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CFD SIMULATIONS AND EXPERIMENTAL STUDY OF TWO-PHASE FLOW IN SAND COREMAKING PROCESS

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ABSTRACT

The results of an experimental study and 3D numerical simulations of resin bonded sand/air flow in a square corebox with an H-shape insertion and passage between upper and lower pockets of the pattern are presented. A computer controlled electronic system was designed and built to measure pressures and flow rates inside the corebox during mold filling, gassing and purging cycles of Phenolic Urethane Amine (*PUA*) process. Contour maps of the pressure distributions inside the corebox were created based on barometric measurements. A good agreement between experimental results and numerical simulations was found.

INTRODUCTION

To optimize the structure and properties of cast metals a variety of casting techniques has evolved over the past few decades. Cold box or Phenolic Urethane Amine (PUA) process has many advantages in terms of productivity, reduced energy consumption, tolerance and high quality of the mold. This particular processing technique involves room-temperature curing of a resin-bonded sand core accelerated by a gas catalyst passed through the sand-binder mixture. Chemical binders provide a flowability to the sand mix that easily is blown into complicated patterns. In principle, the process possesses relatively fast *Sand Blowing, Gassing, Purging,* and *Stripping* cycles, which are mainly affected by sand properties (density, grain size and size distribution, shape, moisture content, close-pack volume fraction, etc.), type and amount of binders (ratios for two or more part binders system), tooling design (blow tubes, sand magazine, input and exhaust piping and manifolds, vents, exhaust ports, core box, etc.), gassing and purging performance (gas type, pressure, time, temperature, flowrate, etc.).

Recently, we investigated the flow dynamics of phenolic-urethane-amine process in a core box of an inverted "*U*" configuration experimentally using a commercial core shooter (Bakhtiyarov and Overfelt, 1998b). The effects of reduction in area of the vents were evaluated by manual reduction of the active vent areas. In addition, experimental data on the pressure drop and friction factor for the vents were obtained as a function of the amounts of sand deposited in the vent area. The experimental data were compared with the predictions of the Blake-Kozeny and Ergun porous flow equations and good agreement was found.

Special experiments were conducted to measure the variation of the pressure with the amount of resin bonded sand bed deposited in cylindrical corebox (Bakhtiyarov and Overfelt, 2001). A non-linear relationship between pressure and air flowrate was established. Due to the sand compaction, the pressure increased with increasing the air flowrate for resin-bonded sands. It was shown that the pressure drop also increases non-linearly with amount of deposited resin bonded sand. Moreover, at certain values of the air flowrate (~ 250 cm^3/s) a significant increase in pressure drop was observed for resin-bonded sand, which was attributed to the complex rheological behavior of the test material. The plasticity of the sand+binders mixture was characterized by a shear yield stress, which provides some "resistance" to the system against compaction. Significant differences in pressure were observed in the hopper, blowtube, and inside the corebox. These differences were related to the cross section area changes and transition of the system from packed bed to fluidized bed. A good agreement was found between the numerically simulated and experimentally measured values of pressure along the vertical symmetry axis of the corebox.

In this paper we present the results of numerical predictions and experimental measurements of pressure variations and flow rate during bonded sand/air two-phase system flow in core molding process. A square corebox with H-shape insertion and passage between upper and lower pockets of the pattern was used in this study.

CFD MODELING OF SAND CORE SHOOTING PROCESS

CFD modeling of sand core shooting process was based on a two-fluid flow approach. The following governing equations were used in our computations.

Continuity equations:

$$\frac{\partial \varepsilon_g}{\partial t} + \nabla \cdot \left(\varepsilon_g \upsilon_g\right) = 0, \quad (1)$$

$$\frac{\partial \varepsilon_s}{\partial t} + \nabla \cdot \left(\varepsilon_s \upsilon_s\right) = 0. \quad (2)$$

Momentum equations:

$$\rho_g \left[\frac{\partial \upsilon_g}{\partial t} + \upsilon_g \nabla \upsilon_g\right] = \nabla \cdot \widetilde{\tau}_g - \nabla P - \frac{\beta}{\varepsilon_g}\left(\upsilon_g - \upsilon_s\right) + \rho_g g \quad , \quad (3)$$

$$\rho_s \varepsilon_s \left[\frac{\partial \upsilon_s}{\partial t} + \upsilon_s \nabla \upsilon_s\right] - \rho_g \varepsilon_s \left[\frac{\partial \upsilon_g}{\partial t} + \upsilon_g \nabla \upsilon_g\right] = \nabla \cdot \widetilde{\tau}_s - \nabla P_s + \frac{\beta}{\varepsilon_g}\left(\upsilon_g - \upsilon_s\right) + \varepsilon_s\left(\rho_s - \rho_g\right) \quad (4)$$

where

$$\widetilde{\tau}_i = 2 \quad \mu_i \, \widetilde{D}_i + \left(\lambda_i - \frac{2}{3}\mu_i\right) tr\left(\widetilde{D}_i\right)\widetilde{I}, \quad (5)$$

$$\widetilde{D}_i = \frac{1}{2}\left(\nabla \upsilon_i + \left(\nabla \upsilon_i\right)^T\right). \quad (6)$$

If the momentum equations are considered in terms of the resulting coefficients C_{ij}, and nodal velocities u_j, then the pressure gradients may be determined from:

$$C_{ii}\, u_i = -\sum C_{ij}\, u_i + \varepsilon_i - \int n_i \frac{\partial p}{\partial x} dv, \quad (7)$$

$$u_i = \hat{u} - \frac{1}{C_{ii}} \int n_i \frac{\partial p}{\partial x} dv = \hat{u} - K_i \frac{\partial p}{\partial x}, \quad (8)$$

$$\hat{u} = \frac{-\sum C_{ij} + \varepsilon_i}{C_{ii}}, \qquad K_i = \frac{\int n_i \, dv}{C_{ii}}, \quad (9)$$

where ε is volume fraction; υ is velocity; ρ is density; τ is viscous stress tensor; P is pressure; β is drag coefficient; $\widetilde{D}$ is strain tensor rate; μ is viscosity; K is conductivity matrix; n is an interpolating function; subscripts g and s refer to gas and solid phases, respectively.

Earlier we investigated the rheological properties of resin bonded sand/air mixture (Bakhtiyarov and Overfelt, 1998b) using both capillary and rotational viscometers. It was demonstrated that resin bonded sand/air mixture exhibits strong non-Newtonian, shear thinning behavior over wide ranges of shear rates. Therefore in our simulations we used Ostwald model as a rheological equation to describe resin bonded sand/air flow:

$$\eta = \kappa \, \dot{\gamma}^{n-1}, \quad (10)$$

where κ is a measure of the consistency of the system, n is a measure of the degree of non-Newtonian behavior.

Typical results of 3-dimensional transient CFD simulations are presented in Figures 1-3. As seen from the simulations, the actual mold filling cycle at 500 kPa blow pressure takes only 0.2 sec. The results of 3-dimensional CFD simulations showed that a variation of the velocity component in the transverse direction is small compared to other two velocity components.

EXPERIMENTAL APPARATUS AND PROCEDURE

Silica sand was used in our experiments. As a cold box binder system we used ISOCURE LF-305/904 G system. This system consists of an ISOCURE Part I LF-305 phenol-formaldehyde binder and an ISOCURE Part II 52-904 GR binder containing a polymeric isocyanate with solvents and additives. The reaction between Parts I and II results in the formation of phenolic urethane polymer. According to industry procedures and the manufacturer's instructions, in our experiments we used the composition at a 55/45 ratio of ISOCURE Part I binder to ISOCURE Part II binder components. Increasing the amount of the Part I decreases the humidity resistance of the core and benchlife of mixed sand. Increasing the amount of the Part II increases the cost and shakeout time of the core product. Recently we experimentally investigated the rheological and thermal properties of the phenolic resin and polymeric isocyanate (ISOCURE© and TECHNIKURE®), and their blends (Bakhtiyarov and Overfelt, 1997a, 1997b, 1998a). We determined that although both binders are Newtonian liquids, their blends exhibit non-Newtonian shear thinning fluid flow behavior and elasticity. The dynamic viscosity of the blends increases both with time and with increasing the ISOCURE Part I LF-305 content, and may reach comparatively large values at large values of either parameter. The increase in viscosity of blends is explained as the result of the rubbery nature of the phenolic urethane polymer produced as a product of reaction between Parts I and II. Due to degradation effects at high shear rates, the viscosity of blends decreases. At fixed shear rates we observed a temperature rise during the mixing of binders. Following the manufacturer's instructions the total binder level was 1.5% based on sand weight. Before being blown into the pattern, sand was coated with the binders. The bulk density of the coated sand was 1.426 g/cm^3. For gassing we used liquid triethylamine (Catalyst 700), which was vaporized during curing.

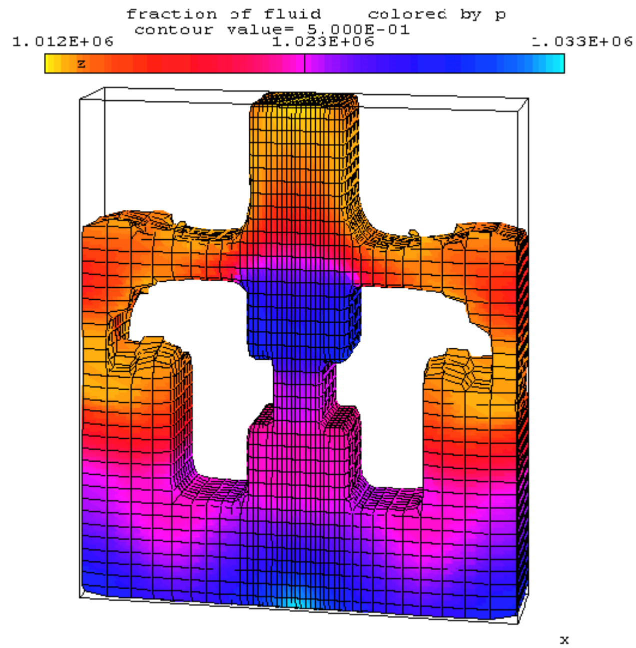

Figure 3. 3D CFD simulations of mold filling process: *P*=500 kPa, *t* = 0.14 s.

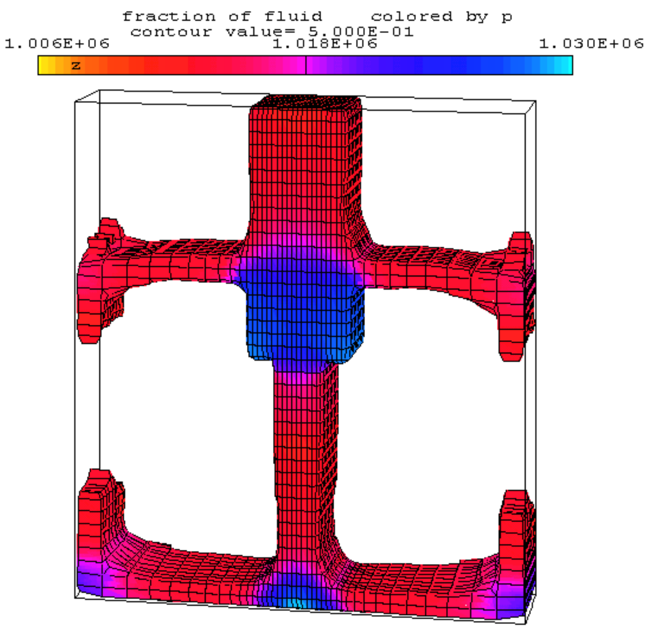

Figure 1. 3D CFD simulations of mold filling process: *P*=500 kPa, *t* = 0.06 s.

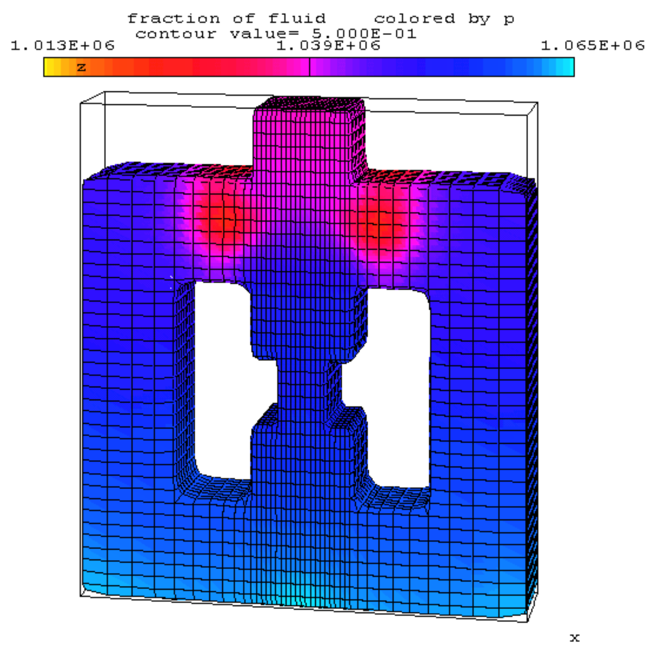

Figure 3.3D CFD simulations of mold filling process: *P*=500 kPa, *t* =0.2s.

A special pressure measurement system was designed and built with safety and portability requirements of the foundry environment. All sensor electronics were housed in a special briefcase and were connected to a computer controlled data acquisition system through PC-LPM-16/DAQCard-700. Up to

14 piezoresistive absolute pressure sensors PX72-100V suitable for PC board mounting (linearity: ± 0.5% FS, repeatability: ± 0.3% FS, operating temperature range: -15 to 85^0 C) were used in a single experiment. These are stable, high performance micromachined silicon diaphragm sensors without temperature compensation for operating ranges of 0 to 690 kPa. The sensors exhibit a response time of 0.1 s and were operated from a constant current excitation supply. To prevent penetration of sand and dust particles into the measurement system, porous metallic element brass pressure snubbers were mounted on each pressure tap. The snubbers also protect transducers and other delicate line installations from shock damage caused by pressure pulsation, surges, and fluctuations. The snubbers contain a Type 316 stainless steel porous disc (porosity designation D and rating 40-45 μm). After each experiment all snubbers were brushed and washed in acetone. Special experiments were run to determine the effect of the snubbers on measured pressure values. The test results for all pressure transducers showed that the influence of the snubbers on measured pressure values were negligible (less than 1%).

The calibration results showed that the output voltage (V_{out}) of pressure transducers increases linearly with increasing pressure. This relationship can be expressed as

$$P = \alpha V_{out} - \beta \tag{11}$$

where α and β are calibration coefficients of the pressure sensors. These coefficients were determined experimentally for each pressure sensor system (sensors, hoses, connectors, etc.).

One would assume that during the mold filling process coated-sand depositions in the vent areas would cause the vent permeability to decrease. In our previous studies the variation of the pressure losses with the amount of sand+binders depositions in vent area was experimentally measured (Bakhtiyarov and Overfelt, 1998b). In this study we modified the test section to obtain more precise and consistent data for the test sand+binders system. An experimental set up shown in Figures 4 and 5, consists of PVC round tube with an internal diameter D = 19 mm and a length of L = 428 mm. A test vent was installed at the end of the tube. Compressed, dried and pre-filtered air under pressure between 300-500 kPa was provided to the tube filled by the test material. The airflow rate was electronically controlled through proportioning valve (ECPV) and controller CN 8511-F1. Rotameters were used to measure the airflow rate. The locations of the pressure sensors along the test tube are presented in Figure 6.

Figure 4. Experimental technique to study pressure losses in core box due to sand deposition in vent area during mold filling process.

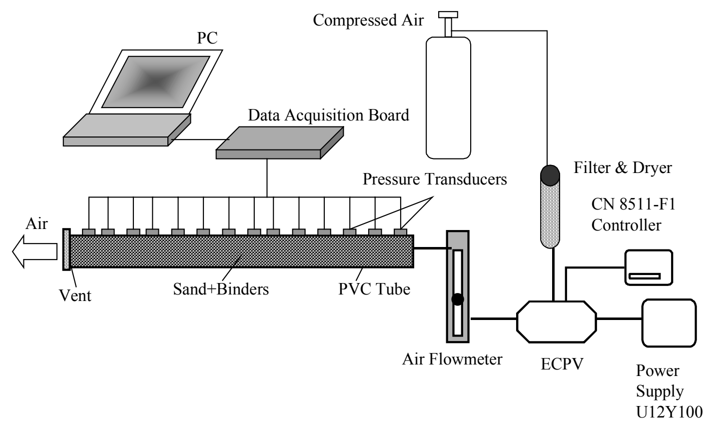

Figure 5. Schematics of experimental technique to study pressure losses in core box due to sand deposition in vent area during mold filling process.

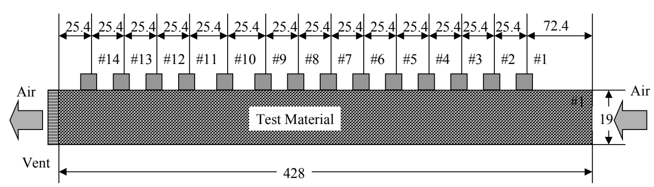

Figure 6. Positions of pressure sensors along the test tube.

The total pressure drop ΔP due to air flow in the cylindrical tube filled by sand (bonded or unbonded) with the vent at the outlet can be represented as,

$$\Delta P = \Delta P_t + \Delta P_v + \Delta P_s, \tag{12}$$

where ΔP_t , ΔP_v and ΔP_s are the pressure losses in the tube, in the vent and in the sand, respectively. We performed special experiments to estimate the pressure losses due to the tube walls and vent.

The pressure variations against air flowrate in cylindrical tube filled with resin-bonded sand are presented in Figure 7. To simulate the actual sand core-blowing process, sand was not preliminarily compacted in the test tube. Therefore a non-linear relationship between pressure and air flowrate was established. Due to the sand compaction, the pressure increased with increasing the air flowrate for resin-bonded sands. It is shown that the pressure drop increases non-linearly with amount of deposited resin bonded sand in tube (Figure 8). Moreover, at certain values of the air flowrate (~ 250 cm^3/s) a significant increase in pressure drop was observed for resin-bonded sand. We suggest that this behavior is related to the complex rheological behavior of the resin-bonded sand (Bakhtiyarov and Overfelt, 1998b). It was demonstrated, that the resin binders provide some "plasticity" to the sand. The plasticity of the sand+binders mixture is characterized by a shear yield stress, which will provide some resistance to the system against compaction. However, further investigations and analyses are needed to quantify this behavior more precisely.

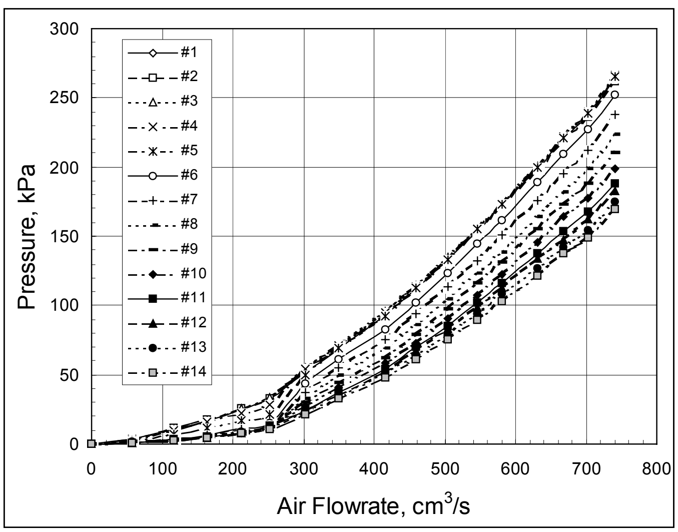

Figure 7. Variation of pressure with air flowrate through resin coated sand.

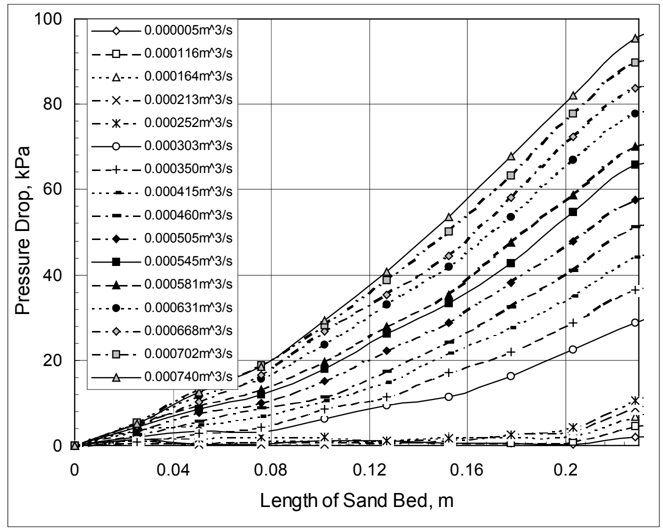

Figure 8. Variation of pressure drop with amount of resin coated sand deposited in vent area.

The flow dynamics of sand and sand-binder system in core box were evaluated in the system shown schematically in Figures 9 and 10. The test core specimens were produced using LAEMPE® core-shooting machine. This machine consists of a column, a shooting unit, a table, fixed and moveable side clamps, a gas carriage, a cabin and a control unit. The machine also houses the control box, the valve manifold and the gas generator. The machine table moves pneumatically under the shooting unit for shooting a sand-binder mixture. When the table has moved down, the gassing plate moves in pneumatically and is pressed between the shoot head and core box when the table has moved up again. Then gassing of the core is started. The gas generator heats liquid catalyst until it reaches a gaseous form. The liquid is dosed (0.2 cm^3/stroke) into a heater where the catalyst evaporates to gas, which is fed to the sand core through a system of gassing plates. The gas together with heated air is blown through the core to purge it. When gassing is complete, the table moves down again, the gassing plate moves out and when the side clamps and cabin doors have opened, the core can be removed from the machine. All functions of the machine are pneumatically moved and controlled. An exhaust system with an exhaust capacity ~500 m^3/h was provided to the cabin. The shape and size (in millimeters) of the core box are shown in Figure 11. The core boxes consisted of the aluminum pattern with clear Plexiglas plate mounted on the front wall to perform visual observations of the flow. The sealing of the core box is achieved when the table is lifted and pressed, creating very strong closing forces on the tooling.

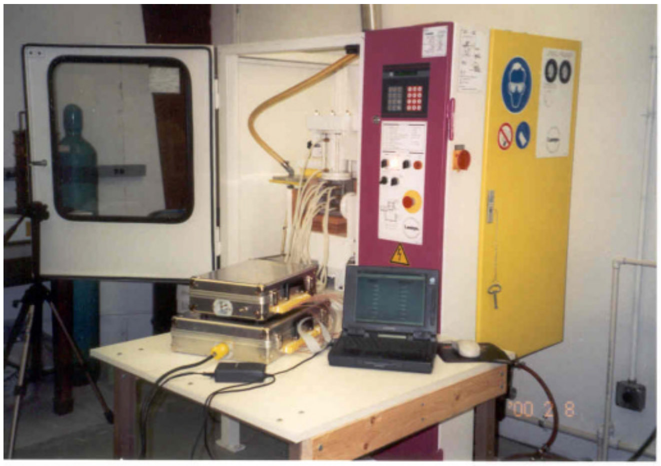

Figure 9. Experimental apparatus used to study dynamics of core shooting process.

In the cold box process, the type, number, size and placement of vents are important factors for core quality, core density and catalyst consumption. They affect the ability to blow a dense and uniform core, and uniform permeation of catalyst gas throughout the core. Recommended total vent area in the cope side is 356 x 10^{-5} to 569 x 10^{-5} cm^2 per gram of core (Carey and Sturtz, 1977). In our experiments we used four slotted steel vents of 12.7 mm diameter and two slotted steel vents of 10 mm diameter with 0.5 mm slots. To evaluate the vent area available to the flow we introduced the mean hydraulic radius R_h, which is the ratio of the cross sectional area of vent available to the flow to the wetted perimeter. Regarding the vent as an opening with a complicated cross section we run experiments to determine the mean hydraulic radius R_h of vent used. A special experimental apparatus was designed and used to determine the hydraulic radius of vents. An average velocity was defined by the Hagen - Poiseuille equation:

$$\langle v \rangle = \frac{\Delta P \, R^2}{4 \, \mu \, L} \, . \qquad (13)$$

The mean hydraulic radius of the vent was defined in terms of the average flow rate and the average velocity in the tube as,

$$R_h = \left(\frac{Q}{\pi \, \langle v \rangle} \right)^{0.5} . \qquad (14)$$

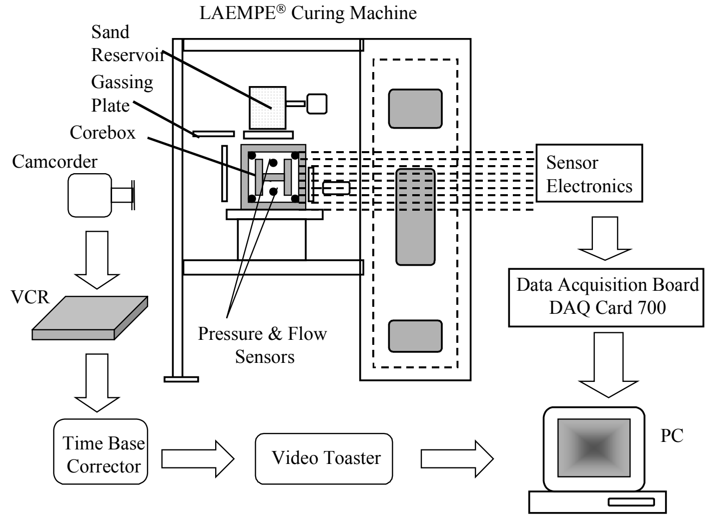

Figure 10. Schematic diagram of experimental apparatus used to study dynamics of core shooting process.

The experimental data suggest that the hydraulic radii of the vents tested are 4.26 mm and 3.35 mm, respectively for vents 12.7 mm and 10 mm in diameter. Hence the hydraulic cross-section areas of the vents are 0.57 cm^2 and 0.35 cm^2, respectively. Following the recommendations of Carey and Sturtz (1977) we placed vents in low pockets and near sharp corners so as to direct the sand and the gas catalyst vapors toward those points. During the experiments the total vent area was 3.88×10^{-3} cm^2 per gram of core for core box. The total area of box exhaust vents was 365 % of the total vent input area.

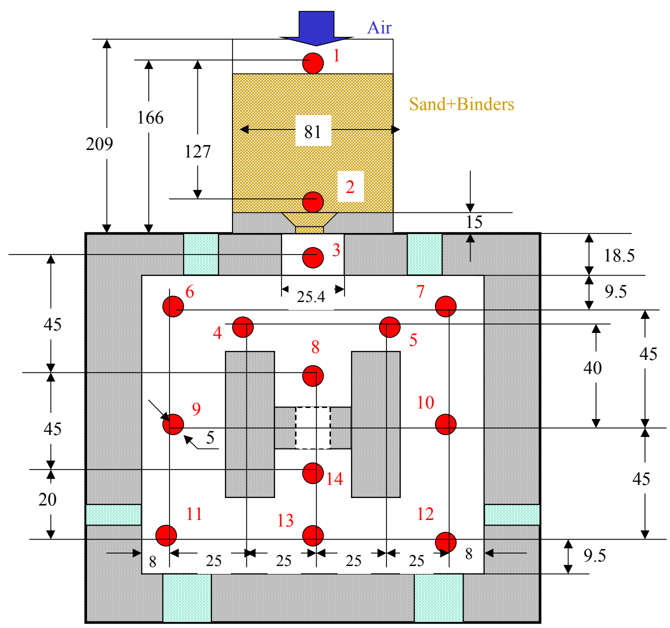

Figure 11. Positions of pressure transducers over the core box.

Visual observations of the dynamics of the sand blowing process were made by using a video camera recorder (Figure 10). The sand filling patterns and interface displacements were computerized by means of TBC (Time Base Corrector), VT (Video Toaster) and PC "AMIGA". Fourteen piezoresistive absolute pressure sensors were used to measure the pressure variations during the sand blowing and gassing/purging processes in the hopper, blowtube area and in the corebox. The locations of the pressure taps were chosen based on the visual observations of the sand+binders/air flow dynamics.

RESULTS AND DISCUSSION

A variation of CFD simulated and experimentally determined corebox filling time versus blow pressure is presented in Figure 12. As seen from this figure, actual sand shooting takes only 0.2-0.24 s. The corebox filling time linearly decreases with increasing a blow pressure. There is a significant difference in simulated corebox fill time with and without consideration of the sand deposition effect on vent areas during the simulations. The simulations conducted with the consideration of this effect are in a good agreement with experimentally measured fill time values. As one would expect, the fill times are lower than actual ones if the effect of the sand deposition would not considered. As seen from Figure 12, this difference is more pronounced at higher blow pressures. Also, some non-linearity can be noticed in the fill time vs. blow pressure relationship if the sand deposition effect was ignored.

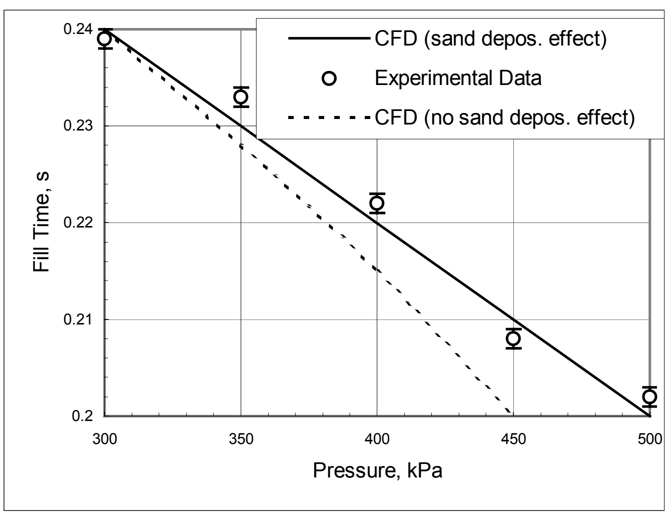

Figure 12. Variation of fill time versus blow pressure.

In figure 13 we present the results of CFD simulations (both with and without consideration of the sand deposition effect) and experiments for pressure variations along the vertical symmetry line of corebox. Here, *y* is a vertical axis with origin at pressure tap No. 3, and *H* is the distance between pressure taps No. 3 and No. 13. As seen from this figure, there is good agreement between numerically simulated and measured values of pressure when the sand deposition effect is included in the simulations.

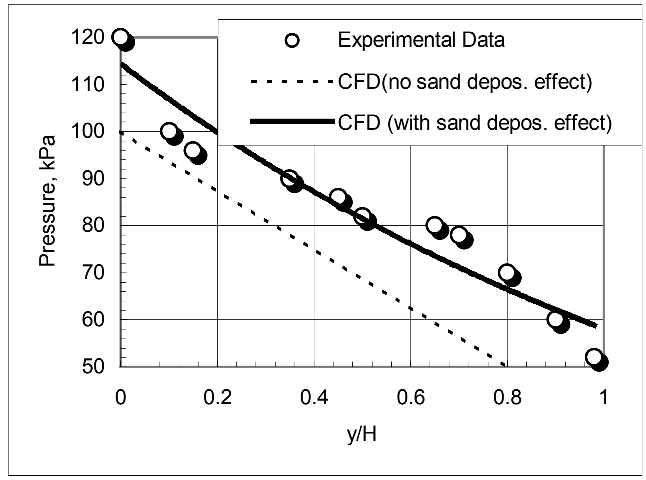

Figure 13. Pressure variations in central vertical line of corebox during mold filling.

CONCLUSIONS

Special experiments were conducted to measure the variation of the pressure with the length of resin bonded sand bed. A non-linear relationship between pressure and air flowrate was established. Due to the sand compaction, the pressure increased with increasing the air flowrate for resin-bonded sands. It is shown that the pressure drop also increases non-linearly with amount of deposited resin bonded sand in tube. Moreover, at certain values of the air flowrate (~ 250 cm^3/s) a significant increase in pressure drop was observed for resin-bonded sand, which is attributed to the complex rheological behavior of the test material. The plasticity of the sand+binders mixture is characterized by a shear yield stress, which provides some "resistance" to the system against compaction. However, further investigations and analyses are needed to precisely quantify this pressure drop behavior.

A variation of CFD simulated and experimentally determined corebox filling time versus blow pressure showed that an actual sand shooting takes only 0.2-0.24 s. The corebox filling time linearly decreases with increasing a blow pressure. There is a significant difference in simulated corebox fill time with and without consideration of the sand deposition effect on vent areas during the simulations. The simulations conducted with the consideration of this effect are in a good agreement with experimentally measured fill time values. The fill times are lower when the effect of the sand deposition is not considered. There is some non-linearity in the relationship between a fill time and a blow pressure when the sand deposition effect was ignored.

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