Note

Hydrodynamic Investigation to Reflect Actual Residual Water Levels in Simulation of Strip Cooling after Hot Rolling

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(Received on June 19, 2014; accepted on July 28, 2014)

Water jet impingement onto a moving steel strip surface was numerically simulated using a three-dimensional computational model. A continuous supply of cooling water causes residual water to accumulate on the moving strip surface, which reaches a certain water level according to the flow rate. Because this residual water significantly affects the water jet impingement and strip cooling, it is essential to accurately reflect its level in a simulation of strip cooling. In this study, we developed the concept of artificial sidewalls to apply a more realistic residual water level to a cooling simulation. For various water jet flow rates and longitudinal domain sizes, the residual water levels and impinging pressures were compared in cases with and without these artificial sidewalls.

KEY WORDS: water jet impingement; residual water height; impinging pressure; cooling water flow rate.

1. Introduction

In the cooling process after hot rolling, a hot steel strip is rapidly cooled by water jetted from nozzles. The continuous supply of these water jets causes the accumulation of residual water on the moving strip surface. Generally, the level of the residual water increases as the cooling water flow rate increases. Because of the damping effect of the accumulated residual water, the cooling performance does not increase linearly with the cooling water flow rate, but rather becomes saturated with an increase in the cooling water flow rate.¹⁾

It has been empirically determined that a very large amount of heat transfer takes place in the jet-cooling region where the water jets directly impinge on the strip surface.²⁾ Thus, the impinging phenomena on the strip surface should be precisely treated in a strip cooling simulation. Because the residual water significantly affects the water jet impingement and strip cooling, it is essential to precisely predict its level for an accurate simulation of the cooling procedure. Cho *et al.* suggested a useful equation to estimate the residual water level in the jet-cooling region for various cooling water flow rates and strip widths.³⁾

In general, the main concern for the cooling process after rolling is the cooling history along the strip running direction. Thus numerous numerical studies have selected a single pitch in the spanwise direction for the calculation domain and attempted to enlarge the simulation domain in the longitudinal direction. However, if we only enlarge the calculation domain in the longitudinal direction, the imbalance between the supplied water amount and the drainage area will cause an unrealistic distortion in the residual water level to appear in the numerical simulation. In this study, to prevent such an unrealistic water level distortion when enlarging the longitudinal domain, we developed the concept of artificial sidewalls to reflect the realistic residual water level reported by Cho *et al.*³⁾ in a numerical simulation. The residual water levels and impinging pressures were examined for various longitudinal domain sizes with and without these sidewalls.

2. Numerical Methods

The impingement of the water jets onto the running strip surface was numerically simulated using the commercial CFD code Fluent 6.3. The mass and momentum conservation equations were calculated for the conditions of unsteady, turbulent, and incompressible flows. The standard *k-ε* model was used for the turbulence modeling. To track the interface (free surface) between the cooling water and the surrounding air, the VOF (volume of fluid) method was adopted. The time step for the unsteady simulation was set to 0.001 s. In addition, the numerical simulation was conducted until the flow field reached a steady state.

Figure 1 shows a representative computational domain and the boundary conditions. Although the cooling process is not solved in this study, as mentioned before, since the strip cooling histories in the strip running direction is very essential, a longitudinally very long computational domain was adopted, as shown in Fig. 1. In addition, to reduce the computational cost, only one spanwise pitch is selected as a computational domain.

3. Distortion of Residual Water Level and Artificial Sidewalls

Figure 2 shows the free surface shape of the residual water, which has reached a steady state for the cases with lengthwise domain sizes of 1, 2, and 3 m. Although the same mass flux is applied for the supply of cooling water, the residual water level increases as the longitudinal size of simulation domain becomes larger. This is because symmetry conditions were applied on both side boundaries of the computational domain. In other words, this occurred because the drainage of the supplied cooling water was limited only in the entrance and exit regions of the strip, and because we did not select the entire widthwise region as a calculation domain out of consideration for excessively increasing the computational cost.

Cho *et al.*³⁾ developed the following relations for the residual water level and the supply water flow rate by comparing experimental observations:

$$H[m] = 0.275^{-2/3} \cdot b[m]^{-2/3} \cdot g^{-1/3} \cdot Q[m^3/s]^{2/3} \dots (1)$$

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DOI: <http://dx.doi.org/10.2355/isijinternational.54.2936>

Fig. 1. Computational domains and boundary conditions.

Fig. 2. Shapes of residual water layers for various lengthwise domain sizes at cooling water mass flux of 22.58 kg/m²s.

where H is the water pool height [m], b is the width of the draining passage through the strip side edge [m], g is gravitational acceleration, and Q is half of the total supply water flow rate [m^3/s] on the shaded area in Fig. 3, which is a top view of the cooling water supply system. The total flow rate in the shaded area in Fig. 3, $2Q$ [m^3/s], could be defined as the product of the velocity at the nozzle exit (V [m/s]), area of the nozzle exit (A_n [m^2]), and number of nozzles in the shaded area (N).

In this study, with preventing an unrealistic distortion of the water level, to enable to enlarge the longitudinal domain size for tracking a cooling history in a longer longitudinal domain, we set artificial sidewalls in Fig. 1(b), which have a height equal to the residual water height predicted from Eq. (1). When the artificial sidewalls are adopted in case 2

Fig. 3. Top view of water jet cooling system.

(a) without sidewalls

(b) with sidewalls

Fig. 4. Residual water levels for various lengthwise domain sizes and flow rates in cases (a) without sidewalls and (b) with sidewalls.

of Fig. 1, by applying the zero gauge pressure condition at all of the side boundaries above the artificial walls, the residual water freely floods out to all the side boundaries.

4. Results and Discussions

Figure 4 presents the residual water heights from the numerical simulations for various supply water flow rates and lengthwise domain sizes. In Fig. 4(a), for all of the

Fig. 5. Impinging pressures and residual water heights for various lengthwise domain sizes at cooling water mass flux of $22.58 \text{ kg/m}^2\text{s}$ in cases (a) without sidewalls and (b) with sidewalls.

lengthwise domain size cases, the residual water height increases as the flow rate increases. Although the cooling water is supplied with the same mass flux, the residual water height varies according to the longitudinal domain size. The residual water heights for 1 and 2 m lengthwise domain sizes were underestimated in comparison with the results by Eq. (1). The opposite results occurred for the 3 m domain size. For longer domain sizes, the deviation from the results by Eq. (1) is expected to be larger. On the other hand, the cases that adopted the artificial sidewalls showed no dependency on the longitudinal domain sizes and good agreement with the results of Eq. (1), as shown in Fig. 4(b).

Figure 5 shows the distributions of the impinging pressure on the strip surface and the residual water heights for

the various lengthwise domain sizes, with a supply water mass flux of $22.58 \text{ kg/m}^2\text{s}$. There are peak values for the impinging pressure directly below the supply nozzles. In Fig. 5(a), the impinging pressures below each header vary markedly with the lengthwise domain size. The impinging pressure is closely related to the residual water level. In particular, for the 3 m case of Fig. 5(a), the peak values below the first and third headers are significantly decreased as a result of the residual water's strong cross flow toward the drain passage. In Fig. 5(b), the residual water levels have similar values for all the lengthwise domain sizes. The impinging pressures below each header region also show similar values because the strong draining cross flows are prevented by allowing the residual water to flood out over the artificial sidewalls. Thus, it can be observed that the peak values of impinging pressure below the headers are nearly even.

5. Conclusions

The impingement of water jets onto a moving surface was numerically simulated. The impinging pressure was greatly affected by the state of the residual water. In order to reflect the correct level of residual water in the numerical analysis, we applied artificial sidewalls to forcibly regulate the residual water level according to the flow rate. The height of the wall was fixed using a simple equation representing the relation between the flow rate and the residual water height. By adopting the concept of artificial sidewalls, we could prevent unrealistic distortions in the residual water level and impinging pressure in the circumstances of longitudinally very long and one spanwise pitch domain, which is selected to effectively predict the steel plate's longitudinal cooling history. It is expected that this could be usefully applied to thermal analyses or lab.-scale experiments of the cooling process.

Acknowledgement

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (the Grant 2013059593).

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