Numerical Simulation of Cooling Process after Hot Rolling with Realistic Residual Water Levels

Myeon Jae KWON and Il Seouk PARK*

School of Mechanical Engineering, Kyungpook National University, 80, Daehakro, Bukgu, Daegu, 702-701 Korea.

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The cooling process of a moving hot steel plate after hot rolling was numerically investigated. Many important parameters affect the cooling process. This study focuses on residual water, which accumulates on the surface of the moving plate by the continuous supply of cooling water. This residual water may significantly interfere with the impingement of water jets and the cooling of the steel plate. In this study, we devised a concept of artificial sidewalls to apply a realistic residual water level in a numerical simulation of a cooling hot steel plate. The necessity for this concept of an artificial sidewall for simulations of moving plate cooling was investigated by comparing the cooling history of the plate for three different longitudinal domain cases with and without artificial sidewalls.

KEY WORDS: boiling heat transfer; water jet impingement; residual water.

1. Introduction

In the cooling process after hot rolling, a hot steel plate comes in at a certain running speed and is cooled by impinging water jets injected from a cooling water supply device. The cooling process includes many complex physical elements such as boiling heat transfer, free surface motion of residual water, and high-speed movement of the plate. Park1) recently suggested a numerical model to simultaneously consider all these effects.

Many important parameters govern the cooling process, such as the temperature and velocity of the plate, the temperature and flow rate of the water jet, and the nozzle arrangement of the cooling water supply. In this study, we focus on the residual water level. The residual water accumulated on the moving plate surface has a certain water level, largely depending on the cooling water flow rate and plate width. The level and flow behavior of residual water significantly affect the impingement of water jets as well as the resultant heat transfer between the plate and the cooling water.

Because Park’s original study1) and succeeding works2,3) largely focused on the cooling history of the plate in the running direction, a longitudinally lengthy calculation domain has been adopted in which only a one-pitch cooling water supply nozzle in the width direction as a computational domain was selected using symmetric condition. Unfortunately, in these numerical analyses, because the supplied cooling water could only be drained through the plate’s entrance and exit, the longitudinal extension of the calculation domain indicated an unrealistic increase in the residual water level. Of course, it is caused by numerically neglecting the lateral side drain. In an actual plate cooling process, the supplied cooling water is mostly drained through plate’s lateral ends.

Therefore, for valid numerical simulations of the cooling process, it is necessary to apply a more realistic residual water level to the numerical analysis, rather than depending on the numerically selected longitudinal domain size. To adjust the residual water level to a realistic value in the numerical simulation while maintaining one-pitch domain width, we adopted the concept of artificial sidewalls.

In this study, to reveal that simply expanding the longitudinal domain size to obtain a plate’s cooling history within a longer longitudinal range can lead to false cooling predictions, the plate cooling process was simulated for three different longitudinal calculation domains. Additionally, to avoid the unrealistic increase in water level depending on the longitudinal size of the calculation domain, cases with artificial sidewalls were simulated. The plate’s cooling histories, residual water levels, and local and average heat fluxes were compared.

2. Numerical Modeling for Realistic Residual Water Levels

The numerical method employed in this study fully follows the procedure suggested by Park,1) which simultaneously addresses film boiling, free surface motion, and plate running. Figure 1 shows the basic computational domains and boundary conditions. We assumed the width of the plate to be 1 m. However, to reduce computational costs, only one-pitch nozzle in the width direction was selected as the computational domain.

In case 1, as in many previous studies, symmetric conditions were applied on the lateral side boundaries of the domain. The zero gauge pressure condition was applied on the boundaries above the entrance and exit regions of the plate. The residual water accumulated on the plate surface could be drained through only the zero gauge pressure boundaries, i.e., the boundaries above the entrance and exit of the plate. In this case, if we extend the calculation longitudinally along the plate running direction, the residual water level rises by an increase in the longitudinal domain size because the lateral side drain of the cooling water is blocked by the symmetric boundary condition given on the lateral boundaries. However, this is not realistic. In the previous studies, to save computational costs, and because the plate’s longitudinal cooling history was relatively more important than the cooling pattern in the width direction, the symmetric condition was imposed on the lateral boundaries and only one-pitch width domain was considered.

In case 2, we established artificial sidewalls along the lateral sides of the domain and set the zero gauge pressure condition on the faces above the artificial sidewalls. Thus, the residual water overflowed not only the boundaries over the plate’s entrance and exit but also the lateral side boundaries, which were set as a symmetric plane in case 1. Therefore, we can forcibly control the residual water level by adjusting the height of the artificial sidewall.

Cho et al.4) suggested a simple equation to predict the residual water level according to the plate width and cooling water flow rate. They verified their equation by comparing

* Corresponding author: E-mail: einstein@knu.ac.kr
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its values with the experimental results. Equation (1) is a modified version of that from the result of Cho et al. to match our computational dimensions.

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H[m] = 0.02796 \cdot V[m/s]^{2/3}
\]

Where \(H\) = residual water level [m] and \(V\) = velocity of the cooling water jet at the nozzle exit [m/s]. In this study, we established the height of the artificial sidewall as equal to the residual water level estimated by Eq. (1). Thus, it was possible to apply a more reasonable residual water level, which is only dependent on the plate width and cooling water flow rate, to the plate cooling simulation.

The steel plate is running at a speed of 1 m/s in the \(x\)-direction. The incoming temperature of the plate was 850°C. The nozzle was arranged in a staggered pattern, as shown in the Fig. 1(c).

3. Results and Discussions

Figure 2 shows the results of the numerical simulation for three different longitudinal domain lengths (1, 2 and 3 m). As shown in the figure, the number of headers (group of nozzles) is increased in proportion to the longitudinal domain size. The residual water shapes and temperature changes of the moving plate are visible in the figure. The cooling water jetting velocity is fixed at a constant 6 m/s. That is, the mass fluxes of the cooling water for all cases are same as 22.58 kg/m²s, regardless of changes in domain size. In Fig. 2(a), although the cooling water is supplied with the same mass flux to the computational domains, the residual water level is significantly increased as the domain size increases. In case 1, because we applied symmetric conditions to the lateral sides of the computational domain, the residual water cannot be drained through the lateral boundaries. Additionally, as more residual water is accumulated on the surface of the plate, strong flow sweeps the plate surface from the center to the longitudinal ends of the domain. It may simultaneously work favorably and adversely on the plate cooling. That is, the strong flow of the residual water may work favorably with increasing a convective heat transfer between the residual water and plate, and simultaneously may work adversely by reducing the jet’s impinging effect.

However, these are not actual phenomena but only incorrect results of inappropriate numerical modeling for the problem. As mentioned before, during the actual plate cooling process, the supplied cooling water is largely drained through the plate’s lateral ends, and therefore the residual water level remains similar even if the selected longitudinal domain size changes. However, most previous numerical simulations have solved only one-pitch nozzles in the lateral direction with symmetric boundary conditions; therefore, the supplied cooling water is drained through only the longitudinal ends of the domain and forms different levels of residual water depending on the longitudinal domain size. In Fig. 2(b), the heights of the residual water remain constant, regardless of the longitudinal domain size, because of the artificial sidewalls, whose height is determined by the mass flux of the supplied cooling water and the plate width, as indicated by Eq. (1). (For more details in the related hydrodynamic characteristics including impinging pressure, see Ref. 5)

Figure 3 shows the temperature profiles in the plate running direction at 1 mm below the plate surface for the cases with three different longitudinal domain sizes. The temperature data was captured along the longitudinal meridian line in the span-wise center between two different nozzle placing lines. At the plate exit region, the temperature in case 2 is higher than that in case 1 for the 1 m domain size. This is
because case 1 forms a thinner residual water level than case 2, as shown in Fig. 2. However, as the domain size increases, these results are reversed. This is because case 1 has a larger residual water level than case 2 for longer domain sizes. For case 1 with 3 m domain size, the jet’s impingement under the third header region weakens from the strong sweeping flow of the residual water and the increased residual water level; as a result, the temperature drop is significantly reduced, as shown in Fig. 3. On the other hand, in residual-water-cooling regions such as the entrance region, the sweeping flow of the residual water favorably affects the plate cooling, as shown near the entrance region of case 1 with 3 m domain size in Fig. 3. As the sweeping flow becomes stronger through enlargement of the longitudinal domain size, the plate is cooled more in the entrance region. To obtain a cooling history within a longer longitudinal range, if we enlarge the domain size longitudinally while keeping the side boundaries as symmetric planes, cooling results are expected to be significantly distorted by the abnormally high residual water level and the resultant sweeping flows.

The longitudinal change of the local surface heat flux on the meridian line just under the cooling water supplying nozzle is shown in Fig. 4. As the domain size increases, case 1 shows a different estimate for local heat flux at the same header region; i.e., the maximum local heat flux in the first head region was approximately 20 MW/m² for the 1 m longitudinal domain size, whereas it was only 10 MW/m² at the same head region for the 3 m domain size. However, case 2 does not produce this fault and estimates similar levels of heat fluxes at the same regional area, even if the domain size is changed.

4. Conclusions

Most previous plate cooling studies have been conducted for one very small section out of the entire region of the plate cooling system. Moreover, to save computational costs, only a one-nozzle pitch domain in the plate’s lateral direction was selected. However, cooling results in a much longer longitudinal range are often required to examine the cooling history before or after the metallurgical phase change. In this study, we determined that simply extending the longitudinal domain size to obtain a cooling result for a longer longitudinal range can significantly distort the cooling results because of the unrealistic residual water level. We devised the concept of an artificial sidewall to prevent such wrong estimations for the residual water level affecting the cooling simulation. The height of the artificial sidewall was determined from the numerical and empirical equations of a previous study. We tested three different longitudinal domain sizes with and without artificial sidewalls. The cases with artificial sidewalls displayed reasonable results; that is, the residual water level is independent of the selected longitudinal domain size, and the local heat fluxes in each header region show their natural values, regardless of the selected longitudinal domain size. In this study, to correct the error originated by a selected numerical domain size, the residual water level, one of two main effects for the plate cooling (residual water’s level and sweeping flow) was intensively considered by adopting the artificial side wall concept. But the other main factor, the residual water’s sweeping flow still needs to be investigated to resolve the inconsistency between the numerical simulation and real plant phenomenon.

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