Spray Heat Transfer Analysis of Steel Making Process by Using Particle-Based Numerical Simulation

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ABSTRACT

Spray cooling is often used in the steel manufacturing process, and the steel plate temperature at the time of manufacture affects productivity and quality. Therefore, the spray heat transfer coefficient estimation becomes important when determining manufacturing conditions or when designing manufacturing facilities. The conventional heat transfer coefficient estimation method is obtained by reversely analyzing the temperature of the steel plate when the heated steel plate is cooled by a single nozzle used or an experimental device simulating a real machine manufacturing facility. However, in actual equipment manufacturing facilities, it is difficult to grasp the heat transfer and flow state of heat transfer part details due to the presence of rolls, water staying on steel plates, and spray when a large amount of water is injected, heat transfer by numerical calculation Coefficient prediction has been desired.

In order to calculate the actual physical phenomena even with a single spray, one hundred million droplets of about hundred micrometer diameter are calculated while resolving a few micrometers of vapor film thickness at the time of collision of the steel plates with droplets, so calculation load is huge.Therefore, the authors describe the heat transfer coefficient of the experimental results as a function of the collision pressure because the vapor film is broken and the heat transfer is promoted if the collision pressure of the spray droplets to the steel plate is high [1]. The heat transfer coefficient was calculated by substituting the collision pressure obtained by the numerical calculation into the experimental formula.

The behavior of the spray cooling water includes a complex free interface, but can be calculated by the MPS method, and there is an example [2] where the flow rate of the spray cooling water between rolls of a real steel facility is calculated. In the present examination, the MPS method was similarly used for the prediction of the spray collision pressure, and the

calculated particle diameter was also set to 3 mm as in the case [2]. As a result of examination, the particles were injected from the spray outlet so as to match the actual water density, and the actual droplet size was matched with the actual collision pressure.

1. Introduction

There are various cooling processes using spray in the steel manufacturing process, and play an important role in quality improvement and productivity improvement. In the continuous casting process, solidification non-uniformity caused by cooling non-uniformity of spray water is a problem [2]. In the previous report, it was possible to quantify the macroscopic flow distribution of spray water in a continuous casting machine by numerical analysis. However, the heat transfer coefficient of spray cooling cannot be predicted by numerical analysis, and the solidification state of the entire continuous casting machine was predicted by combining the heat transfer coefficient measurement by experiment and the flow analysis result. In this study, we investigated a method of numerically determining the heat transfer coefficient distribution of spray cooling that could not be predicted by conventional numerical analysis.

2. Impact pressure for cooling capacity estimation

It is difficult to model all physical phenomena by numerical analysis because the spray of the steel cooling process is accompanied by the boiling phenomenon. A steam film is formed between the steel plate and the cooling water, and heat exchange between the steel plate and the cooling water is performed by the steam film having high heat resistance. Therefore, the increase of the water collision pressure makes the vapor film thinner or breaks down, which reduces the thermal resistance and also causes solid-liquid contact phenomenon, thereby promoting heat exchange and improving the heat transfer coefficient (Fig. 1)).

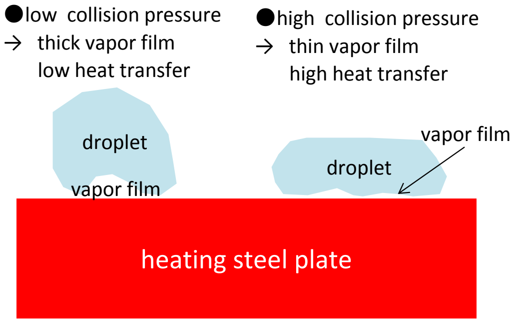
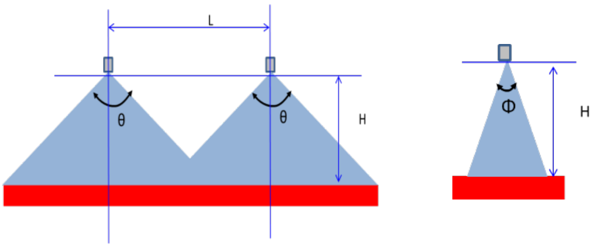


Fig.1. spray heat transfer mechanism



(a) Width direction (x-z plane)

(b) Thickness direction (y-z plane)

Fig.2 spray injection condtion

From this mechanism, the heat transfer coefficient h of the steel plate surface is a function f using the water density W per unit area, the collision pressure Pc of the droplets onto the steel plate surface, and the steel plate surface temperature Ts after cooling as in equation (1) It is known that it can be formulated [1].

$$h = f(W, Pc, T_s) \tag{1}$$

Since Ts is the surface temperature of steel plate which is the result of cooling, it is necessary to obtain the water density w and the collision pressure Pc in order to predict the heat transfer coefficient by calculation. The water density distribution is the spray performance itself and is relatively easily available from the manufacturer of the spray nozzle. In this paper, we apply the particle method that facilitates free interface handling to flow analysis, model spray injection that can simulate the actual spray water density distribution, and calculate the distribution of collision pressure required for heat transfer coefficient prediction.

We examined whether it was possible to ask. Numerical analysis was performed using general-purpose particle method analysis software "Particleworks". Specifically, two sprays as shown in Fig. 2 are wrapped, and the collision pressure against the steel plate when the spray flow rate, the width direction angle, and the thickness direction angle are changed is compared with the experimental value.

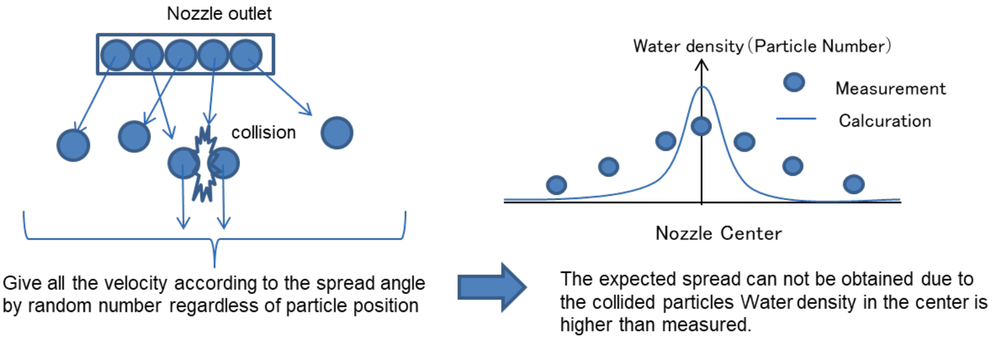


Fig.3 spray injection logic in the standard function of the software

In the standard function of the software, as shown in Fig. 3, random droplet velocity three components Vx, Vy and Vz according to the spray spread angle were given using the equation (2) regardless of the position of the particles.

$$\begin{aligned} v_x &= v_z \tan^{-1}(rand[-H\tan(\theta/2):H\tan(\theta/2)]/H) \\ v_y &= v_z \tan^{-1}(rand[-H\tan(\phi/2):H\tan(\phi/2)]/H) \qquad (2) \\ v_z &= Q_n / A_n \end{aligned}$$

Here, Qn means the flow rate per nozzle, An means the sectional area of the nozzle outlet, and rand [x0: x1] means that numbers are randomly given in the range of x0 ≦ x ≦ x1. However, in this injection logic, the spread of droplets assumed cannot be obtained because the particles collide with each other before reaching the steel plate, and the amount of water is concentrated at the center and there is a problem that it does not match the actually measured water density. Therefore, a spray injection logic as shown in Fig. 4 was considered. The droplet velocity is given using equation (3). In the improved logic, the initial velocity is given at the injection angle obtained by giving the x coordinate with random numbers to the injection range $x_{i-1} \leqq x \leqq x_i$ obtained from the actually measured water density for the ith particle. By injecting the particles in this manner, the particles do not collide with each other before reaching the steel plate, and the particles can be injected according to the actually measured water density. The implementation of the logic was performed using a user subroutine of general purpose software.

$$\begin{aligned} v_x{}^i &= v_z \tan^{-1}(rand[x_{i-1} : x_i]/H) \\ v_y{}^j &= v_z \tan^{-1}(rand[y_{j-1} : y_j]/H) \\ v_z &= Q_n / A_n \end{aligned} \tag{3}$$

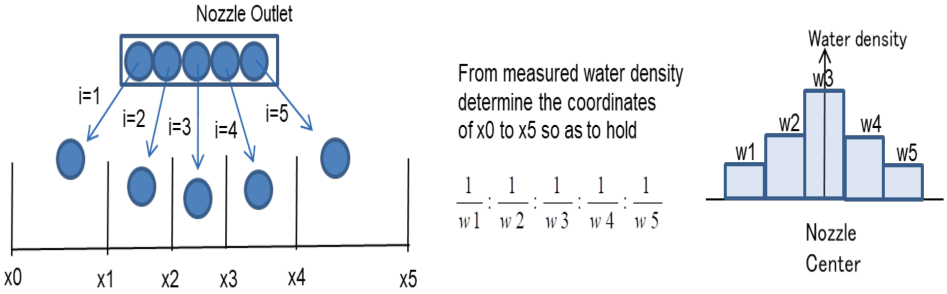


Fig.4. Spray injection logic improved in this paper
(When coming out 5 pieces in a horizontal row from the discharge port)

The governing equations are discretized using the interparticle interaction model when solving the same continuous equation (Equation (4)) and Navier-Stokes equation (Equation (5)) as in the flow calculation with the finite volume method etc. It is carried out.

$$\frac{D\rho}{Dt} = 0 \tag{4}$$

$$\frac{D\mathbf{u}}{Dt} = -\frac{1}{\rho}\nabla p + \nu\nabla^2\mathbf{u} + \mathbf{f} \tag{5}$$

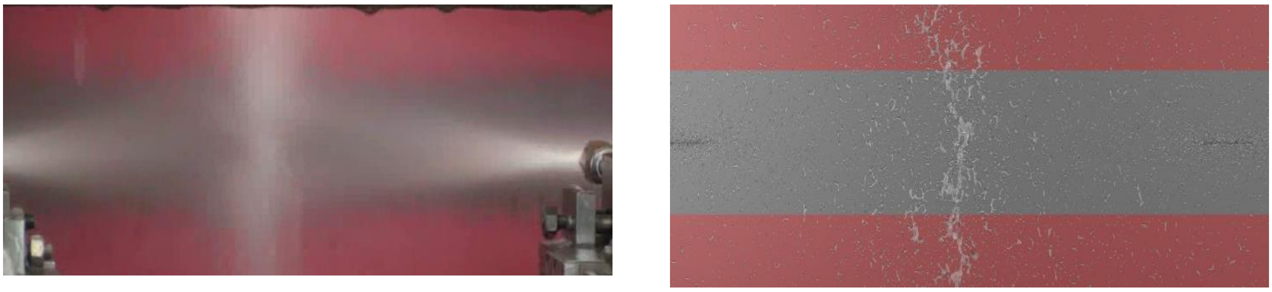
Here, **u** in the equation (5) is a flow velocity vector, p is a pressure, ρ is a density, ν is a kinematic viscosity coefficient, and **f** is an external force vector (gravity and surface tension). For the boundary condition of the wall, we used a model in which the wall of Harada et al. [3] is treated as a polygon wall. The collision pressure of the droplets is determined using equation (6) which is a blend of pressure gradient and penalty method when wall particles are used.

$$P_{i,wall}^{press} = f_{i,wall}^{press} / A = m_i[\beta\{\frac{1}{\rho}\frac{d}{n^0}(P_i^{k+1} - \hat{P}_i^{k+1})Z_{grad}(r_{iw})\} + (1-\beta)\{\frac{l_0/2 - |\vec{r}_{iw}|}{\Delta t^2}\}]\vec{n}(\vec{r}_i)/A \qquad (6)$$

Where $P_{i,wall}^{press}$ is the collision pressure, $f_{i,wall}^{press}$ is the force applied when the particle collides with the wall, A is the examination area, m_i is the mass of the particle, $\vec{r}_{iw}$ is the closest distance from the wall to the particle i, and the wall weighting function $Z(\vec{r}_{iw})$ determined by $\vec{r}_{iw}$, P_{wall} is the pressure at the wall , $Z_{grad}(\vec{r}_{iw})$ is the slope of the wall weighting function $Z(\vec{r}_{iw})$ in the wall normal direction, $\vec{n}$ is the normal vector, and β is the weighting parameter.

3. Calculation result of spray injection and collision pressure

When the spray is made to collide with the steel plate under the condition of θ = 110 °, φ = 20 °, H = 145 mm, L = 315 mm according to the definition of Fig. 2 with two nozzles lapped with a flow rate of 24 l / min in Fig.5 . The situation of is compared with experiment and numerical calculation. The particle diameter at the time of calculation was 1 mm. It was confirmed by both experiment and numerical calculation that cooling water collides in the part which two sprays wrap to right and left, and it separates up and down and flows.



(a)experiment

(b)numerical simulation

Fig.5. State of spray injection
24ℓ/min × 2 ,θ=110°,φ=20°,H=145mm,L=315mm

In Fig. 6, two nozzles with a water volume of 30 l / min were used, and injection was performed under the conditions of θ = 114 °, φ = 10 °, H = 80 mm, L = 100 mm. The water density ratio of the central part of the spray thickness of the The water density is a flow rate per unit area measured by placing a container of 20 mm square on one side at a position separated by 80 mm from the spray. The same method was used for measurement in numerical calculation. According to the method proposed this time, the water density distribution near the actual measurement was calculated from Fig.6.

Fig. 7 shows the collision pressure at the center of the thickness when the spray is injected under the same conditions as Fig. The calculated value is the collision pressure obtained by the injection logic of equation (3). The collision pressure was measured by attaching a pressure sensor to a plate having a width of 20 mm and a thickness of 100 mm, and moving the plate over the entire spray injection width. As shown in Fig. 7, the phenomenon that the collision pressure becomes large immediately below the nozzle and the collision pressure decreases as it separates from the region below quantitatively coincides with the measured value and the calculated value.

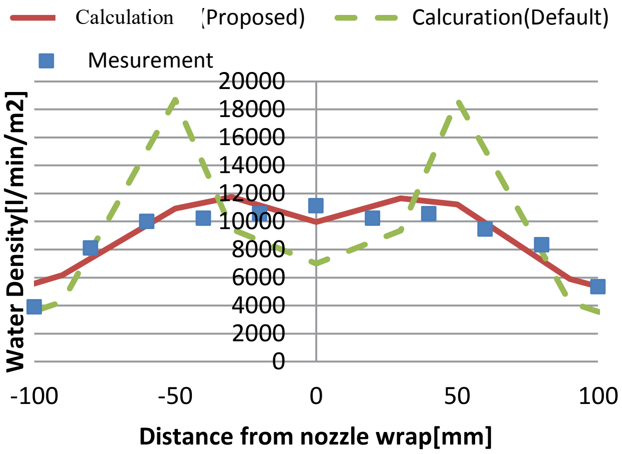


Fig.6. Water density distribution of spray (Thickness center, Frow Rate 30ℓ/min ×2,θ=114°,φ=10°,H=80mm,L=100mm)

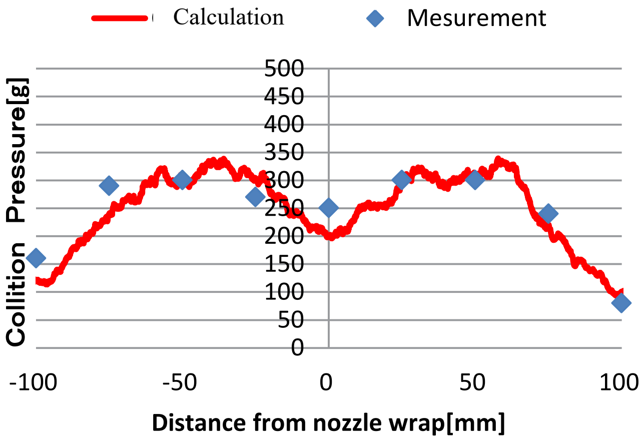


Fig.7. Impact pressure distribution of spray (Thickness center, Flow Rate 30ℓ/min ×2 , θ=114°,φ=10°, H=80mm, L=100mm)

4. Heat Transfer Calculation

Consider numerically predicting the heat transfer coefficient of a single spray. The heat transfer coefficient h of the steel plate surface can be formulated by the function f using the water density W per unit area, the collision pressure Pc of the droplets on the steel plate surface, and the steel plate surface temperature Ts after cooling as in equation (1) It is known [1].

Based on this finding, first, the spray condition of the spray is set to match the water mass density distribution W of the catalog spec, and the flow of the complex free interface of the spray cooling water is calculated using the particle method. The initial velocity of the particles given by calculation is given from the value obtained by back-calculating the pressure obtained by the PQ diagram of the spray or the value measured by PIV.

In this paper, we calculate the heat transfer coefficient of the spray by substituting the collision pressure and water density distribution of the steel plate which is the calculation result of the particle method into the equation (1). The spray conditions for the spray were a flow rate of 14.8 L / min, the distance between the spray and the steel plate was 155 mm, the spread angle in the width direction was 110 °, and the spread angle in the thickness direction was 20 °. The heat transfer coefficients measured in the experiment and the results are compared. The heat transfer coefficient of the experiment was calculated by inversely analyzing the temperature history of the thermocouple embedded in the steel plate after the steel plate was heated to 900 ° C. in a heating furnace. The heat transfer coefficients determined by numerical calculation and the measured heat transfer coefficients are shown in Fig. 8

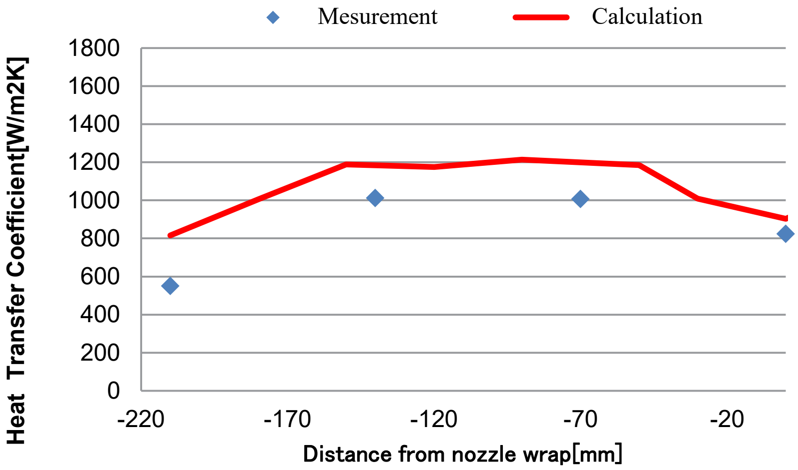


Fig.8 Comparison of Calculated and Measured Spray Heat Transfer Coefficients

5. Conclusion

By calculating the spray injection using the particle method, it becomes possible to calculate the distribution of the collision pressure Pc quantitatively by calculation by combining the water density W with the actual measurement value. From this, it was found that the flow analysis of W, Pc, etc. could predict not only the macro behavior of the spray water but also the heat transfer coefficient h.

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