Influence of core box vents distribution on flow dynamics of core shooting process based on experiment and numerical simulation

Chang-jiang Ni¹, Gao-chun Lu², Qing-dong Zhang¹, * Tao Jing¹, Jun-jiao Wu¹, Lin-long Yang² and Qin-fang Wu²

1. School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

2. Suzhou Mingzhi Technology Co., Ltd., Suzhou 215217, China

Abstract: Core shooting process plays a decisive role in the quality of sand cores, and core box vents distribution is one of the most important factor determining the effectiveness of core shooting process. In this paper, the influence of core box vents distribution on the flow dynamics of core shooting process was investigated based on in situ experimental observations with transparent core box, high-speed camera and pressure measuring system. Attention was focused on the variation of both the flow behavior of sand and pressure curves due to different vents distribution. Taking both kinetic and frictional stress into account, a kinetic-frictional constitutive model was established to describe the internal momentum transfer in the solid phase. Two-fluid model (TFM) simulation was then performed and good agreement was achieved between the experimental and simulated results on both the flow behavior of sand and the pressure curves. It was found that vents distribution has direct effect on the pressure difference of different locations in the core box, which determines the buoyancy force exerting on the sand particles and significantly influences the filling process of core sand.

Key words: vents distribution; flow dynamics; pressure variation; core shooting process; kinetic-frictional model; two-fluid model

CLC numbers: TG231.6/TP391.9

Document code: A

Article ID: 1672-6421(2016)01-022-08

Sand cores are used extensively for the manufacturing of complicated castings in metal casting industry. Core shooting process is the most widely used process to make sand cores and plays a decisive role in the quality of sand cores^[1].

As shown in Fig. 1, the core shooting process starts from abrupt transportation of compressed air into a sand magazine. Then the sand-air mixture is shot into a core box through blow tubes. Finally, the core box is filled with compacted core sand and the remaining air escapes through vents. Effectiveness of core shooting process is mainly affected by shooting parameters, core sand properties, and tooling (i.e., core box) design, in which core box vents distribution is of particular importance^[2]. In recent years, research and development have been carried out increasingly to improve the

quality of sand cores. However, most effort has gone to the development of new binders system^[3-5] and there are only few studies on the flow dynamics of core shooting process.

Chen et al.^[2] and Cui et al.^[6] qualitatively demonstrated by experiments that vents distribution has a significant effect on the filling result. However, there are still very few experimental studies on the underlying mechanism that could clearly describe the influence of core box vents distribution on the flow dynamics of core shooting process, in particular correlating the effect on the pressure variation and subsequent influence on the hydrodynamic behavior of core sand filling the core box.

Besides experimental research, numerical modeling was also applied to simulate the flow dynamics of core shooting process. Wu et al.^[7] applied two-fluid model (TFM) for core shooting process simulation. The kinetic theory of granular flow (KTGF)^[8-9] was adopted to describe the internal momentum transfer in the solid phase in their model and the sand flow behavior at dilute regions was predicted quite well. Winartomo et al.^[10] modeled the core shooting process in the same way and they also did some experiments to verify simulation results qualitatively. These simulations could

* Tao Jing

Born in 1965, Ph. D., Professor. His research interests mainly focus on materials processing technology and integrated computational materials engineering (ICME). He has published more than 100 papers.

E-mail: jingtao@mail.tsinghua.edu.cn

Received: 2015-11-02; Accepted: 2015-12-10

Fig. 1: Diagram of core shooting process

partially describe the flow dynamics of core shooting process, but were inconsistent with the flow behavior of sand in dense regions.

To reveal the influence of core box vents distribution on the flow dynamics of core shooting process, in this study, a computer controlled high-speed camera was used to record the hydrodynamic behavior of core sand filling the core box. To synchronously detect the pressure variation, a computer controlled data acquisition instrument and 4 pressure sensors were used to measure pressure curves at four specified locations. Taking both kinetic and frictional stress into account, a two-fluid model (TFM) in which a kinetic-frictional constitutive model was incorporated was established to predict the flow dynamics of core shooting process.

1 Experimental procedures

1.1 Core sand

Silica sand (The size distribution of the sand particles is shown in Fig. 2) and “two-part” cold box resin binder system were used in the experiments. According to the manufacturer’s instructions, the total binder level was 1.5% (based on sand weight) with 1:1 ratio of the two binder components. Core sand was mixed in a vane-type mixer. The mixing time was 120 s and the bulk density of the core sand was $1,417 \text{ kg}\cdot\text{m}^{-3}$.

Fig. 2: Size distribution of silica sand (Inset: SEM picture of a sample of silica sand)

1.2 Experimental setup

The experiment apparatus and the dimensions of the core box used in the experiment are illustrated in Fig. 3. The core box was installed in a core shooting machine (Mingzhi MLA1), and 4 pressure sensors (Keyence AP-C30C) were installed on the core box in a single experiment to measure the pressure variations during core shooting process. All sensors were

Fig. 3: (a) Schematic of experimental apparatus and (b) dimensions of core box used in experiment

Fig. 4: Schematic drawings of (a) locations of pressure sensors, (b) installation method for pressure sensors and (c) three different cases of vents distribution

connected to a computer controlled data acquisition instrument (IMC BUSDAQ), and the collection frequency was set to be 100 Hz. During the experiments, a computer controlled high-speed camera (Mega speed MS55K) was used to photograph the flow behavior through the transparent front wall (made of plexiglas) of the core box and then the photographs were transferred to PC directly.

The respective locations of the four pressure sensors (P1, P2, P3 and P4) are shown in Fig. 4a. A vent was installed in front of every pressure sensor to prevent sand particles contacting the pressure sensor (Fig. 4b). To study the influence of vents distribution on the flow dynamics of the core shooting process, eight different cases of vents distribution were studied and three cases (Fig. 4c) were chosen and discussed in details.

2 Two-fluid model (TFM)

2.1 Governing equations

A two-fluid model (TFM) in which a kinetic-frictional constitutive model is incorporated is established here, and the according governing equations are as follows:

For gas phase:

$$\frac{\partial}{\partial t}(\alpha_g \rho_g) + \nabla \cdot (\alpha_g \rho_g \mathbf{V}_g) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\alpha_g \rho_g \mathbf{V}_g) + \nabla \cdot (\alpha_g \rho_g \mathbf{V}_g \mathbf{V}_g) = \alpha_g \nabla \cdot \boldsymbol{\tau}_g - \beta(\mathbf{V}_g - \mathbf{V}_s) - \alpha_g \nabla P_g + \alpha_g \rho_g \mathbf{g} \quad (2)$$

For the solid phase:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{V}_s) = 0 \quad (3)$$

$$\frac{\partial}{\partial t}(\alpha_s \rho_s \mathbf{V}_s) + \nabla \cdot (\alpha_s \rho_s \mathbf{V}_s \mathbf{V}_s) = \nabla \cdot \boldsymbol{\tau}_s + \beta(\mathbf{V}_g - \mathbf{V}_s) - \alpha_s \nabla P_s - \nabla P_g + \alpha_s \rho_s \mathbf{g} \quad (4)$$

The fluctuation kinetic energy equation, equation (5), is also solved to account for the conservation of the fluctuation energy of solid phase, through the implementation of the kinetic theory of granular flow (KTGF) [9]. In KTGF, a quantity named the ‘granular temperature’, θ , defined as $\theta = \langle C^2 \rangle / 3$ (where C is the particle random fluctuating velocity), is analogous to the thermal temperature found in the kinetic theory of gases.

$$\frac{\partial}{\partial t}(\alpha_s \rho_s \theta) + \nabla \cdot (\alpha_s \rho_s \mathbf{V}_s \theta) = \frac{2}{3} [(\boldsymbol{\tau}_s - P_s \mathbf{I}) : \nabla \mathbf{V}_s - \nabla \cdot (k_s \nabla \theta) - \gamma_s] \quad (5)$$

where α_g is the volume fraction of air and α_s is the sand volume fraction; ρ_g is the air density and ρ_s is the sand density; $\mathbf{V}_g$ is velocity vector of air and $\mathbf{V}_s$ is the velocity vector of sand; $\boldsymbol{\tau}_g$ is shear stress tensor of the gas phase and $\boldsymbol{\tau}_s$ is the shear stress tensor of the sand phase; β is the drag coefficient; P_g is the gas pressure and P_s is the sand pressure; $\mathbf{g}$ is the gravitational acceleration vector; t is the time; $\mathbf{I}$ is unit tensor; k_s is the conductivity of fluctuating energy; γ_s is the collision dissipation fluctuating energy.

2.2 Kinetic-frictional constitutive model

As the concept of particles has disappeared in the TFM, the constitutive correlations of the internal momentum transfer in the solid phase are required to indirectly account for the effect of particle-particle interactions. A kinetic-frictional constitutive

model is established to predict the hydrodynamic behavior of core shooting process. Kinetic-frictional theory assumes that the frictional and kinetic stresses can be treated in an additive manner^[11]:

$$P_s = P_s^k + P_s^f \quad (6)$$

$$\mu_s = \mu_s^k + \mu_s^f \quad (7)$$

The kinetic part of solid phase pressure, P_s^k , and the kinetic part of solid phase viscosity, μ_s^k , are defined from the KTGF, which assumes that the particle-particle interactions are largely dominated by binary collisions and stresses rise because of collisional transfer of momentum^[8-9] and given as:

$$P_s^k = \rho_s \alpha_s \theta \left[1 + 2(1+e)g_0 \alpha_s \right] \quad (8)$$

$$\mu_s^k = \frac{4}{5} \alpha_s^2 \rho_s d_s g_0 (1+e) \sqrt{\frac{\theta}{\pi}} + \frac{10 \rho_s d_s \sqrt{\pi \theta}}{96(1+e) \alpha_s g_0} \left[1 + \frac{4}{5} g_0 \alpha_s (1+e) \right]^2 \quad (9)$$

where e is the restitution coefficient of sand particles; d_s is the mean sand diameter; g_0 is the radial distribution function and presented as $g_0 = [1 - (\alpha_s/\alpha_{max})^{1/3}]^{-1}$, where α_{max} is the maximum sand volume fraction.

The frictional part of solid phase pressure, P_s^f , and the frictional part of solid phase viscosity, μ_s^f , are associated with sustained particle contact at high sand volume concentration and modeled by a combination of the normal stress correlation proposed by Johnson et al.^[12] and the modeled frictional shear viscosity model proposed by Srivastava and Sundaresan^[13].

$$P_s^f(\alpha_s) = \begin{cases} F \frac{(\alpha_s - \alpha_{min})^c}{(\alpha_{max} - \alpha_s)^s} & \alpha_s > \alpha_{min} \\ 0 & \alpha_s \leq \alpha_{min} \end{cases} \quad (10)$$

where F , c , s and α_{min} are empirical constants and assigned 0.05, 2, 5 and 0.5 respectively.

$$\mu_s^f = \frac{P_s^f(\alpha_s) \sqrt{2} \sin \phi}{2 \sqrt{\mathbf{D}_{ij} : \mathbf{D}_{ij}} + \theta / d_s^2} \quad (11)$$

$$\text{where } \mathbf{D}_{ij} = \frac{1}{2} \left\{ \nabla V_s + (\nabla V_s)^T \right\} - \frac{1}{3} (\nabla \cdot V_s) \mathbf{I} \quad (12)$$

ϕ is the angle of internal friction; $\mathbf{I}$ is unit tensor.

2.3 Simulation sets

The governing equations discussed above were discretized into linear equations using the finite difference method and then a procedure was developed based on the FORTRAN language.

The experimental conditions and the parameters used in numerical simulations are given in Table 1. The average sand particle diameter was set to be 243 μm according to size distribution of the sand particles which is shown in Fig. 2. The sand velocity at the inlet was determined by analyzing the pictures from the high speed camera and it was set to be 8.6 $\text{m}\cdot\text{s}^{-1}$ at 0.4 MPa shooting pressure. Using the correlation between the inlet area, the inlet velocity and the mass flux, which was assumed to be invariable throughout the core shooting process, the sand volume fraction at the inlet was set to be 0.3. The angle of internal friction was set to be 0.3 according to M. Pelzer^[10].

Table 1: Experimental conditions and parameters used in simulations

Property	Value	Property	Value
Sand density, $\rho_s(\text{kg}\cdot\text{m}^{-3})$	2,650	Angle of internal friction (ϕ)	0.3
Mean sand diameter, $d_s(\mu\text{m})$	243	Restitution coefficient (e)	0.99
Air density, $\rho_g(\text{kg}\cdot\text{m}^{-3})$	1.293	Max. sand volume fraction (α_{max})	0.65
Air viscosity ($\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$)	18.08×10^{-6}	Shooting pressure (MPa)	0.4
Inlet sand volume fraction	0.3	Inlet sand velocity ($\text{m}\cdot\text{s}^{-1}$)	8.6

3 Results and discussion

3.1 Influence of vents distribution on flow behavior of core sand

The flow behavior of core sand during the core shooting process was in situ recorded with a high-speed camera. Comparison of the sand filling process between the three different cases of vents distribution is shown in Fig. 5. From the comparison, a significant difference can be seen: For case A (Fig. 5a), the sand filling channel at the bottom of the core box starts to shut down at $t = 60$ ms and then it shut down completely at $t = 95$ ms when the side part of the core box is not yet completely filled; For case B (Fig. 5b), the sand filling channel at the bottom of the core box starts to shut down at $t = 70$ ms and then the sand filling channel is completely shut down at $t = 110$ ms when the side part of the core box is completely filled; The flow behavior of case C (Fig. 5c) is considerably different from that of case A and case B: the side part of the core box is almost not filled after the sand filling channel is completely shut down.

Figure 6 shows the predicted flow behavior of sand in the core box. Remarkably, the flow behavior found in the experiment can always be successfully simulated by the current TFM simulation: the vents at the bottom of the core box lead to an earlier closed sand filling channel (Fig. 6a for case A and Fig. 6c for case C) while the vents at the side wall of the core box give rise to a good filling of the side part of the core box (Fig. 6b for case B).

Both the experimental and simulation results show clearly that the core box vents distribution has a significant influence on the flow behavior of core sand: A favourable vents distribution (case B) can achieve a sequential filling which realizes a uniformly filled core box. However, an undesirable vents distribution (case A and case C) can lead to an earlier shutdown of the sand filling channel and results in an incompletely filled core box or an unevenly filled core box.

3.2 Influence of vents distribution on pressure variation

The pressure variation during the core shooting process was in situ measured with the pressure measuring system. Comparison of pressure curves at P1, P2, P3 and P4 between the three different cases of vents distribution is shown in Fig. 7. As shown in Fig. 7a, both the pressure values and pressure difference between P3 and P4 in case A are lower than those in case B. For case C, pressures at P4 and P3 are significantly higher (Fig.

Fig. 5: Visualized photo sequences recording flow behavior of sand in core box with vents distribution of (a) case A, (b) case B, and (c) case C by high speed camera (As the core box is symmetrical, only right part of it is showed). Arrows are used to indicate location of closing sand filling channel

Fig. 6: Predicted flow behavior of sand in core box with vents distribution of (a) case A, (b) case B and (c) case C

Fig.7: Comparison of measured pressure curves at P1, P2, P3 and P4 between (a) case A and case B, (b) case B and case C

7b), and thus the pressure difference between P2 and P4 is remarkably lower than that in case B. From the experiment, it can be seen that the vents at the bottom of the core box lead to a lower pressure at P2 and lower the pressure difference between P3 and P4 (case A and case C). While vents at the side wall of the core box lower the pressure at P4 and give rise to a higher pressure difference between P3 and P4 (case B).

Pressure curves at 9 specified locations (Fig. 8d) are extracted from simulation results and shown in Fig. 8a to 8c. The predicted results agree well with the experimental results: case A (Fig. 8a) shows an overall pressure drop and also a significantly lower pressure difference between point 1 and point 9 than that in case B (Fig. 8b); Case C (Fig. 8c) is

strikingly different from case A and case B on that the pressure value from point 3 to point 9 remains unchanged and maintains at a higher value while it decreases progressively for case B and case A.

From the experimental and simulation results, it can be seen that vents distribution has remarkable influence on the pressure variation and pressure difference. A favourable vents distribution (case B) gives rise to a higher pressure difference during the core shooting process while an undesirable vents distribution (case A and case C) leads to an overall lower pressure value (case A) or a significant higher pressure value at the side part of the core box, which lower the pressure difference.

Fig. 8: Predicted pressure curves at 9 specified locations for vents distribution of (a) case A, (b) case B and (c) case C, and (d) schematic of 9 specified locations

3.3 Mechanism

As shown in Fig. 9a, compressed air enters into the core box from the blow tube and it prefers to escape through the nearest vents during the core shooting process. The escape of air leads to a pressure drop locally and thus results in a change of the

Fig. 9: Schematic of (a) flow route of compressed gas and (b) external force state of sand particles

As discussed above, vents distribution has a direct effect on the pressure difference which determines the buoyancy force exerting on the sand particles and can subsequently influence the flow behavior of sand in the core box according to equation (4). For vents distribution of case B, vents at the side wall of the core box lower the pressure value at P4, which generates a higher pressure difference between P3 and P4 (Fig. 7a and Fig. 8b). The higher pressure difference promotes sand particles to flow from P3 to P4 and it helps to maintain an unclosed sand filling channel until the end of the core shooting process. Therefore a sequential filling is achieved, as clearly indicated in Fig. 5b and Fig. 6b. However, for case A and case C, vents at the bottom of the core box lower the pressure value at P2, which lowers the pressure difference between P3 and P4 (Fig. 8a and Fig. 8c). The lower pressure difference subsequently leads to an underpowered filling from P3 to P4, which causes the sand particles to pile up at the bottom of the core box. The results are an earlier closed sand filling channel and the side part of the core box are not completely filled.

4 Conclusions

The influence of core box vents distribution on the flow behavior of sand in the core box and the pressure variation during the core shooting process were investigated in situ using high speed camera and pressure measuring system. Based on the established kinetic-frictional constitutive model, two-fluid model (TFM) simulation was then performed and results were compared with that from experiment and used to discuss the effect of vents distribution. Accordingly, the following conclusions can be drawn:

(1) Vents distribution significantly influences the filling sequence of core sand and the pressure difference in the core box. A favourable vents distribution prompts a sequence filling and gives rise to a higher pressure difference in favour of sand

pressure difference, as clearly indicated in Fig. 8.

During the filling process, the main forces on sand particles are drag force (caused by velocity difference between air and sand particle), buoyancy (caused by air pressure difference), and gravity, as shown in Fig. 9b.^[14-15]

filling. An undesirable vents distribution leads to an earlier closed sand filling channel and a lower pressure difference.

(2) By incorporating the established kinetic-frictional constitutive model into the two-fluid model, the simulation results show good similarity to the corresponding experimental results for all the three cases of vents distribution. It indicates that the frictional-kinetic constitutive model is suitable to model the core shooting process.

(3) According to both the experimental and the simulation results, vents distribution has direct effect on the pressure difference which determines the buoyancy force exerting on the sand particles and subsequently influences the flow behavior of sand in the core box. A favourable vents distribution (case B) gives rise to a higher pressure difference which helps to maintain an unclosed sand filling channel and thus a sequence filling is achieved. An undesirable vents distribution (case A and case C) lowers the pressure difference, which leads to an underpowered filling and results in an incompletely filled core box.

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This work was financially supported by the Innovation Platform for Through Process Modeling and Simulation of Advanced Materials Processing Technologies (No. 2012ZX04012011) and the National Science Foundation of China (No. 51575304)