Numerical study on the flow characteristics of slot cooling header after rolling

Jianhui Shi1*, Xingang qi2, Ruquan Liang1 and Danhui Zhang1

1School of Mechanical and Vehicle Engineering, Linyi University, Linyi 276000, China
2Fei County Institute of Scientific and Technical Information, Linyi 273400, China
*Corresponding author: Email: shijianhui@lyu.edu.cn

Abstract. In order to study the flow distribution characteristics of the slot cooling header after hot rolling, and the influence of different structure and technological parameters on the flow uniformity of outlet velocity and length direction was obtained. The three-dimensional steady-state numerical simulation analysis of the flow inside the manifold was carried out by FLUENT analysis software. The influences of inlet pressure, shape and structure of intermediate transition cavity were studied respectively. The results show that within the range of 0.1~ 0.5MPa of the inlet pressure, the velocity fluctuation in the direction of the outlet length increases with the increase of the pressure, and the width decreases from the middle of the gap to both sides. The flow velocity at the jet outlet can be increased by changing the angle of outflow tilt of the water supply pipe.

1. Introduction
Jet impingement is a popular technology to improve the heat transfer efficiency at a specific location and is widely used in the field of engineering[1-7]. For example, cooling of micro-electronic components, cooling of gas turbine blades, cooling of steel manufacturing and food processing, etc. In iron and steel manufacturing, green transformation development characterized by "green manufacturing" has become the strategic target of sustainable development of the current steel industry. At present, the high-strength cooling process[8-9] of hot rolled sheet and strip is a key technology affecting the internal structure and mechanical properties of products. It can give full play to the fact that "water is the cheapest alloy element" and realize the production of high-performance steel and iron materials at a lower cost[10].

2. Computing models and meshing
Fig. 1 (a) shows the internal structure diagram of the cooling slot header after rolling. The structure of the cooling header is mainly composed of four parts: 1-main water supply pipe, 2-intermediate transition chamber, 3-damping plate and 4-small nozzle. The main characteristic dimensions of the cooling header after rolling are as follows: the length of the header is the maximum cooling width L. The diameter of the main water supply pipe (Φ 1 and Φ 2). Height of intermediate transition cavity (H1 and H2). Damping plate height (H1 and H2); Diameter of damping hole (d1 and D2). Small nozzle diameter d or slit width W. Fig. 1 (b) shows the numerical calculation area and grid division of the gap cooling manifold. The grid division of the calculation model adopts the free grid division, and according to the free grid division, the grid unit at the gap nozzle is refined.
3. Numerical procedures

3.1. Governing equations

The incompressible flow assumption is adopted for the fluid inside the header. According to the structure and analysis content of the manifold, the three-dimensional steady-state control equation is adopted, and its mass continuity equation is as follows:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

Momentum conservation equation is:

\[
\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right)
\]  

\[
\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right)
\]  

\[
\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right)
\]  

Where, \(u\), \(v\) and \(w\) are the velocities in the \(x\), \(y\) and \(z\) directions respectively; \(\rho\) is the density of the fluid; \(\mu\) is the dynamic viscosity; \(F_x\), \(F_y\) and \(F_z\) are the volumetric forces in the \(x\), \(y\) and \(z\) directions.

3.2. Boundary conditions and initialization

According to the specific structural parameters of super-fast cooling header in hot rolling production line, and by simplifying some components, a three-dimensional computational model of the fluid inside the slot header was established according to the structural characteristics of the fluid inside the header. Because the computational model adopts the three-dimensional model, the boundary condition adopts the plane setting method. The inlet plane of the main water supply pipe of the header is set as the pressure inlet, and the range is 0.1-0.8MPa, and the pressure is evenly distributed. The outlet plane of the small nozzle is set as the pressure outlet, and the pressure setting value relative to the standard atmospheric pressure is zero. The rest of the boundary is set as the boundary of the fluid wall, and all of its velocity components are zero.

4. Simulation results and analysis

According to different technology and cooling characteristics, the set width of outlet gap of the slot header is also different. As shown in Fig. 2, the field measured parameters of the ultra-fast cold slot
nozzle of a 2160mm production line in a certain factory, and the calculated relationship curve between the flow rate of the ultra-fast cold header and the outlet jet velocity under different outlet gap widths. It can be seen from the figure that the efflux velocity range of ultra-fast cold slot header is 0~45m/s.

According to the specific structural parameters of super-fast cooling slot header in hot rolling production line, the three-dimensional calculation model of the fluid inside the slot header was established, which ranged from 0.1 to 0.5Mpa according to different inlet pressures. The length L of the manifold is 1200mm, 1700mm and 2200mm. The diameter of the main water supply pipe $\Phi_1$, its value is respectively 80 mm and 100 mm and 120 mm and 140 mm; The height of the intermediate transition cavity is $H_1$, whose value is 100mm, 150mm and 200mm respectively. The damping plate height is $H_1$, whose value is 100mm, 125mm and 150mm respectively. The diameter $d_1$ of the damping hole is 16mm, 20mm and 24mm, respectively. The width w of the gap is 1.5mm, 2.0mm and 3.0mm, respectively. The flow characteristics of the fluid inside the gap manifold are analyzed, and the change rules of velocity, pressure and medium flow inside the manifold are studied. The specific analysis and research results are as follows.

Figure 2  Relationship between header flow rate and jet outlet velocity at different gap widths

4.1. Influence of inlet pressure on velocity distribution inside the header

The basic structural parameters of the calculation model are as follows: the width of the header is 1700mm. The diameter of the main water supply pipe is 140mm. The height of the intermediate transition cavity is 250mm. There is no additional damping plate inside The width of the outlet gap of the manifold is 3mm. Fig. 3 below shows the velocity vector distribution inside the super-fast cold slot header when the inlet pressure of the main supply pipe is 0.1MPa.

Figure 3  The distribution of the velocity vector in the slot nozzle

It can be seen from the figure that the internal flow velocity of the main water supply pipe decreases gradually from the pressure inlet to the inside. When the water flow from the main water supply pipe enters into the intermediate transition chamber through each shunt hole, the fluid flow velocity of each
shunt hole increases obviously, but the jet flow velocity in each shunt hole is basically the same along the length direction. When the efflux fluid enters the middle cavity, it diffuses due to the larger flow space, and then the velocity of the internal fluid begins to decrease again. From the flow velocity inside the whole header, the flow velocity at the outlet of the slot jet flow of the ultra-fast cold header is the highest, and the uniformity of the jet flow outlet along the width is also good, which is basically around 9m/s.

4.2. Influence of transition cavity structure on flow field inside header

The basic structural parameters of the calculation model are as follows: the width of the header is 1700mm, the diameter of the main water supply pipe is 140mm, the height of the intermediate transition cavity is 250mm, and the width of the gap at the outlet of the header is 3mm. As shown in Fig. 4 below, the total pressure distribution inside the gap manifold under different intermediate transition cavity structures at 0.3MPa is respectively.

![Figure 4](image)

Figure 4 The total pressure distribution curve in the nozzle for different excessive cavity structure

Among 5 kinds of transition cavity structure characteristics, respectively, in the figure (a) as the basic structure of aperture header, the diagram in figure (b) structure on the basis of figure (a) the change of the tap hole of the main water supply pipe flow Angle, figure (c) in the graph structure on the basis of (b) for the middle chamber increases the level of damping plate, the diagram in figure (c) structure level damping plate will be the basis of export groove change to rectangle, round figure (e) in the graph structure on the basis of figure (c) to middle cavity added vertical damping plate. By analyzing and comparing the total pressure distribution inside the manifold of the five different intermediate transition cavity structures, the pressure at the small nozzles of the structures (a) and (b) is higher, which is about 50% of the inlet pressure; figure (d) The pressure at the small nozzles of the structure is followed by about 37 per cent of the inlet pressure; The lower pressure of (c) structure and (e) structure decreases greatly, which is about 20% of the inlet pressure; The above results indicate that the increase of damping plate will attenuate the pressure inside the manifold.

5. Conclusions

1) Within the range of 0.1~ 0.5mpa for the inlet pressure of the slot manifold, the velocity fluctuation in the direction of the jet outlet length increases with the increase of the pressure, and the width decreases from the middle of the gap to both sides.

2) Changing the outflow tilt Angle of the water supply pipe shunt hole can improve the flow velocity at the jet outlet.

3) When the inlet pressure is less than 0.3mpa, the addition of vertical baffle will reduce the turbulent range of jet outlet velocity and improve the uniformity of outlet velocity to some extent.
4) The uniform outlet shape of the long rectangular parallel separator will also reduce the turbulent range of outlet velocity.

Acknowledgments
This work was supported by the Shandong Provincial Natural Science Foundation of China (Grant NO. ZR2018PEE004) and the National Natural Science Foundation of China (Grant NO. 51976087 and 51676031).

References
[1] Lucas A., Simon P., Bourdon G., et al. (2004) Metallurgical aspects of ultra-fast cooling in front of the down-coiler. Steel Research, 75(2):139-146.
[2] Wang G.D. (2009) New generation TMCP and innovative hot rolling process. Journal of Northeastern University: Natural Science, 30(7):913-922.
[3] Wang G., Liu X.H, Sun L.G., et al. (2009) Ultra-fast cooling on Baotou CSP line and Development of 590 MPa Grade C-Mn Low-Cost Hot-Rolled Dual Phase Steel. Journal of Northeastern University: Natural Science, 30(7):913-922.
[4] Park C.J. (2012) Dynamic temperature control with variable heat flux for high strength steel. International Journal of Control Automation and System, 10(3):659-665.
[5] Park C J, Yoon K S, Lee C H. (2010) Advanced temperature control of high carbon steel for hot strip mills [J]. Journal of Mechanical Science and Technology, 24(5):1011-1016.
[6] Yu Q B, Wang Z D, Wang Z Y, et al. (2003) Improvement of the prediction method for strip coiling temperature. Journal of Iron and Steel Research International, 10(4):75-78.
[7] Wang J., Wang G.D., Liu X. H. (2004) Hot strip laminar cooling control model . Journal of Iron and Steel Research International, 11(5):13-17.
[8] Wang G.D. (2008) The new generation TMCP with the key technology of the ultra-fast cooling. Shanghai Metals, 30(2):1-4.
[9] Hiroshi K. (2006) Production and technology of iron and steel in Japan during 2005. ISIJ International, 46(7):939-958.
[10] Simon P, Fishbach J P, Riche P. (1996) Ultra-fast cooling on the run-out table of the hot strip mill. Revue de Metallurgie, 93(3):409-415.