Core Drying Simulation and Validation

A. Starobin and C.W. Hirt
Flow Science, Inc., Santa Fe, NM

H. Lang
BMW Group, Landshut, Germany

M. Todte
CFD Consultants GmbH, Rottenburg, Germany

ABSTRACT

In the manufacture of inorganic sand cores, it is necessary to remove any moisture remaining in the core before it can be used. Several techniques are employed to remove the water including heating in an oven, microwave heating and forcing hot, dry air through the core. In all cases, heating of a core can be expensive so there is interest in investigating optimum arrangements for achieving the most efficient means of removing the residual water.

This paper describes a computer model that allows for a realistic simulation of the core drying process. The new model considers porous sand cores of arbitrary shapes with properties such as moisture content, temperature and vapor concentration that vary throughout. A fully non-equilibrium phase-change model is used to compute the evaporation and condensation of water vapor in sand. Compressible gas dynamics describes the flow of the mixture of vapor and air in and around a core.

A description of the model is followed by a validation test using a simple core geometry. Further validation is reported based on tests with a realistic, production grade core.

INTRODUCTION

A new inorganic core making process has certain advantages over the traditional organic process. It is environmentally friendly and healthier for the workers on the shop floor because it uses water based binder systems and hence does away with the toxic amine based binders. Furthermore, the inorganic process offers a potential for the improvement of the casting quality due to reduced core gas production and lower tool temperatures. In this process, it is essential to remove water from the sand in order to harden the core after shooting the sand in the mold.

This paper describes a software development for a realistic simulation of the core drying process. A description is given of the new model, which has been validated with data from a simple core arrangement. Further validation is reported based on tests with realistic, production grade cores dried with hot air forced through the bulk of the core.

A similar physical model, restricted numerically to one-dimensional geometries, was used by Pehlke and Kubo[1] to model moisture transport in green sand molds. In our implementation the core can have an arbitrarily prescribed shape with properties such as moisture content, temperature and vapor concentration that vary throughout. Thus, the core may have dried on its surface but still be completely wet on the inside. Air and water vapor existing in or around a core constitute a two-component gas that is treated as compressible. Heat conduction is simulated in all gas and solid regions and a non-equilibrium phase-change model is used to couple the liquid and vapor states of water. Using this model it is possible to simulate transient conditions throughout a core and thereby make detailed investigations of non-uniform initial conditions as well as a variety of drying techniques.

BASIC ASSUMPTIONS OF THE DRYING MODEL

The new model, which is described in the next section, is based on several assumptions and approximations that are summarized next. The model provides a three-dimensional and time-dependent description for the compressible flow of a mixture of air and water vapor through and around porous solids. Heat conduction is included in all solid and gaseous regions.

The mixture of air and water vapor is treated as a two-component, compressible gas described by a polytropic-gas equation-of-state that relates the gas pressure, density and temperature. Specific heat and gas constant of the mixture are computed as mass averages of the two components.

Although variable moisture content is allowed in a core, no account is taken for wicking of water in the material or for displacement by airflow. The neglect of such small displacements is not likely to be significant since the total mass of water in a core is only a small percentage of the core mass in any case.

A further simplification is that the temperatures of the water and core material are always in local equilibrium. This assumption is reasonable because the water and solid material are in intimate contact and distributed on a scale that is fine compared to the thickness of a core. Gas temperature, on the other hand, is generally different from the core/water temperature and that difference is essential for modeling the drying process.

GENERAL MODEL DESCRIPTION

All geometric features are initialized in the modeling program with the core defined as a solid component of given porosity. Thermal properties are defined that include initial temperature, density, specific heat, heat-conduction coefficient, and heat-transfer coefficient between core and gas. The water initially in the porous core material is defined by a set of properties that include water volume fraction, heat capacity, and latent heat.

Gas flow is governed by the equations for its density ρ and vector velocity **u**,

$$V_f \frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{u} A \right) = S_\rho \qquad \text{Equation 1a}$$

$$\frac{\partial \vec{u}}{\partial t} + \frac{1}{V_f} \vec{u} A \bullet \nabla \vec{u} = -\frac{1}{\rho} \nabla p - \vec{D} \qquad \text{Equation 1b}$$

The factors V_f and A are volume and area porosities for porous media. Outside porous media, these factors reduce to values of 1.0. In the density equation, the right-hand side term S_ρ is the source or sink of gas mass arising from the vaporization or condensation of water. On the right side of the velocity equation are the gradient of pressure p and a porous media flow resistance D, which is given by

$$\vec{D} = F_d \vec{u} \qquad \text{Equation 2a}$$

with

$$F_d = \frac{\mu}{\rho} \frac{1 - V_f}{V_f} \left[\frac{180}{d^2} \left(\frac{1 - V_f}{V_f} \right) + \frac{4}{d} \left| \vec{u} \right| \frac{\rho}{\mu} \right] \qquad \text{Equation 2b}$$

In this expression d is the characteristic diameter of sand grains in the core (or of the spaces between the grains) and μ is the viscosity of the gas. Equation 2 is a standard, Reynolds number dependent, porous-media flow loss expression.[2]

In addition, it is assumed that water in a porous material will directly contribute to a lowering of the porosity (V_f) of that material by the local water volume fraction. Because of this, water alters the core permeability and thereby affects the gas flow rate passing though it in a time-dependent way as water either evaporates or condenses. This formulation automatically adjusts the porosity of a core to be its dry value when all water is evaporated.

Equations 1 are for a compressible gas. One reason this is important is that the gas velocity in the core must increase in the direction of gas flow because of the decrease in pressure through the porous material needed to overcome the flow resistance. This means that the gas density and/or temperature must decrease by expansion to give the pressure decrease. Further, significant variations of gas density, and therefore flow velocity, are expected due to cooling of drying air as it passes through the core. Since flow velocity has an important effect on drying rate, compressibility can influence local drying conditions.

Evaporation and condensation of water is modeled using a routine based on kinetic theory rate processes with a dependence on the local vapor saturation level in the air. This has the form,

$$S_\rho = \alpha \frac{A_c}{V_f} \frac{\left(p_{sat} - p_v \right)}{\sqrt{2 \pi r_v T_c}} \qquad \text{Equation 3}$$

In this expression α is the accommodation coefficient, A_c is the surface area per unit volume inside the core, r_v is the vapor gas constant and T_c is the temperature of the core. In the numerator p_{sat} is the saturation pressure of vapor corresponding to the local temperature of the core/water and p_v is the local pressure of the vapor. If the saturation pressure corresponding to the core temperature is less than the actual vapor pressure then S_ρ is negative and vapor will condense in the core, otherwise the water evaporates.

A relation must be defined that relates pressure and temperature at saturation. The model uses a standard Clapeyron equation for this purpose, which requires the specification of a temperature-pressure point lying on the curve (p_1,T_1) and the value of an exponent t_{exp},

$$p_{sat} = p_1 \exp \left(\frac{1}{t_{\exp}} \left(\frac{1}{T_1} - \frac{1}{T} \right) \right). \qquad \text{Equation 4}$$

This exponent can be estimated in terms of the ratio γ of specific heats for vapor at constant pressure c_p and constant volume c_v and the heat of vaporization for water Γ as $t_{exp} = (\gamma - 1) c_v / \Gamma$. The phase-change rate also has an accommodation coefficient whose value is usually close to a value on the order of 0.05. Both evaporation and condensation are included in the phase-change routine, which means that water vapor moving into a cooler region of a core will condense and remain there until it is again heated to a temperature sufficient for evaporation.

An important component of the model is the heat transfer between gas and core (i.e., core solids plus water). It is proportional to the difference between the gas temperature, T_g, and the sand temperature, T_s. Gas-to-sand heat transfer coefficient, h_{gs}, and surface area per unit volume in the porous material are input quantities and are used for computing heat transfer and phase change rates. A typical value for the surface area per unit volume, if the particles (e.g., sand grains) are assumed to be spherical, is $A_c=6F_s/d$, where F_s is the volume fraction of the solid in the porous medium, i.e., the complement of the porosity and d the particle size

The full gas energy transport equation (Equation 5) also includes energy loss, or gain associated with condensation, or evaporation, energy advection and possible flow work due to gas expansion into lower pressure regions. The conductive heat transport in the gas phase is small and can be neglected. In Equation 5, e_g is specific volumetric energy of the moisture/air mixture and L is the latent heat of water.

$$V_f \frac{\partial e_g}{\partial t} + \nabla \bullet \left((e_g + p)\vec{u}A \right) = S_\rho L - h_{gs}(T_g - T_s)A_c \qquad \text{Equation 5}$$

VALIDATION OF MODEL

For the validation of the model at BMW two cores were analyzed, a generic core with a simplified geometry and a core for a production casting. Figure 1 shows the generic core and its mold.

In the core manufacturing process the molding sand is shot into a heated mold. The mold is heated during the complete process, i.e. shooting and drying, and it is desired to achieve a uniform temperature distribution in the mold. As a consequence of the hot mold the core dries and hardens first in a thin layer adjacent to the wall. After the shooting process the core is vented through all the top nozzles (shooting and venting nozzles) using hot pressurized air. The water in the core is vaporized by the hot air and the air-vapor mixture leaves the core through the bottom venting nozzles. Removal of the water results in the hardening of the core by a chemical reaction of the binder.

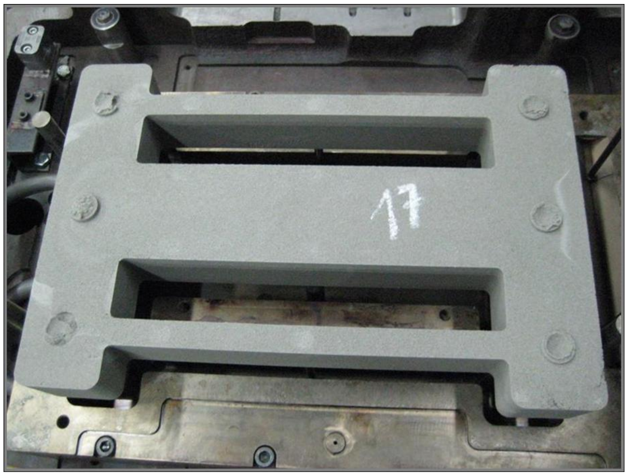

Fig. 1. Generic core and mold used for the validation of the model at BMW.

One goal of the experiments was to establish a functional relationship between the duration of the venting with hot air and the residual moisture content in the core. For this purpose, the cores were weighed immediately after the venting process. Subsequently the core was put in an oven in order to remove the water completely and weighed a second time. The difference in weight is the residual moisture after the venting. A series of simulation runs were carried out and the model parameters (accommodation coefficient, surface area of sand core, heat transfer coefficient) varied in order to match the experimental data. Results of the calibrated model are shown in Fig.2.

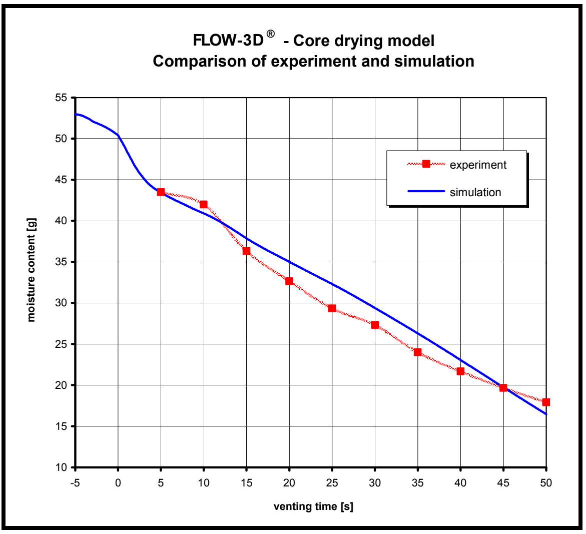

Fig. 2. Experimental and numerical results for residual moisture content vs. venting time.

In addition to the experimental determination of the residual moisture content, the cores were fragmented into pieces. In areas that were still wet the sand fell out or was easily removed by scratching. Figure 3 shows the middle ligament of three simple cores with sand removed in the wet areas.

Fig 3. Middle ligament of three generic cores with sand removed in the wet areas.

Figure 4 shows an iso-surface of the remaining residual moisture predicted by the model. The iso-surface is the complement of the hardened core volume. Its shape corresponds very well with the experimentally obtained shape of the hardened core.

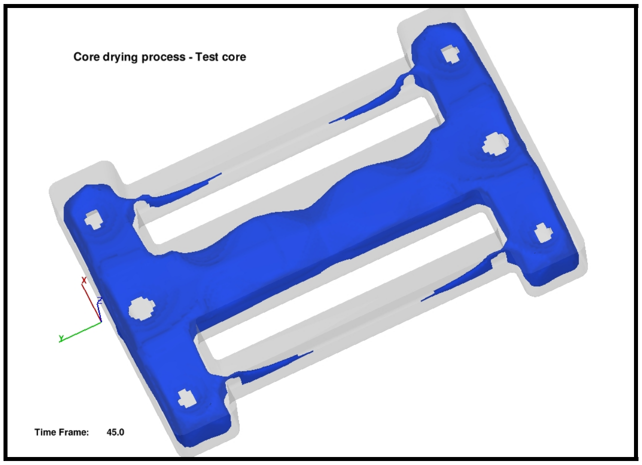

Fig 4. Iso-surface of the computed residual moisture.

After the calibration of the parameters of the numerical model using the generic core the model was applied to a real core which was close to the production start but still exhibited two minor imperfections as a consequence of too much residual moisture in these areas (Fig. 5).

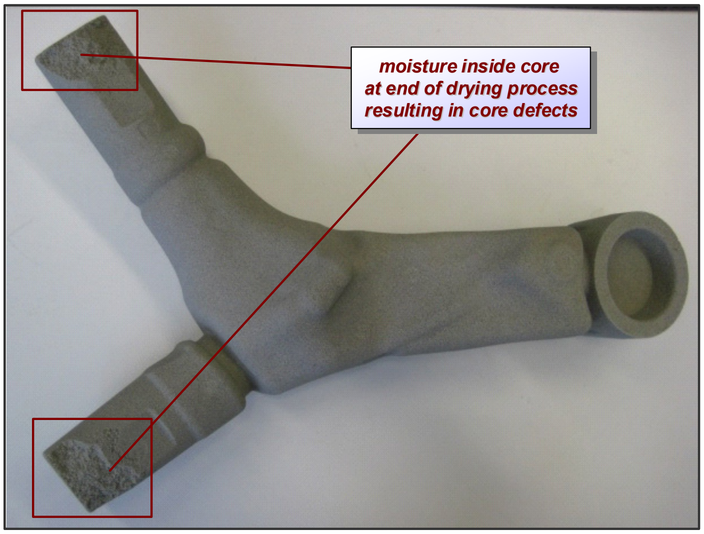

Fig. 5. Real core exhibiting imperfections due to residual moisture.

The geometry of the core and the nozzles was set up in a CAD system (see Fig. 6) and imported into the simulation program* in STL format.

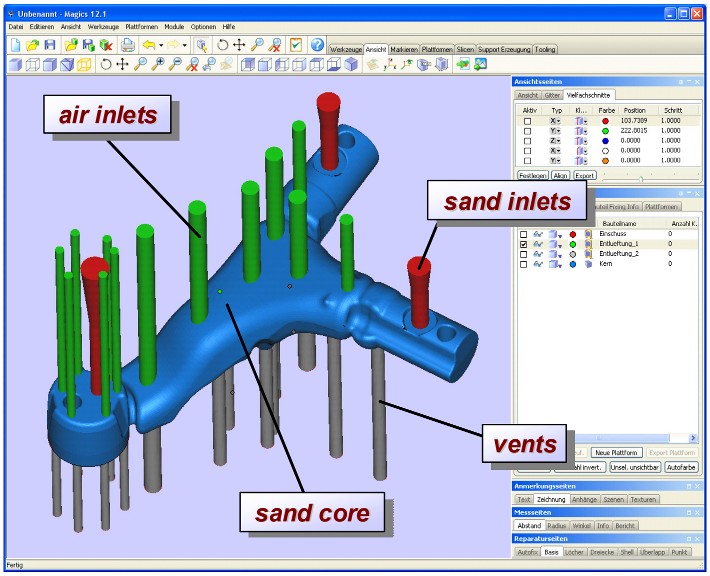

Fig 6. CAD geometry of core and nozzles.

The simulated residual moisture detected was exactly in the areas that had been shown to be critical in reality, see Fig. 7.

Based on the simulation results the number and position of the venting nozzles were modified and a second simulation was performed. The results for this new set-up showed a complete removal of the critical areas of high residual moisture. The results of the simulation were subsequently confirmed in experiments; hence, the new cores showed no critical areas and were suitable for the serial production.

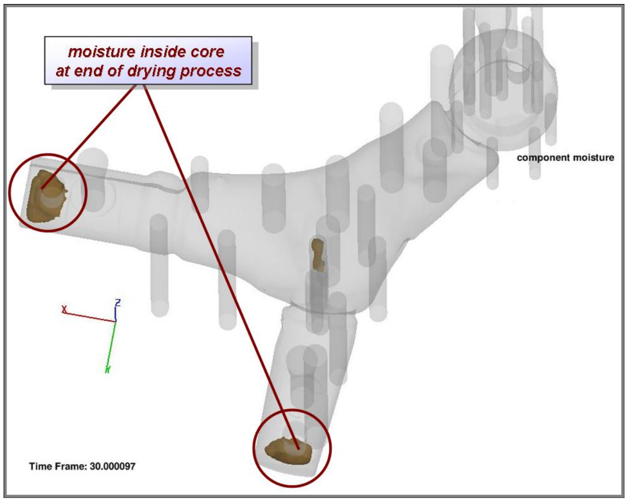

Fig. 7. Simulated residual moisture for the production core.

This example shows that the new core-drying model can be effectively used for the optimization of a production core drying process.

CONCLUSION

A new model for numerically simulating the drying of sand cores has been developed and validated against experimental data. The model is fully three-dimensional and can accommodate any core geometry. Both evaporation and condensation processes are modeled so that an accurate picture can be obtained of repeated evaporation and condensation of water as it tries to flow through a core that is being heated by a forced flow of hot air.

Validation studies presented here are for the drying of inorganic cores confined in a core-blowing cavity in which hot air is injected through filling and venting ports. The model, however, is also suitable for other types of core drying such as by a convective, or a microwave oven. All simulations were performed using a commercial computational fluid dynamics software package.[3] The computing runtimes were found to be sufficiently short for a design environment where a number of core venting geometries will be evaluated before a suitable core box design is chosen.

REFERENCES

1. Kubo, K. and Pehlke, D., “Heat and Moisture Transfer in Sand Molds Containing Water”, Metallurgical Transactions B., 17B, 1986
2. Bear, J., “Dynamics of Fluids in Porous Media,”, Dover Pub., N.Y., (1972)
3. ***FLOW-3D***® from Flow Science, Inc., Santa Fe, NM, USA; www.flow3d.com.