Development of Numerical Model for Water Cooling Boiling Heat Transfer on a Moving Hot Steel Plate

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1. Introduction

Most of the scientific results for boiling heat transfer have been reached through experimentation. This paper focuses on the boiling heat transfer on the moving hot plate with a fully numerical approach. The simulation was conducted only in a very high temperature region (over the Leidenfrost temperature) where the film boiling can be kept steadily on the plate. Actually this phenomenon could be occurred in steel making process, especially the strip cooling process in hot rolling plant. However, the theoretical or numerical setup for boiling heat transfer is acutely required in the nuclear engineering part too. Thus in this paper, the results developing the fully numerical approach for boiling heat transfer during the study of steel plate cooling will be presented.

2. Methods and Results

2.1 Numerical Model

The steam film layer formed on a hot substrate (steel plate) during the film boiling situation is very thin in a micro scale. Thus the numerically considering the layer with real physical dimension produces the bad metric condition in terms of grid quality. Moreover in the case that the thermal history of the substrate should be regarded, the thickness of the film layer can be altered as the thermal condition between the substrate and the cooling water. Thus in this study, the method considering the thermal resistance of the steam film layer without allocating the real computing domain in that region has been developed.

First, to considering the thermal resistance of the film layer, the concept of the effective thermal conductivity has been adopted. As shown in Fig. 1, the first grid cells on a substrate contain the steam film layer contacting the substrate. The thermal conductivities of the first cells are reassigned with the effective thermal conductivities according to the continuity of temperature and heat flux on the interface between the steam layer and the liquid cooling water. Also the thickness of the film layer depends on the thermal communication between the steam layer and the liquid cooling water. Thus the film thickness and the effective thermal conductivity are calculated through the iterative calculation along the following relations.

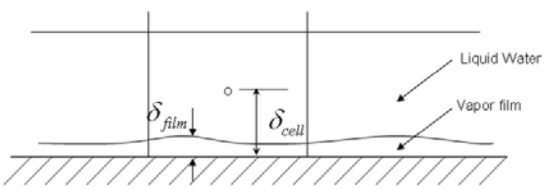

Fig. 1. Mathematical modeling of 1st row cells on plate surface for effective thermal conductivity.

$$Q_{wall} = k_{steam} \frac{T_{wall} - 100}{\delta_{film}} \quad (1)$$

$$Q_{wall} = k_{water} \frac{100 - T_{cell}}{\delta_{cell} - \delta_{film}} \quad (2)$$

$$Q_{wall} = k_{effect} \frac{T_{wall} - T_{cell}}{\delta_{cell}} \quad (3)$$

From a first iteration result using the initially assumed effective thermal conductivity, the wall heat flux is obtained. Then using the wall heat flux, the thickness of the film layer is approximated by the eq. (1) where, k_{steam} is the thermal conductivity of steam, T_{wall} wall surface temperature. Eq. (1) represents the heat transfer between the wall surface and the film-water interface. Next, using the approximated film thickness, the representative temperature, T_{cell} of the first cell is recalculated through the eq. (2) which means the heat transfer between the film-water interface and the cell centered point, where, k_{water} is the thermal conductivity of water and δ_{cell} the distance from substrate to the first cell center point. Using T_{cell}, the effective thermal conductivity, k_{effect} is reassigned through the eq. (3). The assumption is that the heat released from a substrate is completely transmitted through the steam layer without any accumulation or dissipation. Using the reassigned effective thermal conductivity, the solving the thermal fields is repeated until the effective thermal conductivity comes within the specific error bound.

2.2 Results

The present numerical model for the film boiling heat transfer has been successfully applied in hot rolling process [1]. In this paper, the results for the boiling heat transfer in a moving hot steel plate [2~8] will be presented. First, Fig. 2 shows the resultant shape of residual water on a moving plate and the cool-down history of the plate. The moving plate flows in with high temperature and high speed as shown in the figure. The circular impinging water jet is injected toward the moving plate for plate cooling. The shape of the residual water is very similar to the real cases. The calculation was conducted for the various flow rate of cooling water and the various moving speed of plate. The results showed a good agreement with the real case in the aspect of the cool-down history. Especially the present study produced the spatial distributions of the plate temperature induced by the impinging nozzle arrangement and the temperature at the plate surface which is difficult to measure experimentally.

Fig. 3 shows the cooling history of the temperature at the point 1 mm under the plate surface. The present result shows a good agreement with the experimental one. The little deviation in the region of 1st header is caused by the uniform inlet temperature of the steel plate.

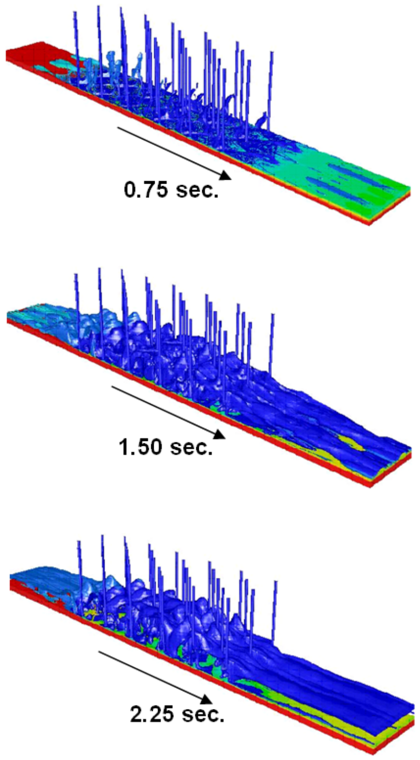

Fig. 2. Residual water shapes and plate temperature as time goes on.

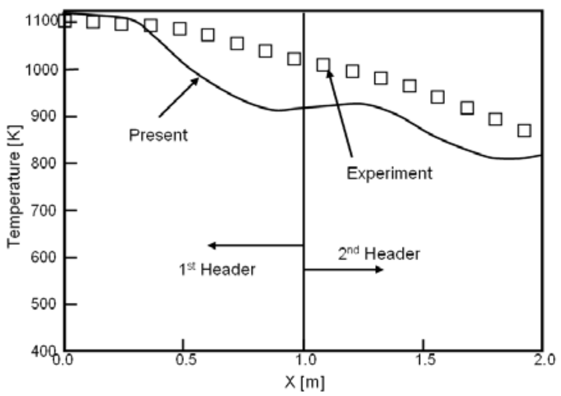

Fig. 3. Cooling history of steel plate temperature.

3. Conclusions

Fully numerical simulation for film boiling heat transfer has been developed. The model was validated through the strip cooling problem in steel making process. The problem was in very severe conditions numerically; the plate moves fast, the cooling water is supplied with the impinging jet form and the very complex air-water interface shape forms. The present numerical model showed a good quality to simulate the boiling heat transfer phenomenon and is expected to be successfully applied to various other applications.

REFERENCES

[1] I. S. Park, Numerical Analysis for Film Boiling Cooling Heat Transfer of a Moving Hot Steel Plate, The Iron and Steel Institute of Japan International, Vol. 51, no. 5, p. 743-747, 2011.

[2] D. H. Wolf, F. P. Incropera, and R. Viskanta, Jet Impingement Boiling, Advances in Heat Transfer, Vol. 23, p. 1-132, 1993.

[3] H. Hatta, J. Kokado, and K. Hanasaki, Numerical Analysis of Cooling Characteristics for Water Bar (Laminar Flow), Trans. Iron Steel Inst. Jpn., Vol. 23, no. 7, p. 555-564, 1983.

[4] L. A. Gabour and J. H. Lienhard V, Wall Roughness Effects on Stagnation-Point Heat Transfer Beneath an Impinging Liquid Jet, Journal of Heat Transfer, Vol. 116, p. 81-87, 1994.

[5] R. L. Webb, Performance Evaluation Criteria for Use of Enhanced Heat Transfer Surfaces in Heat Exchanger Design, International Journal of Heat and Mass Transfer, Vol. 24, p. 751-726, 1981.

[6] S-J. Chen and A. A. Tseng, Spray and Jet Cooling in Steel Rolling, International Journal of Heat and Fluid Flow, Vol. 13, p. 358-369, 1992.

[7] S. Kalpakjian, Manufacturing Processes for Engineering Materials, Addison-Wesley, Massachusetts, 1985.

[8] S. van Stralen and R. Cole, Boiling Phenomena, Hemisphere, New York, 1979.