Numerical analysis of slit laminar cooling of hot moving slab

Y. Takata¹, H. Shirakawa², T. Ito¹, Y. Haraguchi³ & M. Hariki⁴
¹Department of Mechanical Engineering Science, Kyushu University, Japan
²Department of Mechanical Engineering and Material Sciences, Kumamoto University, Japan
³Sumitomo Metal Industry, Japan
⁴Ferrotec Corporation, Japan

Abstract

Numerical analysis has been performed on the slit laminar cooling of a hot moving slab. A hot slab of initial temperature 600°C is cooled by an impinging jet of water and the behavior of the water flow after impingement has been obtained. The numerical method is based on the improved VOF (volume of fluid) method. Flow and temperature fields of the cooling water and the surrounding air and thermal conduction inside the slab are solved simultaneously. The cooling curve and transient heat transfer coefficient are obtained as parameters of the velocity of the slab and the impinging velocity of the cooling water.

1 Introduction

Slit laminar cooling is one of the cooling processes of hot slabs in steel-making industries and has high cooling performance and excellent uniformity to the other cooling processes. However, some problems still remain in this cooling process. First, there is spatial distribution of cooling water that causes from the limit of facility and from the interaction between cooling water ejected from multi-nozzles. Furthermore, cooling characteristic changes because the slab runs in cooling zone. Some experimental researches have been conducted¹⁻³ relating to these problems. Numerical simulation of this process is required to manifest
the cooling characteristics, and however there are still some difficulties in doing complete numerical work. Most of difficulties originate from the fact that it is a free surface flow involving boiling and evaporation of cooling water. As is well known there are several numerical methods to solve free surface flow, such as MAC, VOF, level set, CIP, etc. Authors have developed an improved VOF that has high accuracies in tracking free interface and in calculating the effect of surface tension[4]. Furthermore, a new algorithm has been developed to solve phase change problems[5] and it was successfully applied to simulations of a boiling bubble departure from a heated surface[6] and solidification process of amorphous foil[7].

At this moment, it is very difficult to take account of liquid-vapor phase change to this problem because the gaseous phase is not a vapor of pure substance but a mixture of water vapor and air. To solve this problem completely, mass diffusion should be considered by solving mass transport equation coupled with other basic equations. Our computation code at present cannot be applicable to this type of problems and it will be a future. As a first stage, the present study aims to solve numerically by VOF method the behavior of cooling water on the moving slab, convective heat transfer characteristics and temperature distributions both in water film and inside of the slab.

2 Physical model and numerical method

Physical model is illustrated in Figure 1. The computation domain consists of the water flow region of 100mm×5mm and the hot slab of 10mm in thickness which moves rightward with constant velocity, \( u_{\text{slab}} \). The slit water jet of 5mm in width impinges onto the moving slab. Real nozzle height is much higher than this physical model. However it will not make so much difference if the impinging velocity given as boundary condition here is the same as practical case. In the flow region, equations of continuity, NS and energy are solved simultaneously by the improved VOF (Volume of Fluid) method[4], and on the other hand only the energy equation is solved in moving slab since the heat transport inside is by thermal conduction only. To trace the interface between cooling water and the surrounding air-vapor mixture, the VOF method uses a function \( F \) that is the volume fraction of liquid in the control volume. Transport equation for \( F \) (equation (1)) is solved coupling with mass, momentum and energy equations.

![Figure 1](image_url)
The value of $F$ is unity when control volume is occupied totally with liquid and zero when occupied totally with air-vapor mixture. The gas-liquid interface exists in the control volume of $0 < F < 1$.

As an early stage of the study, phase changes between liquid and vapor are not taken into account. This simulation covers forced convection heat transfer from a hot slab to cooling water. The main interest is placed on the effect of slab movement on cooling performance.

For simplicity of the analysis, the following assumptions are employed:
(a) Flow is transient, two-dimensional, laminar and incompressible.
(b) Density, specific heat capacity and thermal conductivity are fixed constant both in liquid and air.
(c) Radiation heat transfer is not considered.

The basic equations for $F$, mass, momentum and energy are written as follows:

\[
\frac{\partial F}{\partial t} + \nabla \cdot (F \mathbf{v}) = 0 \quad (1) \quad \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (2)
\]

\[
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) = -\nabla p - \nabla \cdot [\mathbf{\tau}] + f_{ps} - \rho g \quad (3)
\]

\[
\rho c_p \left[ \frac{\partial T}{\partial t} + \nabla \cdot (T \mathbf{v}) \right] = \nabla \cdot (\lambda \nabla T) \quad (4)
\]

In equation (3), $f_{ps}$ indicates a force by surface tension that is in the form of body force and appears only in the interface control volume. This term is obtained by calculating curvature of gas-liquid interface. In slab region, heat is transported only by thermal conduction. Nevertheless convection term cannot be eliminated from equation (4) because the slab moves.

Properties are given by averaging those of liquid and gas weighted with respect to $F$.

\[
\rho = \rho_L F + \rho_G (1 - F) \quad \rho c_p = \rho_L c_{pl} F + \rho_G c_{pg} (1 - F) \quad \frac{1}{\mu} = \frac{F}{\mu_L} + \frac{1 - F}{\mu_G} \quad \frac{1}{\lambda} = \frac{F}{\lambda_L} + \frac{1 - F}{\lambda_G} \quad (5)
\]

By the use of thus averaged properties, it is not needed to set any boundary conditions at interface between different phases, and flow and temperature fields can be obtained not only in liquid phase but also in gaseous phase. Bottom boundary for flow field is on the slab surface $(y=10\text{mm})$, while that for temperature is at $y=0\text{mm}$.

Combining equation (1) with (5), continuity equation (2) can be reduced to

\[
\nabla \cdot \mathbf{v} = 0 \quad (6)
\]

which is the continuity equation for incompressible fluid. Rearranging equations
Computational Methods in Multiphase Flow

(1), (3), (4) and (6) to finite difference forms, flow field is solved by SMAC procedure and the temperature field is solved by implicit iterative procedure.

First, we calculate the estimated velocity, $\vec{v}$, using NS equation, and then solve the following Poisson equation to obtain the velocity and pressure fields.

$$\nabla \cdot \left( \frac{\delta}{\rho} \nabla \phi \right) = \nabla \cdot \vec{v}$$

(7)

The computation procedure can be summarized as follows:

1. Solve equation (1) by improved donor-acceptor method\textsuperscript{14} to trace the interface.
2. Calculate the force by surface tension, $f_s$, using the distribution of $F$.
3. Solve the velocity and pressure fields by SMAC algorithm.
4. Solve energy equation (4) to obtain the temperature field.
5. Proceed in time and repeat above procedures until a preset time.

3 Numerical results

3.1 Stationary slab

First, we solved the stationary slab, namely $u_{slab}=0$. As fixed parameters, initial temperatures of slab and cooling water are kept constant at 600°C and 100°C, respectively, throughout all computations including the case for moving slab. The results are shown in Figures 2-4. Figure 2 shows the behaviors of cooling water on the hot slab and temperature distribution that is expressed by gradation. It can be observed that the stagnation region is cooled down rapidly by impinging water. The exit velocity and water film thickness are 0.28m/s and 3mm, respectively. The exit velocity increases almost linearly with the impinging velocity and, on the contrary, film thickness slightly decreases.

Figures 3 and 4 show the distributions of temperature and Nusselt number with time, respectively. It is found from Figure 3 that the temperature at the stagnation region decreases rapidly in a short period and the surrounding temperature also decreases gradually. At the stagnation point, initial temperature decreases by 270K during 1.013s. Referring to Figure 4, the Nusselt number at the stagnation point ($x=50$mm) increases with time and has its maximum at 0.150s, and then slightly decreases. Although the magnitude of Nusselt number at the stagnation point is by 30% smaller than that of the similarity solution for uniform wall temperature, the direct comparison between them is not possible due to the difference in boundary conditions.

Figure 2 Water flow behavior on hot stationary slab at 0.308 sec (initial temperature: 600°C, water temperature: 100°C, impinging velocity: 0.5m/s)
Figure 3 Temperature distribution on the stationary slab surface

Figure 4 Distribution of Nusselt number on the slab surface
3.2 Moving slab

In case of moving slab, computation for moving velocities of 0.25, 0.5 and 1.0m/s were conducted. Figures 5–8 show the results for moving velocity of 1.0m/s. The time required for the slab to move from the left edge to the right is 0.1s for this velocity. Figure 5 shows the behaviors of cooling water and temperature distribution for hot moving slab, which should be compared with Figure 2, the case for stationary slab. Liquid film spreads over the whole region at 0.06s after the onset of cooling. Since the slab moves rightward, as seen from Figure 5, the liquid film in the left-hand of the stagnation point is thicker than that in the right-hand. Temperature decrease at the stagnation point is small compared with the stationary slab. Figure 5 shows that there are higher temperature regions in the left water film.

Temperature distributions on the moving slab surface are shown in Figure 6. Temperature only in the stagnation region decreases at the initial stage of cooling and then the whole region is cooled down as the water film spreads. The right-hand region has larger temperature decrease compared with the left-hand. This temperature difference for moving velocity of 0.5m/s becomes larger than that for 1.0m/s. In addition, it is found from Figure 6 that the surface temperature at the stagnation point decreases to 560°C at best, while in case of stationary slab it is below 350°C in 0.75s. This means that the heat transfer in moving slab deteriorates compared with the stationary slab.

Figure 7 shows the heat transfer characteristic corresponding to Figure 6. The peak in Nusselt number shifts rightward from the impinging point by the movement of hot slab. After 0.75s the Nusselt number slightly increases with x in right-hand side of stagnation point though its distribution is fairly flat over the entire region. These Nusselt numbers are comparable to those at the both ends of the stationary slab as shown in Figure 4.

To understand the relation between water flow and heat transfer characteristics, horizontal velocity profiles of cooling water at six x-locations are illustrated in Figure 8. The vertical location of y=10 is the slab surface and the velocity there equals the slab moving velocity. The velocity profiles at x=0 and x=25 almost coincide with each other, and likewise those at x=75 and x=100 do as well. The velocities at x=0 and x=25 have negative values for y>10.5 and have its maximum nearly at y=11. The location of x=50 is not a computation node where the horizontal velocity is defined. Therefore, the velocities at both sides of the control volume are plotted in Figure 8. They are designated as x=50(left) and x=50(right). The arrows in Figure 8 indicate vertical locations of water surface

Figure 5  Water flow behavior on hot moving slab at 0.285 sec
(initial temperature: 600°C, water temperature 100°C,
impinging velocity: 0.5m/s, moving velocity of slab: 1m/s)
Moving velocity of slab: 1.0 m/s
Impinging velocity: 0.5 m/s

Figure 6  Temperature distribution on the moving slab surface

Figure 7  Distribution of Nusselt number on the slab surface
Computational Methods in Multiphase Flow

Figure 8  Velocity profile of cooling water

Figure 9  Temperature profile of cooling water and slab
and velocities above the arrows are velocity profiles of gaseous phase.

Figure 9 shows temperature profiles of cooling water and slab, corresponding to Figure 8. The region below $y=10$ is inside of slab and the region above it indicates temperature profile of water film. It is found from the temperature gradients at $y=10$ that the right-hand region of impinging point has steeper temperature gradient and consequently better heat transfer coefficient compared with the left-hand region. In addition, water temperatures for $x=0$ and $x=25$ are higher than those for $x=75$ and $x=100$.

Influence of slab velocity on average velocity of water at the both ends ($x=0$ and 100) is shown in Figure 10. The water velocity plotted is averaged over the thickness of water film. Velocity at left edge decreases with slab velocity, while velocity at right edge increases with slab velocity. Figure 10 shows that both velocities change linearly with slab velocity. Although the water film at left edge is thicker than that at right edge, flow rate exiting from left is smaller than that from right because the velocity at left edge is much smaller than that at right edge. The cooling water is distributed much to right region rather than left and, consequently this is one of the reasons why right region undergoes better cooling.

4 Concluding remarks

Numerical simulation has been performed to investigate cooling process of slit laminar on hot moving slab by means of improved VOF method. Behavior of cooling water, distributions of temperature and Nusselt number were obtained. The results show that the cooling performance of moving slab becomes worse
than that of stationary slab and water film in left region is thicker than that in right region.

**Nomenclature**

- $f_{ps}$: force by surface tension in the form of body force [N/m$^3$]
- $F$: volumetric fraction of liquid [-]
- $u$: velocity in x-direction [m/s]
- $u_{slab}$: slab velocity [m/s]
- $v$: velocity vector [m/s]
- $v_\text{in}$: velocity in y-direction [m/s]
- $v_{in}$: inlet velocity of impinging water [m/s]
- $\tau$: viscous tensor [N/m$^2$]

**Subscripts**

- $G$: gaseous phase
- $L$: liquid phase

**References**


