Finite Element Simulation of the Cooling Process of H-shaped Steel after Circular Nozzle Impinging

Gao Zhiyu\textsuperscript{a}, Xu Jianzhong\textsuperscript{b*}

The State Key Laboratory of Rolling and Automation, Northeastern University, Shenyang, Liaoning, China
\textsuperscript{a}email:572732707@qq.com
\textsuperscript{b}email:xujz@ral.neu.edu.cn

Abstract: ANSYS fluent, a finite element numerical simulation software, was used to establish a three-dimensional model of the H-shaped steel web under the impinging impact of nozzle jet. A numerical stimulation analysis was conducted on the mode of water flow and the heat transfer of the H-shaped steel web. In the model, the finite volume method was used to discretize the model into a tetrahedral unstructured grid, the multi-flow VOF model and the achievable K-e model were used to solve the Reynolds average N-S equation, and the numerical solution method adopted the PISO algorithm. This paper aims to calculate the heat transfer performance of the ultra-fast cooling process of the H-shaped steel web under different boundary conditions, as well as explore the influence of impinging time on the distribution of water volume and temperature fields of the web by simulating the cooling process of H-shaped steel web with circular nozzle jet.

1. Introduction

Jet impinging heat transfer is a highly effective and efficient method of heat transfer enhancement, which means that fluid is jetted through a circular or slit nozzle under the impact of pressure difference to cool or heat the solid wall or liquid surface. In such method, fluid is jetted to the surface of the object to be cooled or heated directly, the process is short and fast, and the heat transfer coefficient of the impacted area is about 10 times higher than that of the conventional method, thus the heat transfer effect is significantly enhanced. Therefore, jet impingement heat transfer is widely used in shaped steel cooling. \cite{1-2}. It is also meaningful to study the flow of the cooling water jet to further improve the product quality. Numerical simulation technology has become an efficient and reliable tool for studying various jet processes due to its high efficiency and convenience. Temperature is a basic factor as well as a key factor, which has a great influence on the quality of H-shaped steels.

Jet impinging heat transfer is a very complicated process, including the shape parameters of the nozzle, the cooling medium, the physical parameters of the medium, the shape of the impacted object, the temperature and surface roughness, the inclination angle of the nozzle, the opening degree, the distribution method and many other factors, all of which will have an impact on the process of jet impinging \cite{3}. Since jet impinging heat transfer has the advantages of high-intensive heat transfer and mass transfer capabilities, it has always been paid special attention by the academic community. Many experts and scholars have done a lot of research on jet impinging, and the research methods are becoming more abundant and the research form is constantly updated. The researches on jet impinging have developed from experiment only to a combination of experiment and theory, from a single nozzle to
multiple nozzles, and from a two-dimensional model to a three-dimensional model, and have achieved many high-value results [4-5].

The heat transfer coefficient of the H-shaped steel in the cooling process is not only affected by the heat transfer process of the cooling water, but also by the water flow state after the cooling water is injected from the nozzles [6].

In this paper, the FLUENT computational fluid dynamics software is used and the basic principle of incompressible fluid flow and the finite element method of fluid-solid-thermal coupling are adopted to stimulate the transient heat transfer of the H-shaped steel web under the impinging impact of the circular nozzle jet. The complicated physical cooling process of H-shaped steel webs is of great significance for improving the mechanical properties of the product and reducing production costs. The water-cooled jet and the temperature field generated on the surface of the steel are the key to the problem. In order to study this complex physical process and master its laws, it is necessary to use finite element, a widely used tool, to simulate and analyze the jet flow process.

2. modelling

2.1. The controlling equation of the model

When the jet flow sprays in the impinging area, it is turbulent flow, and thus its motion satisfies the conservation equations of mass, momentum and energy.

According to the basic equations of fluid mechanics, the continuity equation of the steady viscous fluid can be expressed in the rectangular coordinate system (equation (1)):

$$\frac{\partial (\rho u_x)}{\partial x} + \frac{\partial (\rho u_y)}{\partial y} + \frac{\partial (\rho u_z)}{\partial z} = 0 \quad (1)$$

Where: $\rho$ is the fluid density; $v$ is the flow velocity along the coordinate direction.

Conservation of momentum (equation (2)):

$$\rho \left( \frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} \right) = \rho f_x + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} \quad (2)$$

$$\rho \left( \frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} \right) = \rho f_y + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \tau_{yy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z}$$

$$\rho \left( \frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} \right) = \rho f_z + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z}$$

Where: $\rho$ is the fluid density; $u$ is the displacement along the coordinate direction; $t$ is the time; $f$ is the mass force per unit fluid; $r$ is the surface force per unit area.

Conservation of energy (equation (3)):

$$\frac{\partial (\rho T)}{\partial t} + \frac{\partial (\rho u_x T)}{\partial x} + \frac{\partial (\rho u_y T)}{\partial y} + \frac{\partial (\rho u_z T)}{\partial z} = \frac{\partial}{\partial x} \left( \alpha \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \alpha \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \alpha \frac{\partial T}{\partial z} \right) + S \quad (3)$$

Where: $T$ is the thermodynamic temperature; $\alpha$ is the thermal conductivity of the fluid; $c$ is the specific heat capacity; $S$ is the heat source in the volume.

2.2. Establishment of finite element model

Assuming that the cooling jet flow ejected from the circular nozzle is non-submerged jet flow, the injected cooling medium is normal temperature water, the cooling water flow is incompressible flow, its other physical parameters change with temperature, the jet flow hits onto a smooth surface of an H-shaped steel, and the jet flow sprays at a constant speed. The main geometric parameters of the cylindrical nozzle jet are known, including the nozzle diameter, the height of the jet nozzle from the H-shaped steel web, etc.

The ANSYS/SCDM simulation model used in this paper is shown in Figure 1, which consists of two parts: The H-shaped steel web and the external flow field. For the convenience of calculation, the external flow field is divided into three parts.
The 3D model is established by using the meshing module of ANSYS and is shown in Figure 2:

![Simulation 3D model](image1)

![Jet mesh model](image2)

Fig. 1 Simulation 3D model  Fig. 2 Jet mesh model

2.3. **Boundary conditions and initial conditions**

1. The flow velocity at the nozzle outlet and the water temperature are known, VFRC=1, and the pressure is the standard atmospheric pressure;
2. Wall surface: The H-shaped steel web is a non-slip wall, the speed of each wall is zero, and the initial temperature is the temperature of the H-shaped steel web;
3. Fluid outlet: the relative normal pressure gradient imposed by the outlet boundary is zero;
4. The setting inlet is the velocity inlet, the gravitational acceleration is 9.8 m/s$^2$ in the vertical direction, and the atmospheric pressure $P=1.013 \times 10^5$ Pa.

2.4. **Solution method**

In this paper, the finite element numerical simulation software FLUENT solver is used, the cooling water flow is incompressible fluid flow, the multi-flow VOF model is turned on; the energy equation is turned on; the realizable Kε two-equation model is used for the fluid viscosity model, the non-equilibrium wall function is used for wall surface approximation treatment; velocity-pressure coupling scheme adopts SIMPLE algorithm; pressure interpolation format adopts PRESTO!, both the turbulent flow energy and the turbulent dissipation rate are discretized using the first-order upwind algorithm; the relaxation factor remains the default. By solving the control equations of the impinging jet, the distribution cloud diagrams of the surface temperature and water flow state of the H-shaped steel at different times are obtained.

3. **Result analysis**

The plane that passes through the center of the circular nozzle and is perpendicular to the steel web to be cooled is called the midplane. The volume fraction distribution of water on the midplane is shown in Figure 3. The simulation is a transient simulation. After the jet flow is ejected from the nozzle, the water volume fraction diverges slightly after leaving the nozzle due to the higher jet velocity and that the nozzle is not far from the H-shaped steel web. The jet flow vertically hits to the surface of the H-shaped steel web which is directly below the nozzle outlet, then the water flow diverges around and accumulates thickly at the diverging edge under the impact effect. Then the jet flow slows down sharply, the pressure on the surface of the web increases greatly, and obvious velocity gradient and temperature gradient are formed at the water impinging point, indicating that the heat transfer at the point is highly intensive. In the jet diffusion area, the diffusing rate and temperature of the cooling water decrease obviously, causing the heat transfer in this area to decrease.
Fig. 3 The volume fraction of water in the middle surface

3.1. The effect of jet time on the water volume distribution on the surface of H-shaped steel webs

The conditions of simulating the jet flow to impact on the H-shaped steel web are as follows, the height \((H)\) from the nozzle to the H-shaped steel web is 0.1 m, the temperature \((T)\) of the H-shaped steel web is 1200 K, the radius of the nozzle \((r)\) is 0.004 m, the length of the nozzle \((L)\) is 0.02 m, the water temperature is 30 °C, and the jet velocity \((v)\) is 5 m/s. The distribution of water volume fraction on the web at different moments after the start of the jet is shown in Figure 5. Figure 4 (a), (b), (c) and (d) are the top views of the water volume fraction on the web at the moments of 0 s, 0.1 s, 0.2 s and 0.3 s, respectively. Figure 4 shows the water volume fraction at the point directly under the nozzle outlet is the highest, and that it decreases around this point as the center. However, the volume fractions don’t decrease uniformly, instead, it represents the shape of petals, with an approximately red circular part and golden petal-shaped area with lower volume fraction. In the approximately circular area, the water volume fraction is higher, and its surface area expands rapidly with time. Meanwhile, at the outer edge of this area, the water volume fraction is lower and expands rapidly to the outwards. In the green and blue areas, which means lower water volume fraction, there are also some yellow or close to red islands or cantilever-shaped islands, which means higher water volume fraction.

3.2. The effect of jet time on the surface temperature of H-shaped steel webs

The conditions of simulating the jet flow to impact on the H-shaped steel web are as follows, the height \((H)\) from the nozzle to the H-shaped steel web is 0.1 m, the temperature \((T)\) of the H-shaped steel web is 1200 K, the radius of the nozzle \((r)\) is 0.004 m, the length of the nozzle \((L)\) is 0.02 m, the water temperature is 30 °C, and the jet velocity \((v)\) is 5 m/s. The heat transfer condition and the temperature distribution of the surface of the H-shaped steel web are shown in Figure 5. Under the impact of the jet
flow, a circular low temperature area is formed with the impinging point as a point, and the temperature increase from the center to the outwards. The temperature changes obviously with time. At the outer edge of the circular part, the temperature distribution cloud map also presents a distributive trend. At the outermost edge, the cooling effect decreases, and the temperature of the web also decreases slowly. The temperature fields of the web in the water at different moments are shown in Figure 5.

![Temperature field on the upper surface of web at different times](image)

**Fig. 5** Top view cloud image of temperature field on the upper surface of web at different times (a) 0.1 s; (b) 0.3 s

4. **Experimental verification**

Based on the above research results, an experimental platform for ultra-fast cooling of H-shaped steel is established in this paper, as shown in Figure 6. The experimental system is mainly composed of the following key facilities: a water pump, a regulating valve, a nozzle, experimental work pieces, an experimental platform and an infrared thermal imager.

![Experimental platform and thermal imager](image)

**Fig. 6** Experimental device diagram  
(a) Ultra-rapid cooling experimental platform  
(b) infrared thermal imager

The experimental workpiece adopts the Q235 H-shaped steel web of the same size as the model for ultra-fast cooling test verification. Due to the limitation of the experimental condition that it is difficult to control the cooling water to be opened and closed at any time, the cooling water is turned on all the time, and the water flow is controlled by blocking the impinging position with a baffle, which is regarded as a control switch to control the impinging time of the cooling water on the H-shaped steel web. Thus the experimental error is decreased greatly and the reliability of the experiment is increased.

During the experiment, the H-shaped steel web was heated to 900 °C in a heating furnace, then the web was taken out of the heating furnace and placed on the experimental platform, during which period the temperature dropped to about 760 °C. Afterwards, the baffle was removed to let the cooling water hit the web, and then the baffle was removed back to block the cooling water. The temperature of the H-shaped steel web was photographed with a thermal imager and the thermal imaging result is shown in Figure 7. Limited by the experimental conditions, the thermal imaging result shows the temperature of web after cooling for 2 s. The thermal imaging result shows that under the impinging impact of cooling
water, a low temperature point is formed at the impinging point, the temperature of the web increases outwards from the impinging point in a wave pattern, and the temperature gradient is obvious. According to the thermal image, low temperature points are also formed far away from the impinging point. By contrast, the low temperature points are formed because of the spattering of the cooling water under limited experimental conditions, which make the H-shaped steel web cool locally.

Fig.7 Thermal image of H-beam webs at 2 s

Comparing the experimental results and the simulation results, the temperature change of the H-shaped steel web is basically the same after the cooling water is ejected on the web. The temperature around the impinging point is the lowest, it increases gradually outwards from the point, and there is obvious temperature gradient.

5. Conclusions

The finite element method was used to simulate the cooling process of H-shaped steel web with jet flow, which was ejected from a circular nozzle. The impacts of the impinging time on the temperature and water distribution on the surface of the H-shaped steel web were obtained. In the cooling process, in order to control the splattering of the cooling water and maintain better heat transfer performance, an appropriate water flow rate was necessary. Under the condition of a certain flow rate, the impinging time should be reasonable. The simulation process and the accuracy of the results were verified through experiments, and the results obtained have certain theoretical value and practical significance. This provides more accurate boundary conditions for the simulation of the temperature field and stress-strain field in the subsequent H-shaped steel cooling process, and provides a theoretical basis for optimizing the cooling process and ensuring the quality of the steel web.

Acknowledgments

This work was financially supported by the National Key Research and Development Program of China under Grant No.2017YFB0304204-1.

Reference:
[1] Summerfield S, Fraser D. (2006) A New Heat Transfer Correlation for Impinging Zone Heat Transfer on a Hot Steel Plate[J]. Canadian Metallurgical Quarterly, 45(1):69-78.
[2] Xu F, Gadala M S. (2006) Heat Transfer Behavior in the Impingement Zone under Circular Water Jet[J]. International Journal of Heat and Mass Transfer,49(21-22):3785-3799.
[3] Liu Wj, Cheng Xy. (2020) Simulation study on optimization of high pressure water jet nozzle based on Fluent. China Energy and Environmental Protection, 42(5):14-18.
[4] Jambunathan K, Lai E, Moss M.A, et a1. ( 1992) A review of heat transfer data for single circular jet impingement[J]. Int J Heat Fluid Flow, 13(2): 106-115.
[5] Zhou N, Yu M, Wu D. (2008) Numerical Simulation of Round Nozzle Impinging on Plate Cooling [J]. STEEL ROLLING, 25（2）:7-10.
[6] Lu Sh, Li Xn. (2018) Influence of Ratio of Fluidic Width and Wall Curvature on the Performance of Coanda Ejector[J]. Chinese Hydraulics & Pneumatics,1: 110-115.