Technical Report

UDC 621 . 771 . 23 . 016 . 2 : 62 - 71

Water Quenching CFD (Computational Fluid Dynamics) Simulation with Cylindrical Impinging Jets

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Abstract

A computational fluid dynamics simulation model for water quenching processes with cylindrical impinging jets is developed. Water and air multiphase flow often appears in water quenching processes, thus two-fluid model is applied to calculate the multiphase flow. Some empirical equations are used to determine boiling heat transfer. Boiling state is distinguished by plate surface temperature and water temperature nearby surface, and appropriate empirical equations are applied according to the state. To confirm the validity of the model, the plate cooling speed and the boiling curve with cylindrical impinging jets are calculated and compared with experimental one, and it is found that both are in good agreement.

1. Introduction

In recent years, with the continual enhancement of steel material functions such as higher strength and better ductility, the growing demand for cost cutting by reducing the use of alloying elements, and streamlining processes, the thermomechanical control process (TMCP) has become increasingly important. As one of the important elements of this technology, the technique that allows the precise control of the water quenching temperature can be cited along with the metallurgical and controlled rolling techniques.

In the TMCP steel manufacturing process, to impart the required qualities to the products, steel material that has undergone a rolling process in which the temperature and draft are strictly controlled is cooled at a prescribed cooling rate and finishing temperature. In the quenching process, to fulfill the prescribed cooling rate, equipment that jets water as the coolant is commonly used. However, since water quenching of hot steel is accompanied by a complicated phenomenon called boiling, it is difficult to control the cooling process with a high degree of precision.

Typically, the condition of boiling water changes from film boiling to transient boiling to nucleate boiling as the temperature of the cooled surface drops.[1] When film boiling occurs on a high temperature surface, a thin vapor layer is formed between the hot surface of the material and the cooling water, preventing them from making direct contact with one another. In this case, since the heat transfer takes place via the vapor film, the heat flux is small even though the material surface temperature is high (**Fig. 1** (a)). In nucleate boiling, which occurs on surfaces that are at approximately the saturated temperature of cooling water, the material surface is in almost direct contact with the cooling water, producing a large amount of vapor bubbles. In this boiling condition, the heat is transferred efficiently, and a high heat flux is obtained due to the active phase shift and the effect of cooling water agitation by vapor bubbles (Fig. 1 (b)). Transient boiling, which occurs on intermediate temperature surfaces, is a mixed state of film and nucleate boiling. In transient boiling, as the material surface temperature declines, the material surface begins to make contact with the cooling water, and the heat flux increases.

Thus, there is a close correlation between boiling condition, surface temperature, and heat flux. The correlation is diagrammatically represented by a boiling curve (Fig. 1 (c)). In the boiling curve, the point of connection between film boiling and transient boiling is called the point of minimum heat flux (MHF) and the point of connection between transient and nucleate boiling is called the point of critical heat flux (CHF). Those points are considered important since the condition of boiling changes at each of them.

In particular, in the transient boiling region of the curve, the heat flux increases as the surface temperature declines. Therefore, in this region, the surface temperature variation can increase, making the cooling finishing temperature control difficult. In recent years, there is growing demand for cooling control in the transient boiling region to allow manufacturers to obtain the desired material characteristics. Accordingly, more sophisticated cooling prediction and quenching

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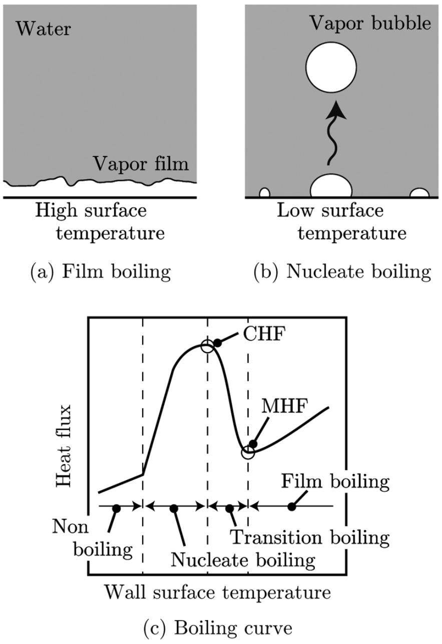

Fig. 1 Schematic diagram of boiling phenomenon

process control technologies are required.

To control the quenching processes precisely, it is sufficient to know how the boiling curve appears at each point of the steel surfaces. However, the boiling state is significantly influenced not only by the steel surface temperature but also by the steel surface properties, cooling water temperature, retained water flow condition, etc. Therefore, the boiling curve temporally and spatially changes. For that reason, it is considered difficult to predict and control water quenching processes accurately.

On the other hand, the progress in numerical simulation technology in recent years has made it possible to directly grasp the flow state of cooling water that influences water quenching. For example, Kunugi [2] and Umemura et al.[3] built gas–liquid multi-phase flow simulation techniques that permit the accurate capture of the interface between water and air. The techniques were applied to analyze flows involving such phase shifts as boiling and condensation. Narumanchi et al.[4] studied the effect of impinging jets on nucleate boiling with the aim of applying them in the cooling of electronic devices.

Incidentally, the techniques developed by Kunugi and Umemura et al. require the detailed capture of the behavior of the interface between the cooling water and its vapor. Therefore, it is very difficult to apply them to the analysis of large-scale equipment in the likes of steel cooling processes due to the huge computing load. The technique of Narumanchi et al. is applicable only to nonboiling and nucleate boiling processes in which the cooled surface temperature is relatively low; it cannot be applied to steel cooling processes in which the cooled surface temperature is high and the boiling condition varies widely from film boiling to nonboiling.

In this paper, we shall describe our numerical simulation technique that permits the analysis of gas–liquid multi-phase flows with comparatively small computing load and high efficiency, together with our water cooling prediction technique for hot steel materials that reflects the boiling condition that changes according to cooling water and steel temperatures.

2. Numerical Methods

2.1 Fluid flow simulation

The flow through a steel quenching process as represented by a run-out table (ROT) of hot rolling is a multi-phase flow of liquid (water jet, retained water) and gas (air, vapor). Therefore, a multiphase flow simulation model should be applied.

The one- and two-fluid models are the main techniques used to simulate gas–liquid flows, and they are described in detail in the following paragraphs.

The one-fluid model is a technique that expresses gas and liquid with one velocity field and directly calculates the flow state of gas and liquid. For the distinction between gas and liquid, a discriminant function is used. For example, when a computational grid is filled with the gas, the function takes the value of 0. When the grid is filled with the liquid, the function is 1. When the value of the function is between 0 and 1, it indicates the interface between the gas and the liquid. By calculating the advection of the discriminant function, the gas–liquid interface is traced, and the multi-phase flow, including the gas–liquid interaction and interfacial tension, is analyzed directly.

Representative techniques that make use of a one-fluid model include the VOF (volume of fluid) method [5] and the level set method.[6] With a one-fluid model, it is possible, for example, to obtain detailed information about multi-phase flows, such as the shapes of scattering water drops or air bubbles rising in water. On the other hand, it requires detailed computational grids to resolve the water drops or air bubbles to be analyzed, and thus the number of computational grids becomes very large. This is a drawback of the one-fluid model. It should be noted that the techniques developed by Kunugi [2] and Umemura et al.[3] are also one-fluid models.

On the other hand, in the two-fluid model, one velocity field is allocated to the gas and one velocity field is allocated to the liquid. This technique is used for large-scale simulations, such as the flow analysis of steam generator tubing in power stations. As in the case of the one-fluid model, the distinction between gas and liquid is made by using a discriminant function. The difference is as follows; when the discriminant function for a computational grid takes a value between 0 and 1, it is assumed that the gas is in the form of air bubbles when the proportion of the gas is small and that the liquid is in the form of water drops when the proportion of the liquid is small. In this situation, the interaction between gas and liquid can be calculated by gas–liquid flow mode models. Thus, it becomes possible to analyze a multi-phase flow of gas and liquid without needing detailed computational grids.

It should be noted, however, that gas–liquid flow mode as an actual phenomenon changes in a complicated manner according to various parameters, such as flow rate, gas–liquid ratio, flow direction against gravitation, pipe diameter, and surface tension. Therefore, there are no models that can perfectly express the mode of flow under all possible conditions. This means that it is necessary to select a model capable of expressing the actual flow mode according to the object of the simulation.

In steel quenching processes, cooling water is jetted out at high speed. It is considered, therefore, that gases, such as air and vapor, have only a weak effect on the flow mode in the entire process. The implication is that detailed information about the effect is unnecessary. Therefore, we selected a two-fluid model that does not require much computing load and that permits the analysis of a wide region. In the actual analysis, the Advance/FrontFlow/MP of AdvanceSoft Corporation was used.

The governing equations used in the two-fluid model are shown below.

• Volume ratio between gas phase and liquid phase

$$\sum_m \alpha_m = 1 \tag{1}$$

• Equation of mass conservation

$$\frac{\partial(\alpha_m \rho_m)}{\partial t} + \nabla \cdot (\alpha_m \rho_m \boldsymbol{u}_m) = \Gamma_m \tag{2}$$

• Equation of momentum conservation

$$\frac{\partial(\alpha_m \rho_m \boldsymbol{u}_m)}{\partial t} + \nabla \cdot (\alpha_m \rho_m \boldsymbol{u}_m \boldsymbol{u}_m) = -\nabla(\alpha_m p) - \nabla \cdot (\alpha_m \boldsymbol{\tau}_m) - \boldsymbol{F}_{\mathrm{w}m} - \boldsymbol{F}_{\mathrm{i}m} - \boldsymbol{F}_{\mathrm{g}m} + \Gamma_m \boldsymbol{u}_{\mathrm{i}m} \tag{3}$$

• Equation of energy conservation

$$\frac{\partial(\rho_m \alpha_m h_m)}{\partial t} + \nabla \cdot (\rho_m \alpha_m h_m \boldsymbol{u}_m) = -\nabla \cdot (\alpha_m \boldsymbol{q}_m) - \frac{D(\alpha_m p)}{Dt} - \Gamma_m h_{\mathrm{s}m} + q_{\mathrm{w}m} + q_{\mathrm{i}m} \tag{4}$$

In the above equations, $\boldsymbol{F}$ denotes applied force; h, specific enthalpy; p, pressure; $\boldsymbol{q}$, heat flux; $\boldsymbol{u}$, flow rate; α, volume ratio; Γ, phase shift speed; ρ, density; and $\boldsymbol{\tau}$, viscous stress. With respect to the subscripts, g denotes gravitation; i, gas–liquid interaction; m, gas phase or liquid phase; s, phase shift; and w, mutual action with wall. The phase shift speed is calculated by using the temperature recovering method.[7]

The above equations were discretized by the finite volume method and solved by the SIMPLE (semi-implicit method for pressure linked equations) method.[8] As the turbulence model, the k-ε model was used. For the wall boundaries of momentum and energy, standard wall functions were used. The third-order upwind differentiating scheme was applied to the advection term and a total variation diminishing (TVD) was used to restrain numerical instability.

2.2 Boiling heat transfer

It was decided to calculate the surface heat flux that changes in a complicated manner on steel plates in terms of both space and time using the water and steel plate temperatures in local simulation zones obtained by a numerical fluid analysis. The surface heat flux was calculated using the following equations:

• Nusselt number for nucleate boiling

$$\mathrm{Nu} = c_1 \mathrm{Pr}^{c2} \mathrm{Re}^{c3} \mathrm{Sp}^{c4} \mathrm{Sb}^{c5} \tag{5}$$

• Nusselt number for film boiling

$$\mathrm{Nu} = c_6 \mathrm{Pr}^{c7} \mathrm{Re}^{c8} \tag{6}$$

where c denotes an empirical constant; Nu, Nusselt number; Pr, Prandtl number; Re, Reynolds number; Sb, subcool number; and Sp, degree of superheat. They are all dimensionless. The representative length is the distance from the center of the impinging jet, and the representative speed is the water flow rate near the steel plate surface. The heat transfer in transient boiling shall be described in the next section.

Equation (5) was formulated with reference to the existing semi-theoretical formula on jet cooling.[9] Equation (6) was formulated with reference to the theoretical formula[10] for film boiling heat transfer in turbulent flow derived from the two-phase boundary layer theory that takes into account the vapor film and the retained water flow in the neighborhood of the vapor film. The heat transfer in nonboiling forced convection is heat transfer in an ordinary single-phase flow, which is decided by the wall function as is widely known.

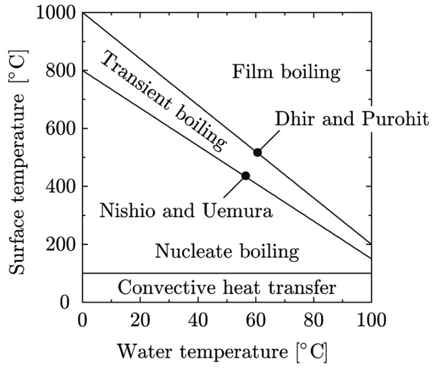

Fig. 2 Boiling transition diagram under atmospheric pressure [13]

2.3 Transition of boiling condition

The modes of film and nucleate boiling, or the MHF and CHF points, are influenced by steel plate temperature, cooling water temperature, etc. Therefore, in order to take into account those effects, we judged the modes of boiling using the equation of Dhir and Purohit[11] (Equation (7)) for the MHF point and the equation of Nishio and Uemura[12] (Equation (8)) for the CHF point.

$$T_{\mathrm{MHF}} = 1000 - 8\ T_{\mathrm{wtr}} \tag{7}$$

$$T_{\mathrm{CHF}} = 800 - 6.5\ T_{\mathrm{wtr}} \tag{8}$$

Where T_{wtr} denotes the cooling water temperature and T_{MHF} and T_{CHF} denote the steel plate surface temperature at MHF and CHF, respectively.

Equations (7) and (8) experimentally evaluate the effects of retained water temperature on the MHF and CHF points. It was assumed that switching from nucleate boiling to nonboiling convective heat transfer was not dependent on the water temperature, and that it occurred when the steel plate surface temperature reached 100°C. The above equations for the transition of boiling condition hold true under atmospheric pressure. At places where the pressure is higher, such as a jet impinging point, the water temperature needs to be re-expressed in terms of the degree of subcooling. The correlation of the above factors is shown in **Fig. 2**.

In Fig. 2, the heat transfer in the transient boiling region was considered as a mixed state of nucleate and film boiling. Therefore, the heat flux of nucleate and film boiling were proportionally distributed according to the steel plate temperature.

It should be noted that it is considered that the points of change between MHF and CHF and between nucleate boiling and nonboiling heat transfers are influenced not only by the steel plate surface and cooling water temperatures but also by the cooling water flow rate. However, with respect to the prediction of MHF, it has been reported that it is not influenced by the flow rate of cooling water as long as it is 0.5 m/s or less.[11] Therefore, we decided to leave the effect of cooling water flow rate out of consideration when investigating these effects.

3. Analysis of Quenching with Single Jet

To verify the accuracy of our numerical simulation model, we carried out a simulation of cooling in a domain having a single cylindrical jet of water.

3.1 Simulation domain

The computational domain for simulation is schematically shown in **Fig. 3**, and the experimental conditions are shown in **Fig. 4**. As the initial conditions for the numerical analysis, a cylindrical container was set on the upper surface of a hot steel plate, and the

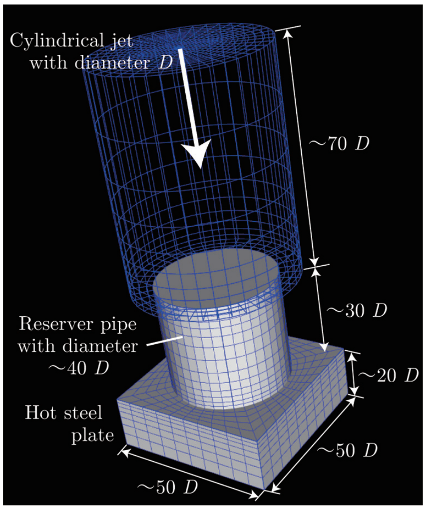

Fig. 3 Computational domain for quenching simulation with a cylindrical jet

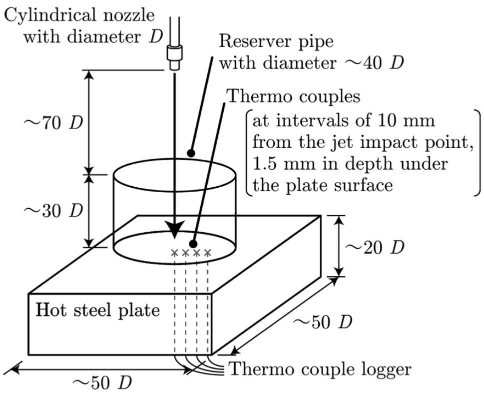

Fig. 4 Schematic diagram of quenching experiment with a cylindrical jet

container was filled with cooling water (to simulate retained water). With only a single water jet made to impinge onto the center of the steel plate from above, the temporal change of quenching was analyzed. A reference experiment, with a cylindrical container on a hot steel plate filled with water, was also performed; only a single stream of water was jetted onto the steel plate, and the quenching process was measured with thermocouples. The thermocouples were embedded to depths of 1.5 mm from the steel plate surface at intervals of 10 mm from the point of jet impingement on the steel plate. The conditions for the numerical simulation and experiment are shown in **Table 1**.

Figure 5 [13] shows the time serial changes in temperature measured by the thermocouples, in comparison with those obtained by the numerical simulation. In the figure, a time of 0 s indicates the start of quenching. The experiment was carried out three times, and the width between maximum and minimum values obtained in each of the experiments is shown by a band.

From Fig. 5, it can be judged that the results of the numerical simulation are, on the whole, reproducible, although the rate of temperature drop was slightly lower than in the experiments.

Concerning the slow rate of temperature drop, the following points should be taken into account.

• Boiling heat flux predicted by the model

Table 1 Computational and experimental conditions for quenching with a single jet

Conditions	Values
Nozzle Reynolds number	3×10^4
Jet temp.	30 °C
Initial temp. of water in pipe	30 °C
Initial temp. of plate	800 °C

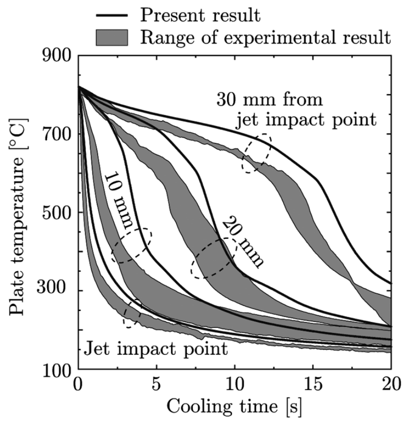

Fig. 5 Comparison of plate temperatures obtained by the present work with experimental ones [13]

• Boiling condition predicted by the model

In the graph, the size of the heat flux appears as the inclination of a curve, whereas the accuracy of prediction of the boiling condition, specifically the MHF point demarcating film and transient boiling, appears at the point where the inclination of the curve sharply changes. In order to improve the above accuracy of prediction, it is considered effective from Fig. 5 to increase the accuracy of prediction of boiling condition.

4. Analysis of Quenching with Multiple Jets

Our numerical simulation model was also applied to analyze the quenching of a moving steel plate by multiple cylindrical water jets, and the analysis results were compared with experimental results to verify the accuracy of the simulation model.

4.1 Computational domain

The computational domain is schematically shown in **Fig. 6**, and the experimental quenching conditions are shown in **Fig. 7**. As the initial condition of the numerical simulation, cooling water simulating retained water was pooled on a hot steel plate. From nozzles arranged above the steel plate in a checker pattern, multiple cylindrical jets were made to impinge onto the steel plate, and the temporal change of the quenching process was analyzed. The steel plate was moved longitudinally. However, since the periodic boundary condition had been set to the sides, the steel plate that had gone out of the computational domain reentered the domain from the other side. In a reference experiment, many cylindrical water jets were made to impinge onto the steel plate from above, and the quenching process was measured from the back with a thermal imaging camera as the steel plate was moved longitudinally. The conditions for the numerical analysis and experiment are shown in **Table 2**.

4.2 Results of simulation and experiment

The results of the simulation are shown in **Fig. 8**. The white isosurface in the figure indicates the surface having a gas phase volume

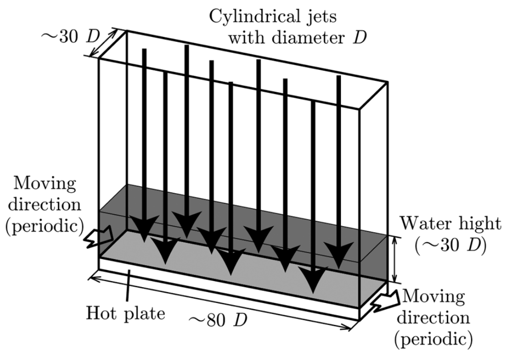

Fig. 6 Computational domain for quenching simulation with cylindrical multi jet

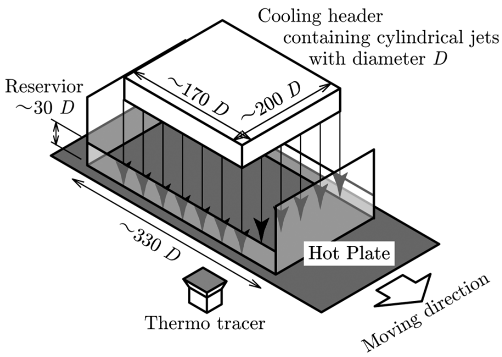

Fig. 7 Schematic diagram of quenching experiment with cylindrical multi jet

Table 2 Computational and experimental conditions for quenching with multi jet

Conditions	Values
Nozzle Reynolds number	3×10^4
Jet temp.	30 °C
Initial temp. of water layer	30 °C
Initial temp. of plate	800 °C
Plate speed	0.5 m/s

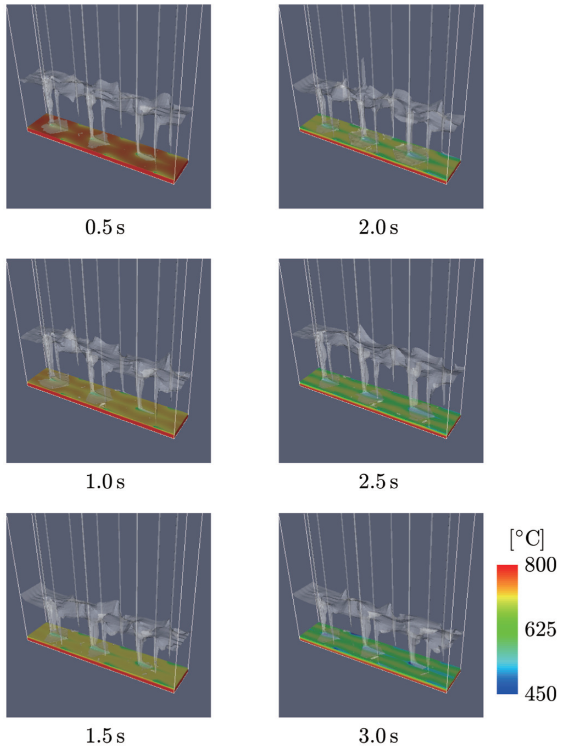

Fig. 8 Computational results of water flow, jets, and plate temperature

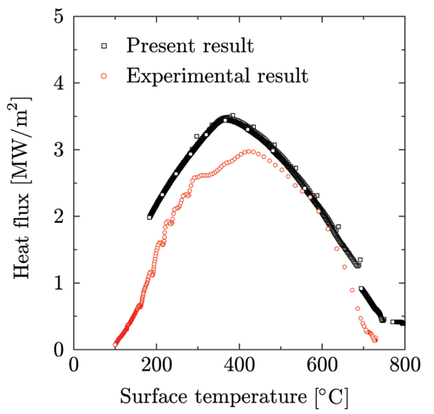

Fig. 9 Comparison of a surface-averaged boiling curve obtained by the present work with an experimental one

ratio of 0.5. From the figure, the following facts can be seen.

- Since the isosurface reaches the steel plate surface, the strong cylindrical jets penetrated the retained water without being scattered.
- Therefore, low-temperature cooling water was constantly supplied to and around the points of impingement of jets. As a result, the quenching process progressed rapidly and the steel plate surface temperature decreased.
- The cooling water that was heated by the steel plate at the points of jet impingement rose in temperature and dispersed radially on the steel plate, losing its speed. As a result, the cooling water lost its cooling capacity rapidly as it went away from the point of impingement.
- With the movement of the steel plate, the low-temperature region around the jet impingement points shifted toward the downstream side, and the high-temperature region on the upstream side moved to right under the jets. As a result, the entire steel plate was cooled almost uniformly.

Figure 9 shows the boiling curve obtained by the simulation and the experiments. The curve shows the relation between surface heat flux and surface temperature and is important for temperature prediction in quenching. For the numerical simulation, the steel plate surface temperature and heat flux distributions obtained were plane-averaged to calculate the boiling curve. For the experiment, the surface temperature and surface heat flux distributions were calculated [14] from the time serial change of temperature distribution at the back of steel plate obtained by the thermal imaging camera. They were then plane-averaged to calculate the boiling curve.

From Fig. 9, the following facts are found.

- Even the boiling curve subjected to plane averaging draws a form similar to the one observable with an ordinary boiling curve; that is, the film boiling region, the MHF point, the transient boiling region, the CHF point, and the nucleate boiling region appear in this order going from the high- to ow-temperature side.

- The boiling curve obtained by the numerical analysis takes a somewhat smaller value near the CHF point than the boiling curve obtained by the experiment. However, they are nearly the same in the film boiling region, MHF point, transient boiling region, and nucleate boiling region.

As shown here, even for steel plate quenching with multiple cylindrical water jets, a boiling curve that is important for quenching prediction can be reproduced. It may be said, therefore, that quenching prediction of a hot steel plate using numerical flow analysis can be implemented.

It should be noted that the present quenching was applied to a moving steel plate. If the steel plate moves, the region right under the water jet where the local cooling takes place rapidly changes, preventing the rapid cooling from continuing. This accounts for the influence of MHF point prediction error observed in the cooling with a single jet decreased. Needless to say, when the equations used in the present analysis for the prediction of heat transfer and judgment on boiling condition are replaced with higher accuracy models taking into account the influences of water flow rate, pressure, etc., it is expected that the accuracy of prediction will further improve.

The computing time required for the analysis shown in Fig. 8 was about one week when using only one core of an Intel® Xeon® processor (X5680, 3.33GHz). By applying the parallelization technology that has become popular in recent years, it is possible to implement larger scale simulations in shorter times.

5. Conclusion

We carried out simulations of quenching of steel plates using numerical fluid analysis. As a result, the following conclusions were obtained.

- By combining the flow state of cooling water obtained by numerical simulation of multi-phase flow using a two-fluid model with the existing equations for the prediction of boiling heat transfer and for deduction of the boiling condition, a new technique to analyze the quenching of hot steel plates was developed.
- The developed technique was applied to a system that cools a hot steel plate under retained water with a single cylindrical water jet. The time serial change in steel plate interior temperature obtained was compared with that obtained by a similar experiment. As a result, it was confirmed that they agreed well.
- The technique was applied to a system that cools a hot steel plate moving under retained water with multiple cylindrical water jets. The boiling curve for the steel plate obtained was compared with that obtained by a similar experiment. As a result, it was confirmed that they agreed well.
- By replacing the equations used in the present analysis for the prediction of heat transfer and for judgment on boiling condition with higher accuracy models, it is expected that the accuracy of prediction will be further improved.

References

1) Japan Society of Mechanical Engineers: Boiling Heat Transfer and Cooling. First Edition. Tokyo, Japan Industrial Publishing Co., 1998, p. 8
2) Kunugi, T.: Comput. Fluid Dyn. J. 9, 563-571 (2001)
3) Umemura, H. et al.: Flows. 30, 79-85 (2011)
4) Narumanchi, S. et al.: Int. J. Heat Mass Transfer. 51, 1-12 (2008)
5) Hirt, C. W., Nichols, D. B.: J. Comput. Phys. 39, 201-225 (1981)
6) Osher, S., Sethian, J. A.: J. Comput. Phys. 79, 12-49 (1988)
7) Ohnaka, H.: Introductory to Computer Heat Transfer/Solidification Analysis. Tokyo, Maruzen, 1985
8) Caretto, L. S. et al.: Proc. Third Int. Conf. Num. Methods Fluid Mech., Lecture Notes in Physics. 19, New York, Springer-Verlag, 1972, p. 60-68
9) Hirata, K., Morioka, S.: Trans. JSME. 42, 236-243 (1976)
10) Wang, B. -X., Shi, D. -H.: Int. J. Heat Mass Transfer. 28, 499-1505 (1985)
11) Dhir, V. K., Purohit, G. P.: Nucl. Eng. Des. 47, 49-66 (1978)
12) Nishio, S., Uemura, M.: J. Japan Soc. Heat Treat. 23, 260-265 (1983)
13) Kobayashi, K.: Bull. Iron Steel Inst. Japan. 18 (1), 29-32 (2013)
14) Beck, J. V. et al.: Numerical Heat Transfer, Part A: Applications. 5, 275-286 (1982)

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