PIC computation suggest that the core will show regions of good compaction but the region identified as Area 1 in Fig 17 will probably result in a non-fill condition. Figure 18 compares the computed result with a photograph of the core taken at MGG produced using the same parameters that were used to define the computational model. Agreement is excellent.

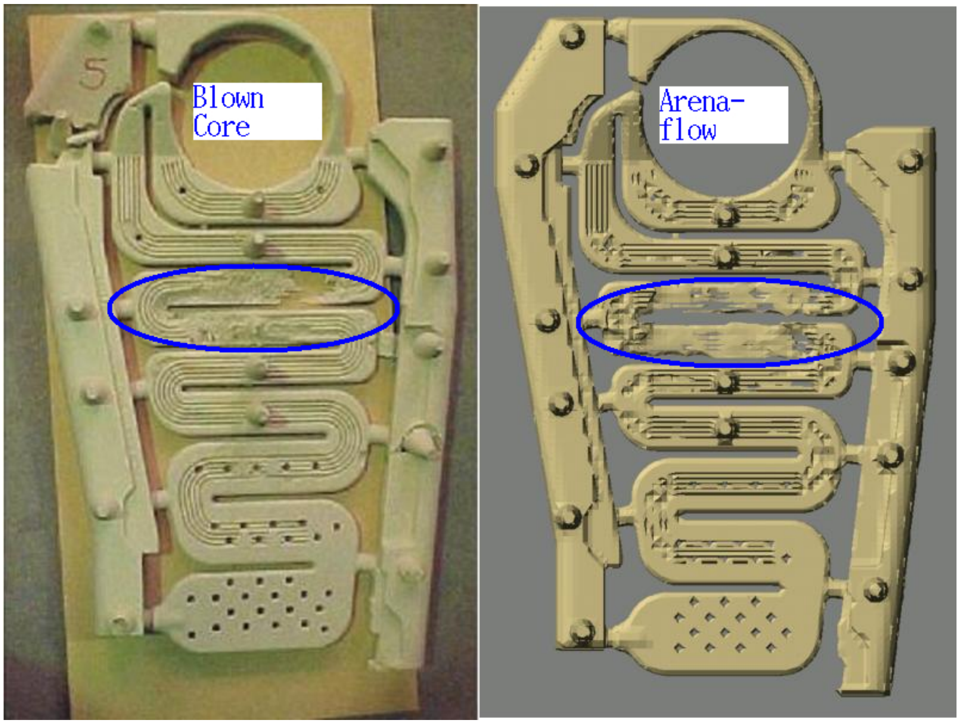


Figure 18a: Photograph of blown core b: MP-PIC calculation result

CATALYST GASSING

A recent development of the MP-PIC code[8] is the inclusion of a new proprietary gassing model. Research and development into the gassing of sand binder mixtures with amine catalysts to yield polyurethane resin cores, in conjunction with process models to interpret and supplement the data, has revealed some characteristics of the process that have not been fully understood or investigated in the past. The research is currently ongoing but initial trial results have been implemented into a model which demonstrates remarkable correlation with laboratory testing and binder development.

Experiments to date have been carried out using the Ashland T-Tool core box in conjunction with indicators in the sand binder mix to enable video data capture of the curing process. Figure 19 shows a comparison between the video data and the calculated transient curing for the T-Tool core. The darker region in the computation indicates a region that is likely to cure. The darker region in the video indicates a region with sufficient amine presence to trigger the catalytic reaction. Agreement is excellent.

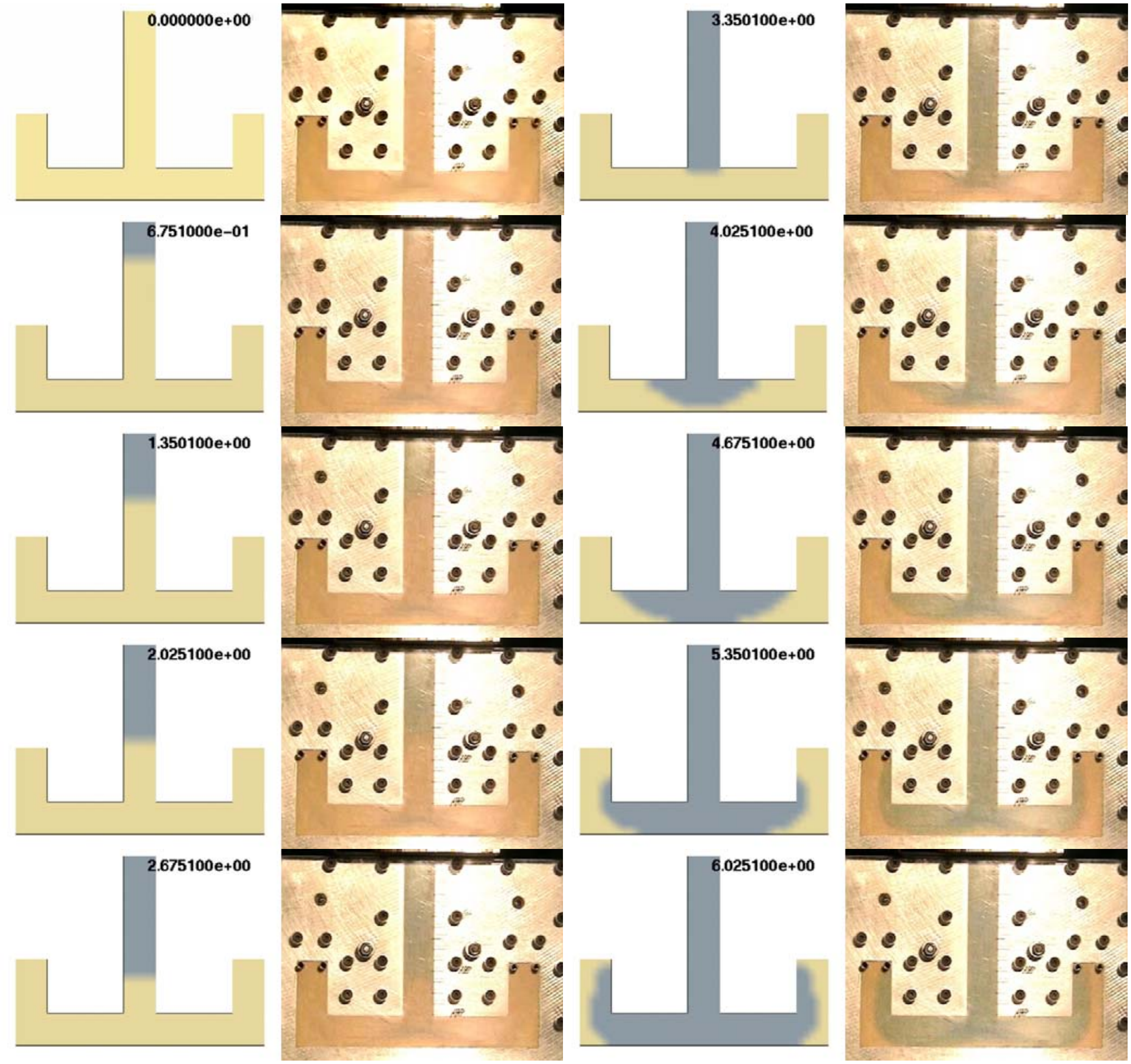


Figure 19: Transient gassing calculation compared to video data

CONCLUSION

Core and mold pattern filling behavior is dominated by a complex, three-dimensional, multi-phase flow of air and sand. The granular nature of sand has been demonstrated, and as such any process model which attempts to correctly predict core filling must not assume that sand is a fluid. It is not. Although it is desirable to mix the sand with high volumes of air in order to "fluidize" it, the air and sand remain a mixture of a fluid transporting a granular material. The discrete particles are transported by drag from the air flow, while at the same time the air flow is greatly influenced by the particles within and surrounding the flow. Other non-fluid forces such as inter-particle contact, wall contact and inter-granular frictional forces also greatly affect the sand.

The MP-PIC math-based tool described in this paper efficiently performs the calculations for the air flow, sand motion and the complex interaction between the two. Agreement with both fundamental physics experiments and actual blown cores is excellent. The use of well validated problem scope reduction techniques and sound engineering judgment in combination with the math-based tool has been shown to yield efficient computational results while maintaining accurate predictions of the process.

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