DEVELOPMENT AND USE OF SIMULATION IN THE DESIGN OF BLOWN CORES AND MOULDS

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ABSTRACT

Core box design has traditionally been achieved by a trial and error method which can lead to a lengthy and expensive development for core production. The present paper describes the development of simulation software capable of predicting the behaviour of sand and gas flow during the blowing stages of the core making process. Details are presented of the visualisation and examination techniques which were developed for the validation of the software, together with industrial examples illustrating the benefits of the simulation package in the optimisation of core box design.
Keywords: Core manufacturing process, Sand flow models, Gas flow through porous media, Finite difference, Casting simulation.

INTRODUCTION

The manufacturing of iron, steel and non-ferrous castings is achieved using a variety of casting process routes, and most of these involve the use of cores which form the internal shape of the casting. The core is often of intricate and complex shape and many cores are required for each casting. For example, in automotive cylinder head castings, cores often form internal passageways for fluid flow in valves, pumps, compressors and manifolds. The manufacturing of sand cores and moulds is commonly made using chemically bonded sands in two distinct stages. First, the sand is blown from a sand magazine into a core box at high speed. The blowing process is driven by the release of a high pressured air cartridge. A catalyst (amine) or hardening (methyl-formate or CO_2) gas is then passed through the core box to harden and cure the sand.
The design and manufacture of core boxes is a complex process and is traditionally achieved through an experienced based custom and practice technique. This lengthy and expensive trial and error development process aims at finding the most appropriate process parameters which include blowing pressures, gassing pressures and times but also the positioning of nozzles and venting channels necessary in the core box to let gases escape. The manufacturing of cores has traditionally suffered from defects arising from poor sand compaction, low strength and poor surface finish.

These typical core defects are responsible for a large proportion of scrap rates in the casting industry. With the availability of numerical simulation solutions, core blowing process parameters can be optimised and reliable and cost effective quality core production can be achieved.

The present paper describes the development of a simulation solution capable of modelling the core manufacturing process including sand blowing and gassing. Specific numerical models were developed for this purpose and are briefly described here. Obtained numerical results are confronted to experimental measurements and real time visualisations specifically conducted for validation purposes. More industrial applications are also presented to illustrate the benefits for the optimisation of core box designs.

DEVELOPMENT OF PROVING TEST METHODS

The blowing and gassing processes depend strongly on the physical characteristics of the different components used: grading and type of sand, type of resin and type of gas. Different sand systems and machine capabilities were examined in order to define an experimental program giving the widest industrial cover. Three sand systems characteristic of the industry were retained: amine catalyst (coldbox process), methyl-formate alkaline phenolate and CO_2 alkaline phenolate. Several other process parameters must be taken into account for blowing and gassing. The most important ones are the blowing and gassing pressures, the location and sizes of shooting nozzles and the core box venting configuration. Whatever process is used, the sand blowing proceeds in the same way: the coated sand is injected through the nozzles into the core box by the released air pressure. The vents allow the evacuation of air during blowing and of gas during gassing. Here one of the difficulties is to define the optimum venting arrangement valid for both stages of the process.

Simple core shapes were also designed to reproduce a wide range of test configurations. The initial test shape depicted in Figure 1 is a simple 2D finger core geometry designed from experiences with core blowing where the sand has often to be blown through sharp changes of directions. Core boxes were developed using glass fronts giving a full view of the cavity. High speed digital and video cameras were used to record sand filling and also gassing in real time. A wide range of blowing conditions was tested with varying blowing pressures from 3 to 6 bars. Vents were positioned at locations indicated on Figure 1 and different vent combinations from fully open to half the box vented were tested. Porous metallic bands were used here in place of standard cylindrical vents so as to reproduce as closely as possible a 2D flow situation. Additional trials were performed with coloured sand positioned in different layers to study dead zones in the shooting head and sand movements inside the cavity (see figure 2). Contrary to what was initially believed, these trials showed that the sand is not fluidised in the shooting head and core cavity. The various colour layers are clearly separated and in the same order as they were positioned in the cartridge.

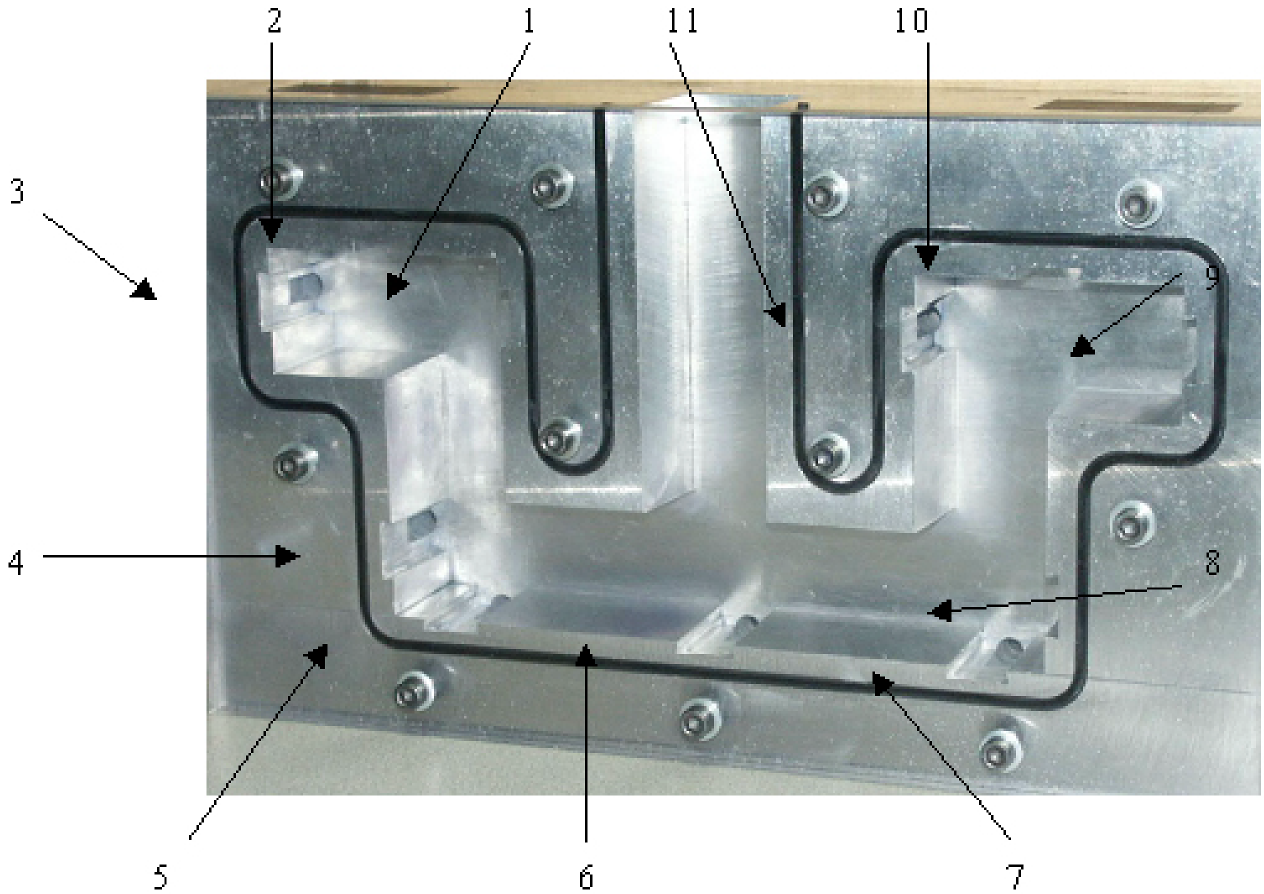

Figure 1: Test core geometry with glass cover. Arrows indicate the 11 different venting locations.

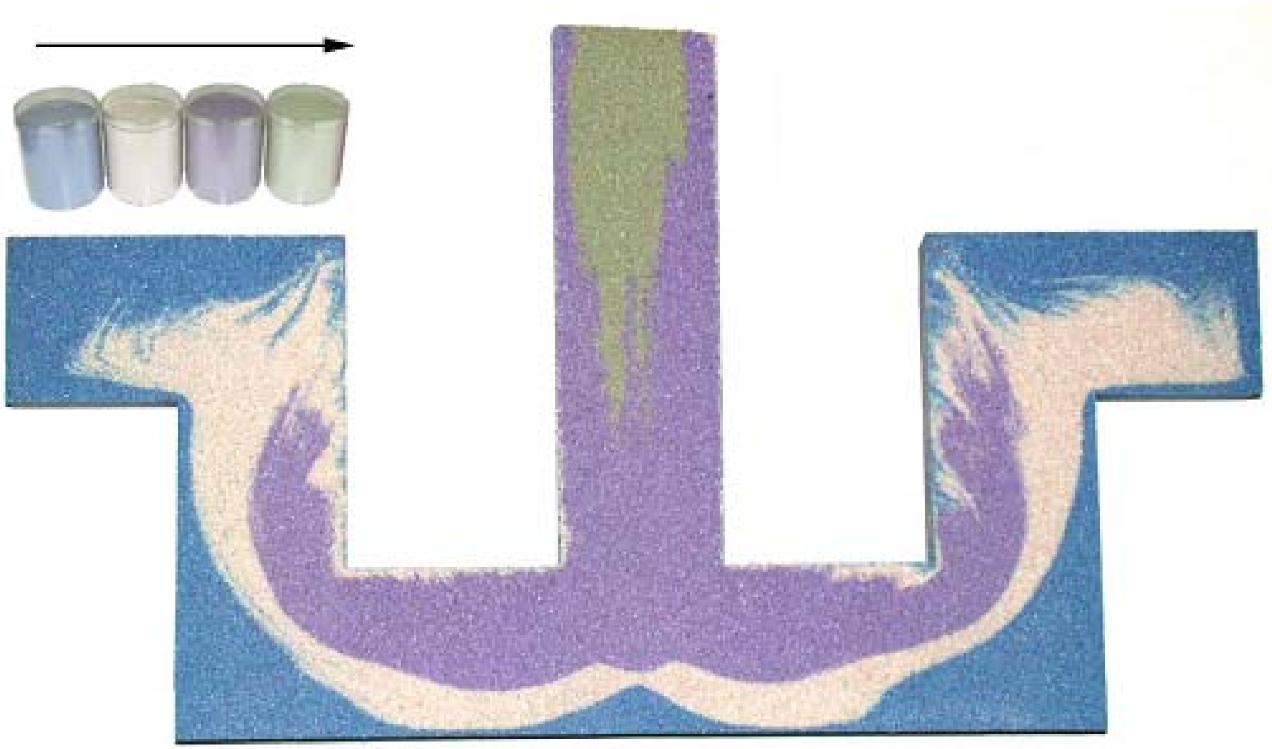

Figure 2: Coloured sand layers after blowing

For the visualisation of the gas flow during the gassing, Bromophenol blue or phenolphtalein dies were mixed with the sand depending on the type of process. These additives acted as colour indicators and allowed for real time visualisation of the gassing front inside the core. An experimental results database was documented in this way for the validation of the blowing and gassing numerical models.

MODELLING OF SAND BLOWING

Hydrodynamic models that capture the key features of particle gas flow, binder particle gas contacting and agglomeration in a single model is a challenging task and is the subject of active research. This can be attributed to the inherent complexity of the multi-phase hydrodynamics and contact mechanics involved. Two fluid continuum models and discrete element models have been the major two approaches in the direct simulation of fluidised bed. In discrete element methods, particles are traced individually by the direct solution of Newton's equations of motion (see for example Mikami et al [1]). However, the number of particles that these models can handle is at least one order of magnitude lower than that needed to fill a core box. In the two fluid continuum approach, the air and sand phases are viewed as two continuum media with additional equations describing particle to particle and wall interactions (reference [2]).

In the work described here and as a first approach, it was decided to represent the flow of sand using an extension of a two phase flow model as used in the commercial casting simulation software PAMCAST™. The Navier-Stokes equations are solved to predict velocities and pressures in the sand/gas mixture and gas phases using a Finite Difference approach. The sand/air mixture is modelled as a single phase non Newtonian fluid in which the density is assumed to be constant corresponding to the sand bulk density at nominal fluidisation and the dynamic viscosity is represented by a relationship of the form:

$$\mu = \mu_\infty + \gamma \frac{(\mu_0 - \mu_\infty)}{\boldsymbol{k}_1} + \boldsymbol{k}_2 \left(\nabla \cdot \frac{\vec{\boldsymbol{v}}}{|\vec{\boldsymbol{v}}|} \right) \tag{1}$$

In equation (1), μ_0 is the minimum viscosity occurring at high shear rate, μ_∞ is the maximum viscosity occurring at zero shear rate, $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are model parameters, $\vec{\boldsymbol{v}}$ is the velocity vector and γ the magnitude of shear rate defined as:

$$\gamma = \sqrt{\boldsymbol{trace}\left(\dot{\gamma} : \dot{\gamma} \right)} \tag{2}$$

The sand core shooting simulation requires the definition of an applied pressure corresponding to the shooting pressure. To allow for pressure variations across the shooting plate and down the blowing nozzles, this pressure boundary condition is applied at the top of the sand shooting plate. The different experiments conducted for various core shapes and configurations have shown that a key process parameter is the location of the different venting channels. For the simulation, vents are taken into account as a pressure loss boundary condition of the form:

$$\Delta \boldsymbol{P} = \rho \boldsymbol{k} \, \boldsymbol{v}^2 / 2 \tag{3}$$

where ρ is the density, $\boldsymbol{v}$ the velocity and $\boldsymbol{k}$ a coefficient depending on the vent geometry. This coefficient is also weighted by the amount of sand present around each vent location so as to account for reduced venting effect when filled.

This model was applied to the simple core geometry and validated against experimental results. As can be seen on figure 3, results agree qualitatively with experiments and the proposed model is able to correctly describe the transient stages of the blowing process. In this example, all the vents on the left (vents numbered 1 to 6 on figure 1) were closed which explains the unsymmetrical filling pattern obtained.

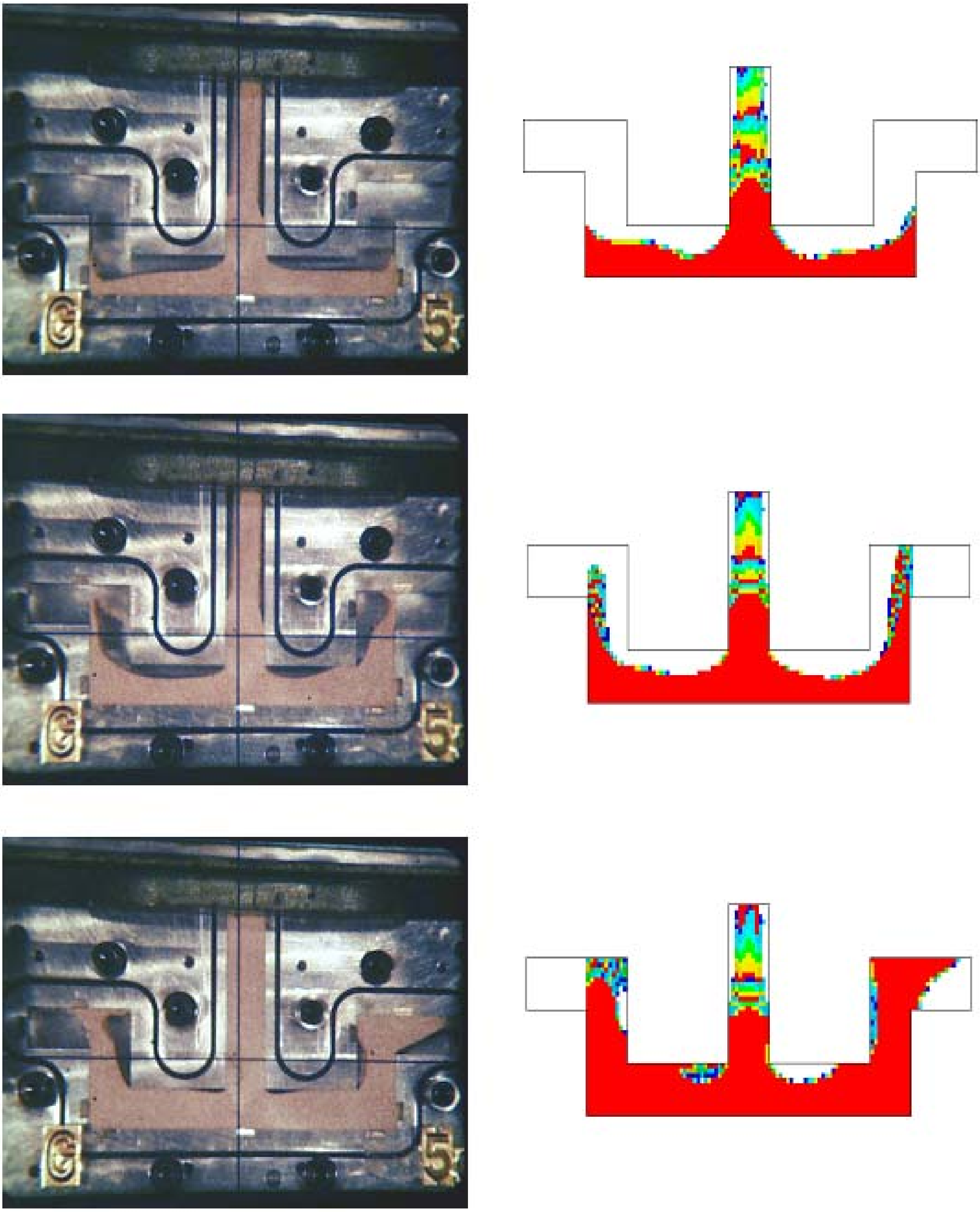

Figure 3: Comparison between experiments and simulations for sand blowing.

MODELLING OF GASSING

As the sand injected in the mould is first coated with an organic resin, capillarity bridges are formed between sand grains. The consolidation of these bridges is achieved by the supply of a gas mixture containing the right chemical agent to obtain the hardening reaction. Depending on the process, this chemical agent can either take part in the reaction as a co-reactant or just as a catalyst. Once the gassing stage is completed, the core box is finally purged from its remaining active gasses by injecting air in the core box.

The gassing process can be described as the transport of an active agent in a porous media and requires the determination of four macroscopic variables defined at a scale larger than the size of the sand grains:

- ω_A the mass fraction of active agent,
- ρ the density of the gas mixture,
- $\mathbf{v}$ the velocity of the gas mixture flow field,
- P the total pressure of the gas mixture.

These variables can be related to one another by three equations of conservation and one equation of state (reference [3]) and were implemented in the commercial casting simulation software PAMCAST™ using a Finite Difference approach.

Mass balance equation:

$$\varepsilon \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{4}$$

Momentum balance equation:

$$\mathbf{v} = -\frac{\mathbf{K}}{\mu} (\nabla \cdot P - \rho g) \tag{5}$$

Active agent mass balance equation:

$$\varepsilon \frac{\partial \rho \omega_A}{\partial t} + \nabla \cdot (\omega_A \rho \mathbf{v}) = \nabla \cdot (\rho D \nabla \omega_A) + \sigma_A \tag{6}$$

Ideal gas equation:

$$P = \rho r T = \rho (\omega_A r_A + \omega_B r_B) T \tag{7}$$

where ε represents the porosity, μ the viscosity of the gas mixture, D the diffusion tensor and r the molar constants. The permeability $\mathbf{K}$ can be determined from the grain diameter d and sand porosity ε using a Kozeny-Carman formula:

$$K = \frac{2 \varepsilon^3 d^2}{72 \pi (1 - \varepsilon)^2} \tag{8}$$

A sensitivity analysis shows that, given the ratio of heat capacities between gas mixture and sand, it can reasonably be assumed that the temperature is constant and uniform. The energy balance equation was therefore not considered in the model. σ_A represents a sink term which can be used to represent the consumption of active agent during the chemical reaction.

The core gassing simulation requires the definition of the gassing pressure applied at the top of the shooting plate and of the initial fraction of active gas. Here again, vents are a key process parameter. They are taken into account as a pressure head loss boundary condition in the same way as for the sand blowing stage. The optimum venting configuration is generally different for blowing and gassing. It is therefore necessary to find the best compromise between the two stages.

Gassing simulations were performed and compared to real time visualisation of the gassing front. In figure 4, the colour change obtained experimentally with the dies coincides with the arrival of the catalyst gas and can be directly compared with the computed mass fraction of active agent. Simulation results are in good agreement with experiments for the gassing front profile but also for corresponding gassing times.

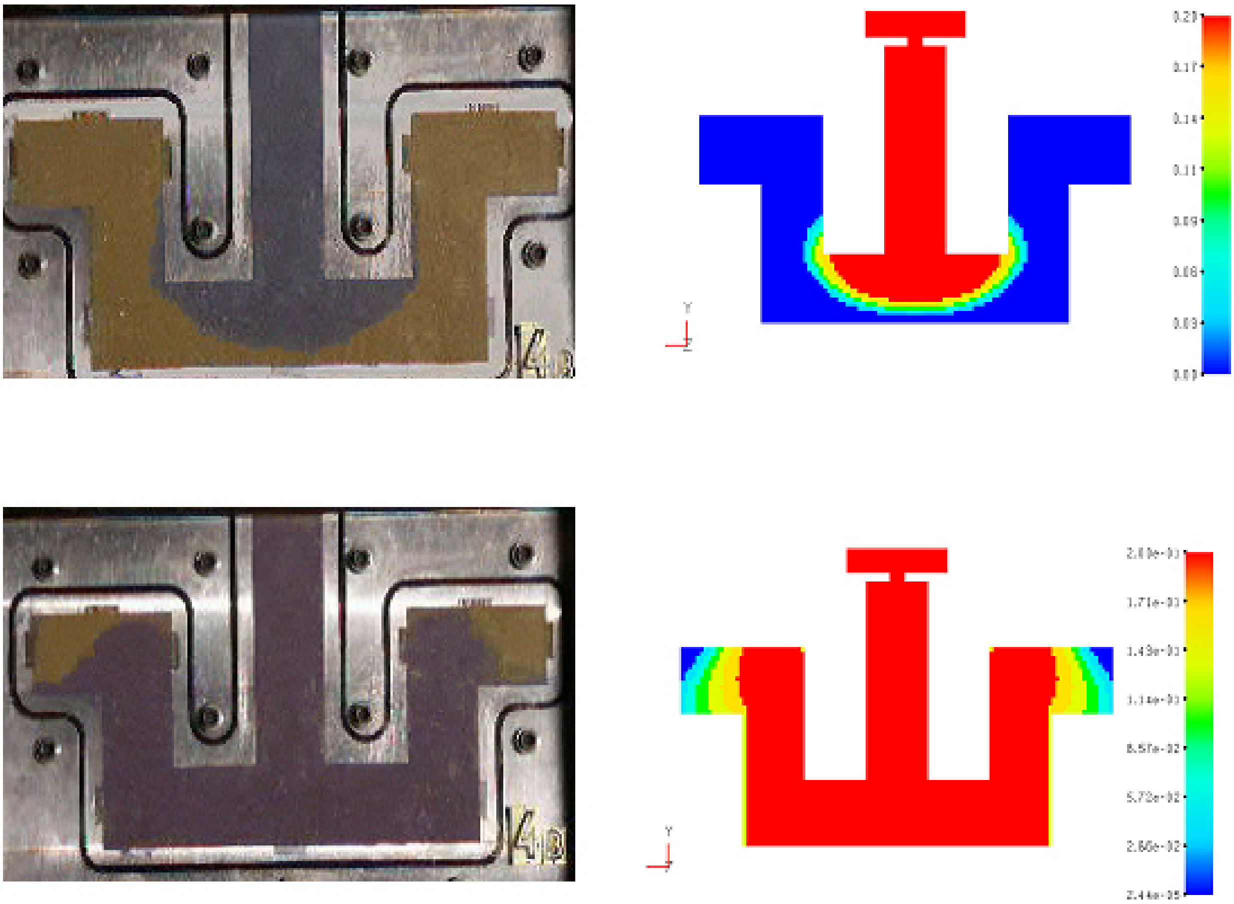

Figure 4: Comparison between experiments and simulations for gassing.

INDUSTRIAL APPLICATIONS

The standard numerical method used in the software PAMCAST™ is based on Finite Differences and requires the construction of a 3D Cartesian grid. Prior to generating the volume mesh, the core box geometry is first represented by a surface triangulation. This surface triangulation can easily be obtained from the CAD definition of the core box. It should be noted that volume and surface correction factors are automatically computed and applied to account for geometrical discrepancies between the geometry and the structured mesh representation.

A three cavity core box with venting channels as used industrially by the foundry Infun in Spain for the production of axle iron castings is illustrated on figure 5. Here again the positioning of vents is of critical importance for producing good quality cores. Initial experimental trials show that with air vents positioned as indicated on figure 5, unfilled areas are obtained at two different locations at the top and lower part of the core (figure 6). Only one of the three cores is considered for the simulation with a simplified representation of the shooting plate and sand magazine and a constant pressure of 4 bars is applied throughout the blowing simulation. Figure 7 shows detailed views of the sand fill rate obtained at the end of the simulation. These results show a good qualitative agreement between observed defects and simulation results at the upper end but more importantly at the lower arm of the core. Other partially filled areas are also visible in figure 7 which were not observed in practice. These differences can be explained by the additional venting effects of the ejectors and core box parting line which was not taken into account for the simulation. This observation was confirmed by further experiments. The computational model used here consists of 350000 finite difference cells and the computation time corresponds to 20 hours on a PC workstation.

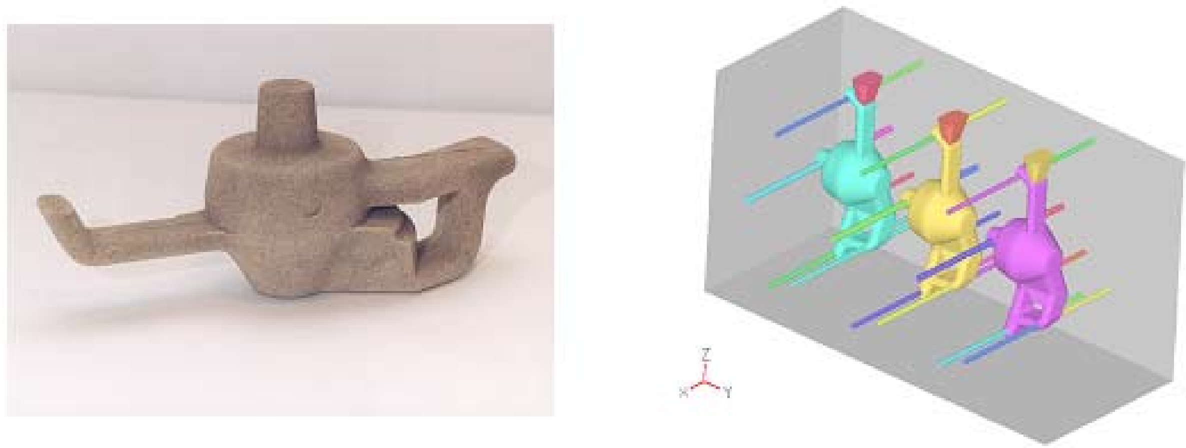

Figure 5: Axle core and CAD definition of the core box including core geometries and venting channels (courtesy of Infun).

Figure 6: Unfilled areas observed on the axle core (courtesy of Infun).

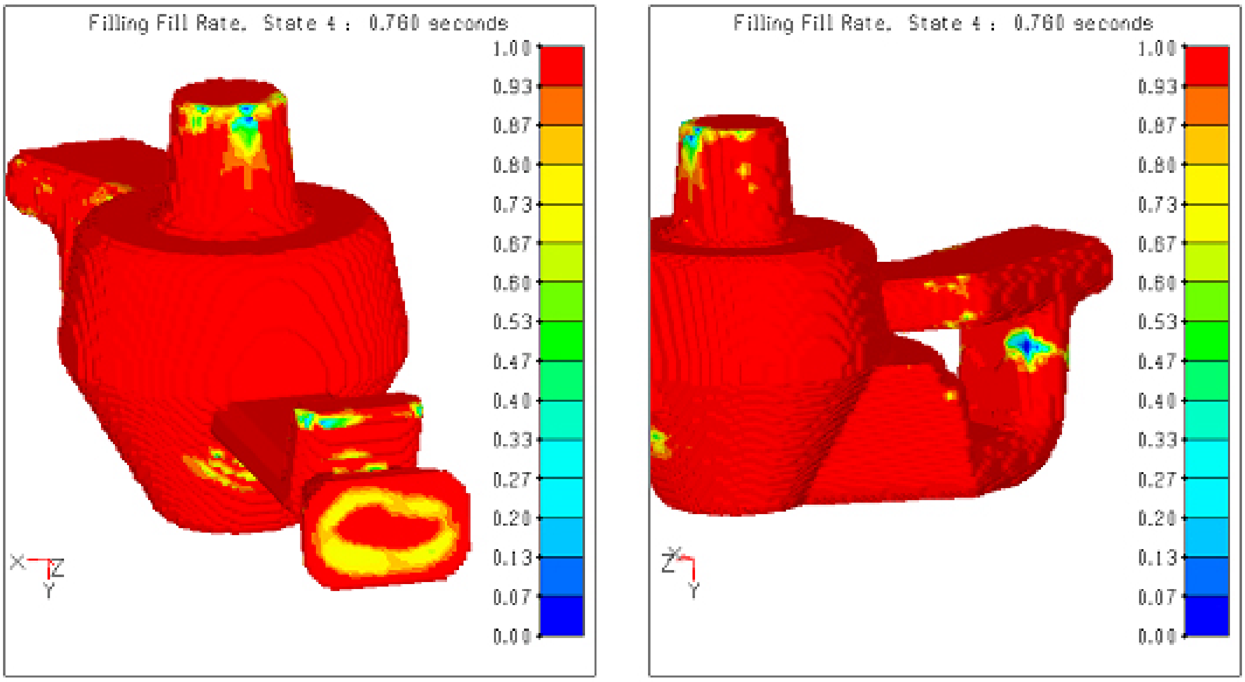

Figure 7: Simulation results. Details of predicted fill rates showing unfilled and poorly compacted areas.

A second industrial application is now used to illustrate the gassing simulation. The core geometry, illustrated on figure 8 together with the venting arrangement, is used for the manufacturing of aluminium suspension arms by Teksid in Italy. A constant gassing pressure of 2 bars is applied throughout the gassing simulation. An incomplete gassing process was performed experimentally. Upon removal of the core, the remaining sand in the core box corresponds to areas that were not hardened (see figure 9). These trials can be compared with the predicted gassing front position towards the last stages of the gassing simulation (figure10). These results show a good qualitative agreement, the locations of the gassing front indicating the different areas of remaining sand. It should however be noted that, for the simulation, the sand compaction and permeability was assumed constant.

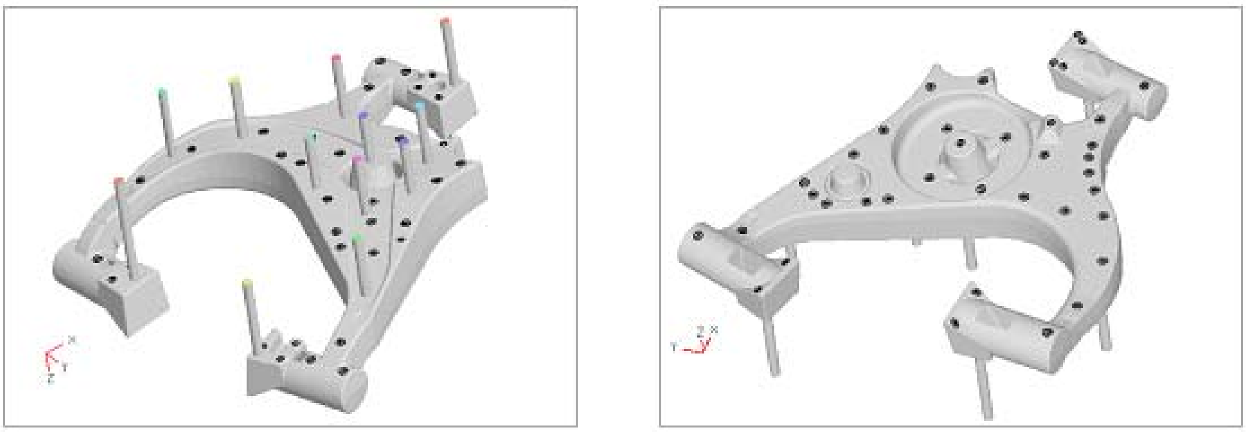

Figure 8: Suspension arm core geometry and vents positioning on upper and lower core box.

Figure 9: Remaining sand in the core box after an incomplete gassing process.

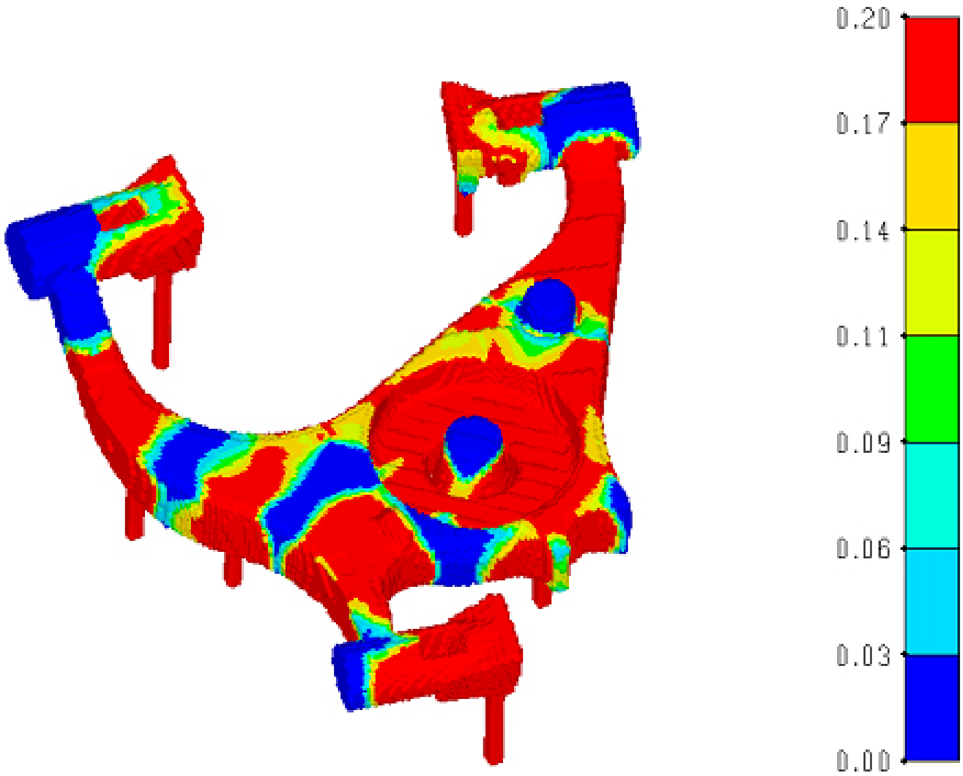

Figure 10: Simulated gas front position towards the end of the gassing.

CONCLUSIONS

The core manufacturing process is a difficult process involving the flow of bounded sand material and the transport of reactive gases through compacted sand. Extensive experimental trials have been performed and documented to better understand the different steps of the process and derive better industrial practices. Some of this experimental work together with visualisation techniques used have been reported in the present paper.

Numerical models for the simulation of core blowing and gassing processes were developed and incorporated in the casting simulation software PAMCAST™ using a finite difference approach. Although simplified models are proposed for the sand flow behaviour, the comparison with experimental results shows good overall agreement. The application to the prediction of typical core defects obtained industrially has proved successful and demonstrates that numerical simulation can be a cost effective alternative to lengthy trial and errors development procedures.

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