Influence of the Pressure of Open-Close Water-Cooled Moulds on Casting/Mould Interface Heat Transfer and Casting Solidification Process

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Abstract. In this paper, the experimental model for a self-designed open-close water-cooled mould was utilized to measure the temperature curves of various points inside the casting and mould under different mould pressure. The Interface heat transfer coefficient (IHTC) of the casting/water-cooled mould interface was calculated by using the Beck nonlinear estimation back-calculation method, and on this basis, the rule of how pressure affects heat transfer coefficient was obtained. Then the coefficient can be defined as the boundary condition (BC) to simulate the solidification process of the experimental casting. The results showed that the simulation outcome considering the influence of pressure was completely different from those of general water-cooled moulds, which can be proved by the about 35% solidification time decrease, visibly reduced shrinkage porosity area in the casting and more accurate simulation results. The anatomical results of the experimental casting also confirmed this.

1. Introduction
Before putting the casting into practical production or designing new technologies, engineers can use computers to carry out pouring tests through solidification numerical simulation (referred to as solidification simulation) in order to find out potential defects or evaluate the rationality of new technologies. This can greatly save the time and cost of experiments and trial production and also improve the production yield. Therefore, before practical pouring, producers will generally require solidification simulation to verify the technology. This is why its accuracy becomes so important. As a new casting technology, open-close water-cooled mould casting has received much attention these years. Its main advantage lies in the outstanding cooling performance and it can realize light press during solidification. Thus, the resulting casting enjoys fine structure, few defects and excellent performance. Recent years also saw its successful application examples in large steel ingots production. As such, manufacturers hope solidification simulation will provide a guidance for process design and flawless products.

Different from common ones, the open-close water-cooled mould can perform light press on castings, changing the contact status of the casting and mould, and casting a great influence on the heat exchange between them. From the perspective of solidification simulation, that means the boundary condition, which is a significant prerequisite for accurate simulation results, changes[1]. Inappropriate boundary conditions may lead to results completely deviating from the real one, misleading subsequent analysis and researches. This effect is quite obvious in the numerical simulation of water-cooled moulds with boundary heat transfer coefficients as boundary conditions. So, using original water-cooled mould heat transfer coefficients will cause significant errors to the numerical simulation result. Realizing how important the coefficient is, the researchers have done a lot in this respect, including improving the calculation method and model of the coefficient to improve
calculation efficiency and accuracy[2,3], and exploring the rules of the influence of casting and mould materials[4], casting process[5], interface state[6,7] and multiple factors on the heat transfer coefficient of the casting/mould interface. For a new technology as open-close water-cooled mould casting, it is necessary to study how boundary conditions will change under pressure, so as to improve the accuracy of numerical simulation.

In this paper, the experimental model of a self-designed open-close water-cooled mould was utilized to measure the temperature curves of various points inside the casting and mould under different mould pressure. The heat transfer coefficient of the casting/water-cooled mould interface was calculated by using the heat transfer back-calculation method, and on this basis, the rule of how pressure affects heat transfer coefficient was obtained, which can help raising the accuracy of the coefficient. This is important for the solidification simulation of open-close water-cooled moulds applied in practical production.

2. Experiment
Based on the similarity theory, an experimental model imitating actual production was designed (Fig. 1). The casting used was a 150*80*80 rectangular parallelepiped, and the position of thermocouples placed on the casting and the water-cooled mould was shown in Fig. 1. Four temperature measuring points were put in the mold and casting: point 1, 2 and 3 were inside the casting, 5, 10 and 40 mm from the casting/water-cooled mould interface respectively; point 4, which was designed to measure the wall temperature of the water-cooled mould, was located on the inner wall of the mould and was 1 mm from the interface.

The pressure was set to 0, 70, 150, 200 and 300kg, in order to study how interface heat transfer was affected by pressure if applied a light press. The cooling water flows at a rate of 0.39kg/s. Walls of the water-cooled mould can move to the left and right of other mould walls, and the push rod can control the pressure exerted to the casting/mould interface.

The study used the heat transfer back-calculation method to obtain the heat transfer coefficient of the casting/water-cooled mould interface. Based on different mould pressures, the solidification temperature curve of the experimental casting was measured. Then by the Beck nonlinear estimation back-calculation method[8], the forementioned curve can be used to gain the target coefficient.

3. Experimental results and analysis
3.1. Curves of measured temperature
Fig. 2 shows the temperature curve measured from Point 1~3 under the pressure of 0, 70, 150, 200 and 300kg. Without pressure (Fig. 2a), the cooling of the casting is slow, but after applied pressure (Fig. 2b–e), the process accelerates, and the time shortens as the pressure increases. Taking temperatures of Point 1~3 inside the casting when cooled down to 400 s as an instance. Without any pressure, the
temperature are 564.5, 568.1, 577.4 °C respectively and become 324.7, 330.3, 341.7 °C after applied a 300kg pressure. It can be seen that the interface pressure can greatly affect the solidification process of the casting.

3.2. Influence of Pressure on Interface Heat Transfer Coefficient and Heat Flow

Fig. 3 shows the interface heat transfer coefficient and heat flow under abovementioned conditions. It can be seen that without pressure (Fig. 3a), the interface heat transfer coefficient first decreases rapidly, and then slowly after the casting is cooled by 150 s. After applying pressure (Fig. 3b–e), the coefficient also drops rapidly first, but then rises and slowly decreases again. As the pressure increases, the interface heat transfer coefficient increases and rebounds to higher peaks, from 781.6 to 1002.4 W/(m²·K). Consistent with the heat transfer coefficient, the interface heat flow also increases significantly after the pressure is applied. Compared with the interface heat transfer coefficient when cooled to 400 s, the heat transfer coefficient, with no pressure, decreases to 291.8 W/(m²·K), while those with pressure are 412.8, 303, 621.3 and 824.2 W/(m²·K), respectively, all higher than 291.8 W/(m²·K). That is because increased interface pressure will push closer the casting and the mold. In respect of the three heat transfer modes existing at the casting/mould interface, the proportion of heat conduction increases, resulting in a larger heat transfer coefficient.

Figure 2. Measured temperature at different pressures

(a) pressure 0kg  (b) pressure 70kg  (c) pressure 150kg  (d) pressure 200kg  (e) pressure 300kg
4. The Result of Solidification Simulation

In order to study the change of the solidification simulation results after the heat transfer coefficient is

![Figure 3. IHTC at different pressures](image)

(a) pressure 0kg (b) pressure 70kg (c) pressure 150kg (d) pressure 200kg (e) pressure 300kg

4. The Result of Solidification Simulation

In order to study the change of the solidification simulation results after the heat transfer coefficient is

![Figure 4. Anatomy section of the casting](image)
affected by the pressure, the simulation process and the anatomy are carried out on the experimental casting. Fig. 4 depicts the anatomy section.

Fig. 5 is the solidification time numerical simulation results of different points on the anatomy section, with the heat transfer coefficient of no pressure applied and pressure applied as boundary conditions, respectively. The color bar on the left side of Fig. 5 is the scale of the solidification time. Different colors are used to indicate the solidification time at each point on the casting. In the respect of solidification time, the casting with pressure applied takes less time than the one without, and has rather smaller final solidification region (the red part).

Figure 6 are numerical simulation results of the shrinkage porosity range of the casting under the abovementioned boundary conditions. Colors on the left-side bars represent how large are the shrinkage porosity areas. Obviously, the area of the casting without pressure is larger than the one with, and has larger severely defected area (the blue part). The reason is that the pressure increases the heat transfer coefficient, thereby pacing up the cooling process. Accordingly, the temperature gradient is increased, and the mushy zone, reduced, so the shrinkage porosity defect area shrinks.

Fig. 7 shows the actual casting sections(Fig. 4) with and without pressure .The shrinkage at the top of the casting in Figure 7b is significantly larger than that in Figure 7a, indicating that the internal dispersed shrinkages are less than the latter, which is consistent with the numerical simulation results of Figure 6.

It can be concluded from these experimental results that pressure can greatly affect the heat transfer coefficient. For open-close water-cooled mould casting, which can realize light press, if directly setting the heat transfer coefficient ignoring the influence of pressure (namely with a pressure of 0 kg)
as the boundary condition for solidification simulation, the results will be drastically deviate from reality, not to mention guiding actual production.

5. Conclusions
(1) In the process of applying pressure, the casting/mould interface heat transfer is different from the interface heat transfer in common casting process. Under pressure, the heat transfer coefficient of the casting/mould interface will rapidly increase to the maximum, and then drop as the solidification process goes on. As the interface pressure rises, the heat transfer coefficient between the casting and mould will enlarge.
(2) The interface pressure has a critical influence on the heat transfer coefficient of the casting/mould interface. Under experimental conditions, the coefficient augments by nearly 41% after the pressure applied. Leaving out the influence of pressure will cause a big error to numerical simulation results.
(3) The interface pressure affects the solidification process of the casting. Larger pressure leads to shorter solidification time and significantly reduced shrinkage porosity area.

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