

STUDY ON THE INTERFACIAL HEAT TRANSFER CHARACTERISTICS BETWEEN THE COPPER PLATE AND WATER CHANNELS IN A CONTINUOUS CASTING MOLD

Yazhu ZHANG^a, Huichao LU^a, Jining LI^c, Wenxue WANG^b, Yonghong WANG^b, Jun HUANG^{a*}

^aSchool of Energy and Environment, Inner Mongolia University of Science and Technology, Baotou, 014010, China

^bChina National Heavy Machinery Research Institute Co., Ltd., Xi'an, China, 710018

^cInfrastructure Project Management Branch of Beijing Grainage Group, Beijing, China, 100013

* Corresponding author; E-mail: hjun8420@imust.edu.cn

This study investigates how different cooling water flow velocities affect the cooling performance of copper plates in a water-channel crystallizer. An experimental setup was developed and combined with numerical simulations to analyze the heat transfer and flow behavior of the copper plates. The convective heat transfer coefficient on the water channel wall and the hot-face temperature of the copper plates were quantitatively assessed. Experiments showed that, under a heat flux of 0.2 MW/m² and cooling water flow rates between 5.39 to 9 L/s, the relative errors between the numerical simulation results and the experimental data regarding the average convective heat transfer coefficient are all within the range of 7.5% to 7.8%, each 1 m/s increase in average cooling water velocity raised the convective heat transfer coefficient by 3.21 kW/(m²·K). This confirms that cooling water velocity is a key factor influencing the mold's cooling efficiency. Numerical simulations, conducted under a 1 MW/m² heating flux boundary condition, indicated a similar trend: every 1 m/s increase in water velocity improved the convective heat transfer coefficient by 3.85 kW/(m²·K). The heat transfer coefficient is positively correlated with flow velocity, yet the magnitude of this increase becomes less significant at elevated flow rates compared to lower ones. Additionally, this study establishes a Power function relationship correlation between the Nusselt number (Nu) and the Reynolds number (Re) of the water flow within the channel. These findings offer a theoretical foundation and practical guidance for optimizing the cooling performance of copper plates in continuous casting molds.

Key words: copper plate, water channel, convective heat transfer coefficient, numerical simulation, cooling performance

1. Introduction

The mold is a critical component in the primary cooling stage of the continuous casting process. It solidifies molten steel into a shell, earning its reputation as the "heart" of the continuous casting machine [1, 2]. Its main function is to form an initial solid shell of molten steel and transport the strand

to the secondary cooling zone for further solidification. The quality of this primary shell is significantly influenced by the cooling performance of the mold's copper plates. Therefore, optimizing the heat transfer efficiency of these plates is essential for improving shell quality.

Among the various process parameters that affect the cooling performance of mold copper plates, the flow velocity of cooling water through the channels in the plates is one of the most critical factors. Wang *et al.* [3] demonstrated that increasing water flow velocity in circular cooling channels can effectively improve cooling uniformity, particularly at the corners of copper plates. Zheng *et al.* [4] optimized the slot structure design to enhance heat transfer efficiency, identifying optimal values for slot width, depth, and spacing. Yachikov *et al.* [5] analyzed how casting speed and water flow velocity influence surface temperatures in cooling channels, and proposed structural modifications for wide-face copper plates used in steel plant molds. Zhang *et al.* [6] studied the heat transfer behavior in funnel-type molds with longitudinal parallel-flow layouts, revealing the effects of both cooling water velocity and inlet temperature. Wang, Xu, *et al.* [7-9] investigated heat transfer in composite structures under varying flow conditions to guide the design of more thermally efficient mold cooling systems. Om *et al.* [10] demonstrated that under constant heat flux on the hot face, increasing copper plate thickness elevates temperature extremes while narrowing their difference. Zhang *et al.* [11] developed an efficient speedy multi-grooved (ESMG) mold that increased casting speed from 1.1 to 1.6 m/min and achieved 17.6% higher heat transfer efficiency than conventional molds. Recent studies [12-14] have optimized mold structures and cooling parameters to mitigate thermal stress and defects, thereby enhancing casting quality. Although these studies provide valuable guidance for improving mold cooling performance, many rely heavily on numerical simulations and lack sufficient experimental validation.

This study systematically investigates the heat transfer characteristics of water-joint crystallizers through a combination of experimental and numerical simulation methods. The experimental setup, methodology, and numerical model development process are first described. The reliability of the simulation is validated by comparing experimental and simulated values of convective heat transfer coefficients at a heat flux density of 0.2 MW/m^2 . Building upon this validated model, numerical simulations are conducted at 1 MW/m^2 heat flux density to analyze flow patterns within the copper plate water-joint, along with temperature distributions on the water-joint walls and inside the joint. A quantitative correlation between Nu and Re is established. The findings offer practical guidance for optimizing the water-cooling structure of water-channel crystallizers and provide a theoretical foundation for refining process parameters in actual production.

2. Materials and Methods

2.1. Experimental Setup of Heat transfer

An induction heating device was used to simulate the heat transfer from molten steel to the crystallizer copper plate. A water circulation system was established to replicate the cooling process of a water-cooled crystallizer. Cooling water at a controlled temperature was pumped from a water tank through the copper plate using a pump that maintained constant pressure and flow rate. After absorbing heat from the copper plate, the water was cooled in a heat exchanger and returned to the tank, forming a closed-loop circulation system. Throughout the experiment, K-type thermocouples, liquid-in-glass thermometers and electromagnetic flow meters thermocouples, and flow meters were used to measure the surface temperature of the water-channel wall, the inlet and outlet water temperatures, and the

cooling water flow rate. The thermocouple temperature measurement point is set 14.5 mm above the measured plane. The temperature measurement points of the thermocouple are shown in Figure 1. We used heat-insulating cotton to perform tight heat-insulating treatment on the outer surface of the crystallizer copper plate. The water used meets the requirements for industrial-grade crystallizer water, with relevant values as shown in Table 1 The complete experimental system is illustrated in Figures 2 and 3.

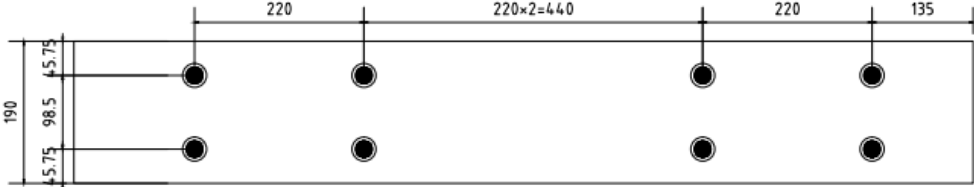


Figure 1. Position diagram of thermocouple temperature measurement

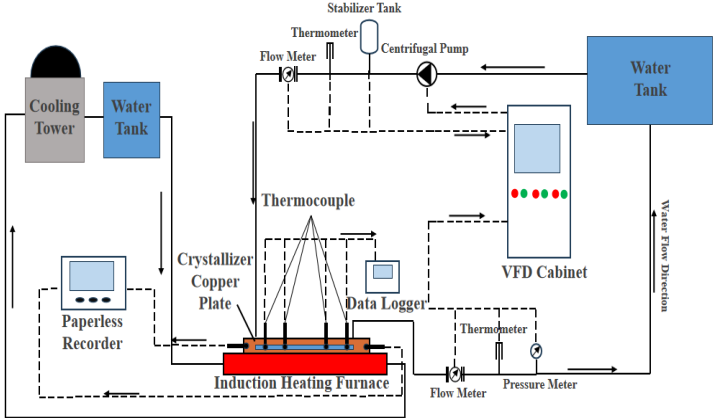


Figure 2. Experimental system setup

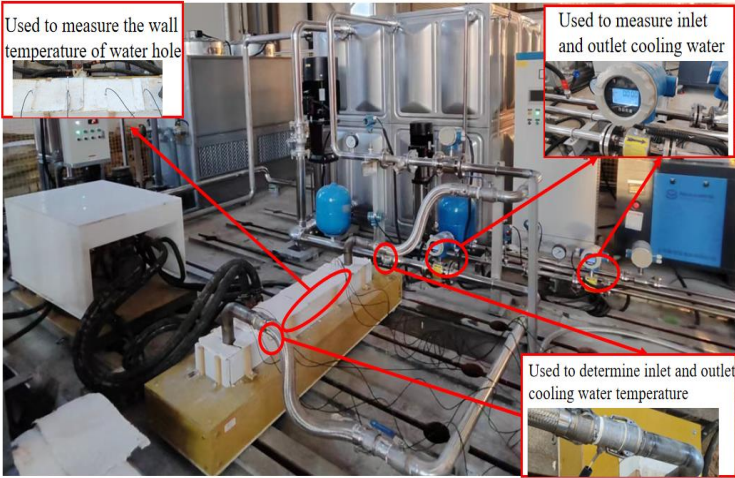


Figure 3. Laboratory setup

Table 1. Parameters of Experimental Water

Parameter	Symbol	Unit	Value
pH Value	pH	-	7.5
Hardness	-	mg/L	< 10
Density	ρ	kg/m ³	998.2
Dynamic Viscosity	μ	Pa·s	1.003×10 ⁻³
Specific Heat Capacity	cp	J/(kg·K)	4182
Thermal Conductivity	λ	W/(m·K)	0.6

2.2. Principle of Heat Transfer

The cooling performance of the water-channel wall in the crystallizer copper plate was evaluated by calculating the average convective heat transfer coefficient (h).

Under steady-state conditions and assuming excellent thermal insulation on the outer surface of the copper plate, the heat absorbed by the cooling water can be described by the energy balance equation:

$$Q = cm(t_2 - t_1) \quad (1)$$

where Q is the heat absorbed by the cooling water (W), c is the specific heat capacity of water at constant pressure (J/(kg·K)), m is the mass flow rate of cooling water (kg/s), t_2 is the outlet temperature of cooling water (K), and t_1 is the inlet temperature of cooling water (K).

Based on the conservation of energy, the heat absorbed by the water equals the heat transferred from the inner wall of the crystallizer copper plate. Thus, the convective heat transfer coefficient (h) is given by:

$$h = \frac{cm(t_2 - t_1)}{A(t_w - t_{av})} \quad (2)$$

where h is the convective heat transfer coefficient (kW/(m²·K)). A is the surface area of the inner wall of the water channel (m²), t_w is the average temperature of the water-channel wall surface (K), and t_{av} is the average temperature of the cooling water (K).

2.3. Experimental Procedure

To investigate the influence of water flow rate on the forced convection heat transfer coefficient in the existing water-channel crystallizer copper plate, the induction heating equipment was set to its maximum nominal power of (520 V, 260 A). It is important to note that this value represents the nominal power input, the induction heating equipment was set to its maximum power. The maximum heat flux on the hot face of the copper plate was then applied. Five different cooling water flow rates were tested. Since the actual heat flux cannot be known in advance—due to the variable heating efficiency of the induction system—it was calculated from the experimental results afterward. The specific heat flux values are listed in Table 2.

Table 2. Experimental scheme for heat transfer in water-channel crystallizer copper plates

Heat flux density of copper plate hot face (kW)	Water channel Average Flow Rate (L/s)	Water channel Average Flow Velocity ($m \cdot s^{-1}$)	Temperature of cooling water at inlet (K)
0.2	5.39	5.56	291.35
	6.33	6.53	292.65
	7.22	7.45	294.15
	8.08	8.34	295.55
	9	9.29	297.15

3. Development of the Physical Model

3.1. Physical Model Formulation

A full-scale (1:1) three-dimensional geometric model of the water-channel crystallizer copper plate was constructed based on the actual dimensions of the physical prototype. The copper plate is made of chromium-zirconium copper (Cr: 1%, Zr: 2%, Cu: 97%) with the code C18150, and the accessories are made of stainless steel with the code AISI 304, No layers on the surface. The prototype and corresponding geometric model are shown in Figures 4 and 5, with detailed structural dimensions provided in Table 3.



Figure 4. Photograph of the physical prototype of the water-channel crystallizer copper plate

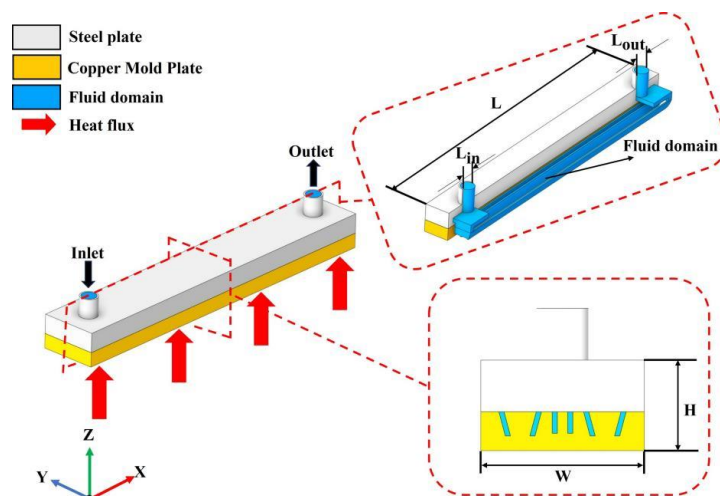


Figure 5. 3D geometric model of the water-channel crystallizer copper plate

Table 3. Geometric parameter comparison of two types of water-channel crystallizer copper plates

Dimension Symbol	Dimension Name	Dimension Parameter (mm)
L	Length of the water-channel crystallizer copper plate	1200
W	Width of the water-channel crystallizer copper plate	190
H	Height of the water-channel crystallizer copper plate	45
L _{in}	Width of the water-channel crystallizer copper plate at the inlet	25
L _{out}	Width of the water-channel crystallizer copper plate at the outlet	25

3.2. Fundamental Assumptions

To simplify the numerical simulation, several assumptions were made during the model development process [15]. These include:

- (1) The heat conduction in the crystallizer is assumed to be three-dimensional and steady-state [16].
- (2) The copper plate is assumed to be isotropic in terms of thermal conductivity.
- (3) The density, viscosity, specific heat capacity, and thermal conductivity of the cooling water are treated as constant.
- (4) Heat loss from the outer surfaces of the copper plate is neglected.

3.3. Governing Equations

3.3.1 Continuity Equation

$$\nabla(\vec{v})=0 \quad (3)$$

where \vec{v} is the fluid velocity vector (m/s).

3.3.2 Momentum Equation

$$\rho(\vec{v} \cdot \nabla \vec{v}) = -\nabla p + \mu \nabla^2 \vec{v} + \rho \vec{g} \quad (4)$$

where μ is the dynamic viscosity (Pa · s), p is the static pressure (Pa), and \vec{g} is the gravitational acceleration (m·s⁻²).

3.3.3 Turbulence Model

The standard $k-\varepsilon$ turbulence model is applied to describe the turbulent flow of cooling water in the water channel.

Turbulent kinetic energy k :

$$\nabla \cdot (\rho \vec{v} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + P_k + P_b - \rho \varepsilon + S_k \quad (5)$$

Turbulent dissipation rate ε :

$$\nabla (\rho \vec{v} \varepsilon) = \nabla \cdot (\mu \cdot \nabla \varepsilon) + C_1 \frac{\varepsilon}{k} (P_k + C_3 P_b) - C_2 \rho \frac{\varepsilon^2}{k} + S_\varepsilon \quad (6)$$

where k is the turbulent kinetic energy (m^2/s^3), ε is the turbulent dissipation rate ($\text{m}^2 \cdot \text{s}^{-3}$), μ_t is the turbulent viscosity ($\text{kg}/(\text{m} \cdot \text{s})$), P_k is the source term due to velocity shear, P_b is the source term due to buoyancy, S_k is the user-defined source term, and $\rho \varepsilon$ is the energy lost due to turbulence. Empirical coefficients include: $C_1=1.44$ $C_2=1.92$ $C_3=0.09$ $\sigma_k=1.0$, and $\sigma_\varepsilon=1.3$ [17].

3.3.4 Energy Equation

$$\text{Solid domain: } \nabla \cdot (\lambda_s \nabla T_s) = 0 \quad (7)$$

$$\text{Fluid domain: } \rho_f C_{p,f} \vec{v} \cdot \nabla (T_f) = \nabla \cdot (\lambda_f \nabla T_f) \quad (8)$$

where λ_s , λ_f are the thermal conductivities of solid and fluid, respectively ($\text{W}/(\text{m} \cdot \text{K})$), ρ_f is the density of fluid (kg/m^3), $C_{p,f}$ is the specific heat capacity of fluid at constant pressure ($\text{J}/(\text{kg} \cdot \text{K})$), T_s , T_f are the temperatures of the fluid and solid, respectively (K).

3.4. Boundary Conditions and Material Properties

In the numerical simulation of the experimental conditions, boundary conditions were applied as follows: the inlet of the crystallizer copper plate was set as a velocity inlet, and the outlet as a pressure outlet. The inlet temperature of the cooling water was assigned based on experimental measurements, and the flow rate was determined from experimental operating conditions. The outlet pressure was set to 0 Pa. An average heat flux of $0.2 \text{ MW}/\text{m}^2$ was applied to the hot face of the copper plate. Due to the excellent thermal insulation observed in experiments, the outer surface of the copper plate was modeled as an adiabatic (i.e., no heat loss).

In actual continuous casting processes, the average heat flux on the hot surface of the copper plate typically exceeds $1 \text{ MW}/\text{m}^2$ [18-20]. Therefore, in subsequent simulations, a uniform heat flux of $1 \text{ MW}/\text{m}^2$ was applied to the hot surface under different cooling water flow rates. The inlet cooling water temperature was set at 300 K, and the flow velocity was adjusted between 2.83 and 5.66 m/s, corresponding to flow rates of 5.56 – 11.11 L/s. The outlet pressure remained at 0 Pa, and the outer surface continued to be treated as adiabatic.

Simulation results showed that the maximum temperature of the copper plate stayed below 500 K, and that of the steel plate was even lower. The cooling water temperature remained under 330 K. For copper below 500 K, thermal conductivity decreased by approximately $10 \text{ W}/(\text{m} \cdot \text{K})$ per 100 K, with minimal change in specific heat capacity. For steel below 500 K, thermal conductivity decreased by $5 \text{ W}/(\text{m} \cdot \text{K})$ per 100 K, with only a small change in specific heat capacity. For cooling water below 330 K, thermal conductivity increased by $0.085 \text{ W}/(\text{m} \cdot \text{K})$ per 50 K, while specific heat capacity decreased by

12 J/(kg·K), density reduced by 16.6 kg/m³, and viscosity decreased by 0.8 × 10⁻³ Pa·s. The material properties at room temperature are listed in Table 4.

Table 4. Material property parameters

Parameters	Value	Parameters	Value
Copper Plate Thermal Conductivity /[W·(m·K) ⁻¹]	387.6	Cooling Water Specific Heat Capacity /[J·(kg·K) ⁻¹]	4182
Copper Plate Specific Heat Capacity /[J·(kg·K) ⁻¹]	381	Cooling Water Density /[kg·m ⁻³]	998.2
Steel Plate Thermal Conductivity /[W·(m·K) ⁻¹]	54	Cooling Water Viscosity /[Pa·s]	1.003×10 ⁻³
Steel Plate Specific Heat Capacity /[J·(kg·K) ⁻¹]	450	Cooling Water Thermal Conductivity /[W·(m·K) ⁻¹]	0.6

3.5. Parameter Definitions

To simplify the analysis, all water channels in the crystallizer copper plate are treated as one large water channel, with a combined hydraulic diameter defined as:

$$D_h = 2\sqrt{\frac{4A_1 + 2A_2}{\pi}} \quad (9)$$

where A_1 is the cross-sectional area of the water hole with diameter D_1 , m² and A_2 is the cross-sectional area of the water hole with diameter D_2 , m².

Reynolds Number (Re):

$$Re = \frac{\rho_f V_{avg} D_h}{\mu} \quad (10)$$

where ρ_f is the fluid density (kg/m³), V_{avg} is the average flow velocity (m/s), and μ is the dynamic viscosity (Pa·s).

Drag Coefficient (f):

$$f = \frac{2D_h \Delta P}{\rho_f V_{avg}^2 L_3} \quad (11)$$

where ΔP is the pressure drop between the inlet and outlet (Pa) and L_3 is the baffle rod length (mm).

Nusselt Number (Nu):

$$Nu = \frac{hD_h}{\lambda_f} \quad (12)$$

where λ_f is the thermal conductivity of the cooling water (W/(m·K)).

3.6. Simulation Setup and Solution Parameters

Numerical simulations were carried out using ANSYS, applying a fluid-solid coupling method to analyze the steady-state temperature distribution in the crystallizer copper plate and the temperature,

pressure, and velocity fields of the cooling water [21]. The SIMPLE algorithm was used for pressure-velocity coupling, and a second-order upwind scheme was applied for discretizing the momentum, turbulent, and energy equations. The numerical simulations were conducted on a desktop workstation running Windows 11 (64-bit). The system was equipped with a 12th Gen Intel Core i5-12500 processor (3.00 GHz, 6 cores) and 16 GB of RAM. All simulations were performed using ANSYS Fluent 2023 R1. The simulation may take 1 to 10 hours (depending on the server configuration). The global initial temperature was set to 298.15 K, the heat flux is set to 1 MW/m² and the cooling water inlet velocity was set to 4.95 m/s. To ensure solution accuracy, the convergence criterion for the energy equation was set to 1×10⁻⁶, while other equations used a tolerance of 1×10⁻³.

Thermal transfer at the fluid-solid interface was fully considered [22]. A mesh independence study was conducted, confirming the reliability of the results. The final mesh count for the crystallizer copper plate (with and without baffle rods) was approximately 3.34 million elements.

3.7. Generation of the Mesh

Polyhedral grids were used for mesh generation. To ensure accurate heat transfer simulation at the fluid-solid interface, a mesh independence study was conducted. The simulation primarily focused on fluid flow and heat transfer behavior, so the average Nusselt number of the cooling water was used as the reference metric. Under controlled conditions (flow rate of 5.56 L/s with all other parameters fixed), the mesh was progressively refined. The final mesh count for the crystallizer copper plates with and without baffle rods reached approximately 4.9 million cells. The relative error between consecutive refinements was kept below 3%, ensuring grid independence. The grid partitioning and computational domain are illustrated in Figure 6, while the grid independence verification is shown in Figure 7.

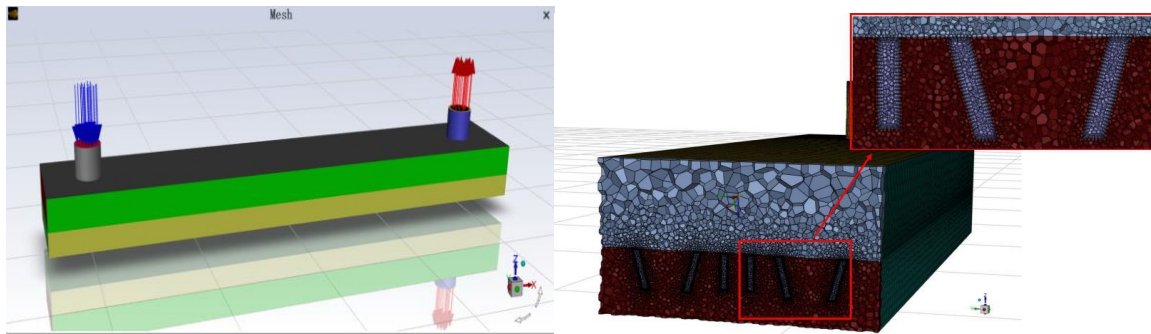


Figure 6. Grid partitioning of the water-channel-type crystallizer copper plate (left) and computational field(right)

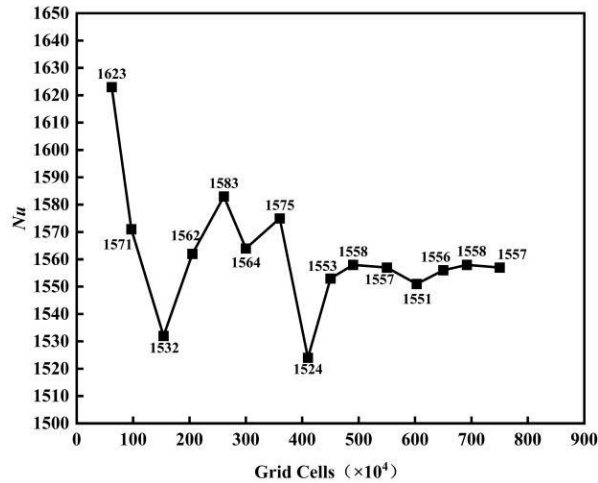


Figure 7. Grid independence verification

4. Experimental Results

4.1. Reliability Verification

An induction heating device was used to heat the crystallizer copper plate, simulating the heat transfer from molten steel. Due to the power rating constraints of the induction heating apparatus, the maximum heat flux density that the device can supply to the hot surface of the crystallizer copper plate was limited to 0.2 MW/m^2 .

To verify the accuracy of the numerical simulation, the convective heat transfer coefficient of the water channel in the crystallizer copper plate was used as a benchmark. The experimental results were then compared with the simulation results. Figure 8 shows a comparison of the experimental and simulated values of the convective heat transfer coefficient under five different flow conditions. In the actual simulation, the heat loss of the copper plate is ignored, so there is a difference between the experimental value and the simulated value. However, the relative error of the experimental value and the simulated value is less than 10% in all cases, which fully proves that the simulation method is highly reliable.

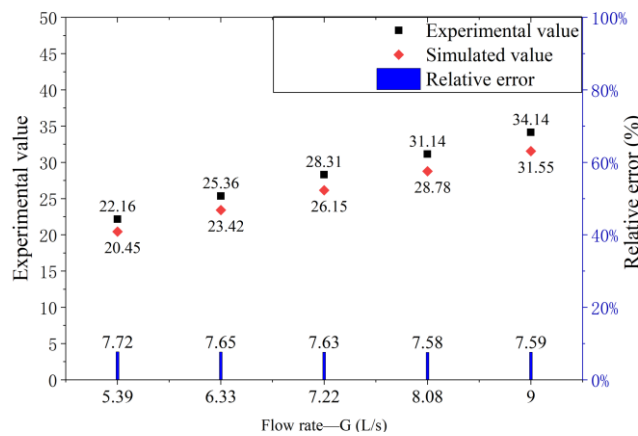


Figure 8. Comparison between experimental values and simulated values of convective heat transfer coefficient

4.2. Effect of Cooling Water Flow Rate on Heat Transfer Performance

Figure 9 presents the experimental results for the average convective heat transfer coefficient on the water channel wall surface of the crystallizer copper plate under five different cooling water flow rates. When the heat flux is 0.2 MW/m^2 and the flow rate ranges from 5.39 to 9 L/s, the convective heat transfer coefficient varies from 22.16 to $34.14 \text{ kW}/(\text{m}^2 \cdot \text{K})$. For every 1 m/s increase in flow velocity, the heat transfer coefficient increases by approximately $3.21 \text{ kW}/(\text{m}^2 \cdot \text{K})$. This indicates that the cooling water velocity plays a key role in determining the cooling and heat transfer efficiency of the crystallizer copper plate.

Due to the limitations of the laboratory induction heating system, the maximum average heat flux applied to the heated surface is restricted to 0.2 MW/m^2 , tests could not be conducted under a heat flux condition of 1 MW/m^2 . However, given the proven accuracy of the simulation, the heat transfer behavior at this higher heat flux condition was analyzed using numerical methods (finite volume method).

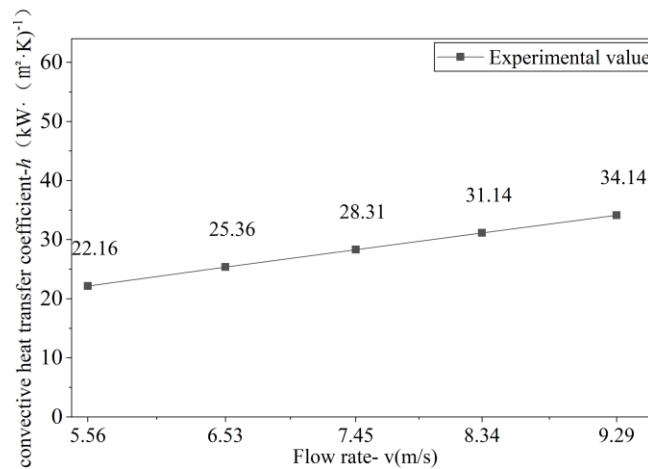


Figure 9. Experimental results of the convective heat transfer coefficient on the water-channel wall surface

5. Numerical Results

In actual continuous casting processes, the average heat flux density on the hot surface of the crystallizer copper plate typically exceeds 1 MW/m^2 . However, due to limitations in experimental equipment, the induction heating device can only provide a maximum heat flux of 0.2 MW/m^2 . Therefore, the following numerical simulation results were obtained under a uniform heat flux density of 1 MW/m^2 on the hot surface of the crystallizer copper plate, with the cooling water flow rate G ranging from 5.56 L/s to 11.11 L/s.

5.1. Flow Field in the Water channel

Due to the multiple cooling water flow rate conditions and the left-right symmetry of the crystallizer copper plate structure, this section analyzes the flow and temperature fields for three water channels on one side of the plate, under a cooling water flow rate of $G = 8.33 \text{ L/s}$.

Figure 10 shows the velocity vector distribution of the three water channels on one side of the crystallizer copper plate at the range $X = 550 - 650 \text{ mm}$. The figure indicates a significant velocity gradient near the water channel walls, resulting from the combined effects of inertial and viscous forces.

The flow velocity is lower near the walls and higher in the central region. Among the three channels, the flow velocity is highest in the straight water channel compared to the two inclined channels. In the central area of the water channels, the flow velocity is relatively uniform and exceeds 9 m/s. Specifically, the straight water channel reaches up to 9.8 m/s, while the two inclined channels reach 9.4 m/s and 9.2 m/s, respectively. Near the channel walls, the flow slows due to viscous drag—down to 5.8 m/s in the straight channel, and 5.2 m/s and 5.0 m/s in the inclined channels. Overall, the closer the channel is to the center of the crystallizer copper plate, the faster the internal cooling water velocity.

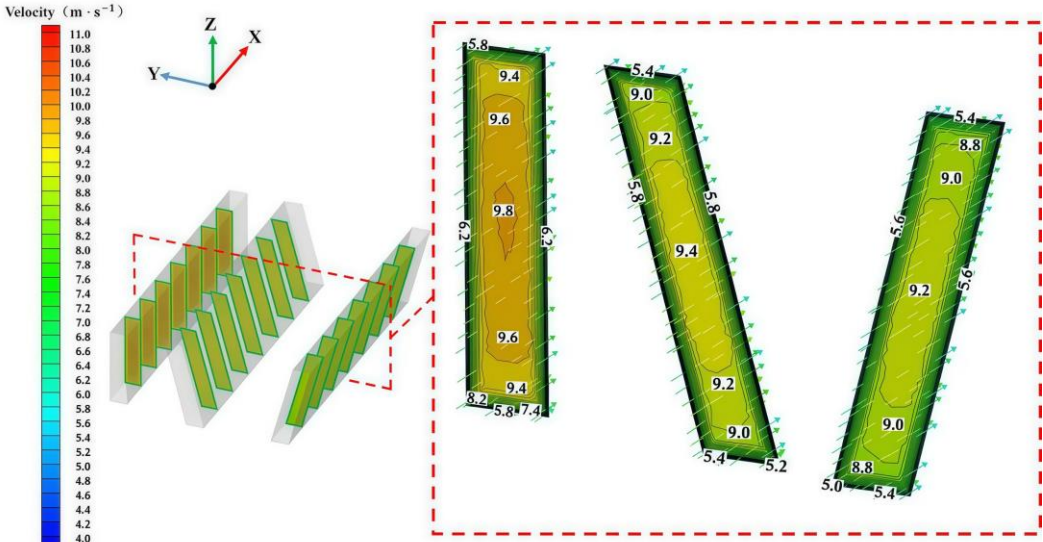


Figure 10. Velocity distribution on the copper plate side of the water-channel mold at X = 550 - 650 mm when G = 8.33 L/s

Figure 11 presents the flow resistance characteristics within the crystallizer copper plate under different cooling water flow rates. In all cases, the Reynolds numbers (Re) exceed 10^5 , indicating fully developed turbulent flow. In addition, the resistance coefficient decreases with increasing Re , primarily due to intensified turbulence, a more uniform velocity profile, reduced velocity gradients near the wall, and lower wall shear stress—all contributing to reduced flow resistance.

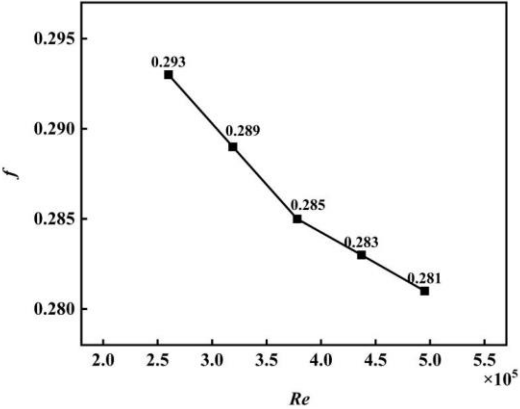


Figure 11. Flow resistance characteristics within the water channels under varying cooling water flow rates

5.2. Temperature Field inside the Water channel and on the Hot Surface of the Crystallizer Copper Plate

Figure 12 shows the temperature distribution of the three water channels on one side of the water-channel-type crystallizer copper plate in the region $X = 550 - 650$ mm. Due to the imposed uniform heat flux boundary condition on the bottom surface, heat is conducted upward (in the positive Z -direction) from the hot surface of the crystallizer copper plate. Since the heat source originates from the bottom hot face, a vertical thermal gradient is established, causing the fluid layer adjacent to the lower wall to absorb heat first and exhibit higher temperatures. The path that the heat has to transfer from bottom to up surface is longer in oblique seam than that in the vertical seam. The vertical seam is short and heat is transfer more quickly, and less heat is accumulated at the bottom edge. Overall, the cooling water in the oblique water channel located near the edge of the plate shows higher temperatures compared to the central straight and oblique channels. This indicates that the cooling effect is more efficient at the center of the crystallizer copper plate than at the edges.

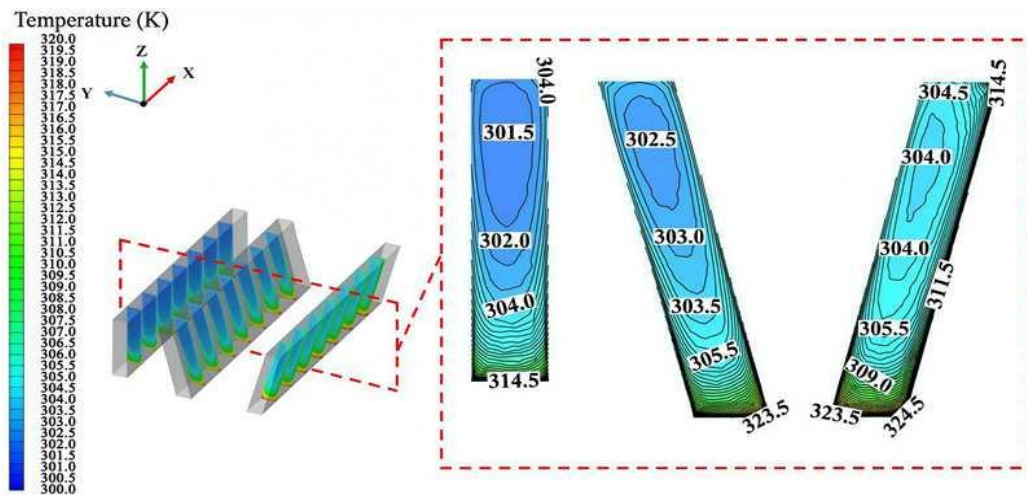
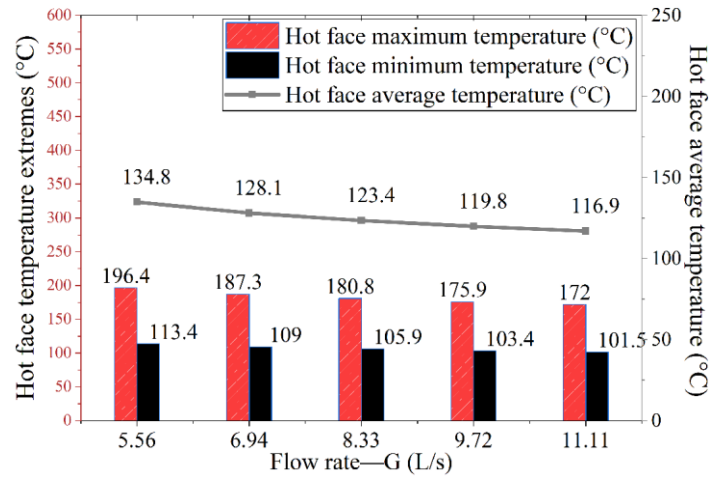
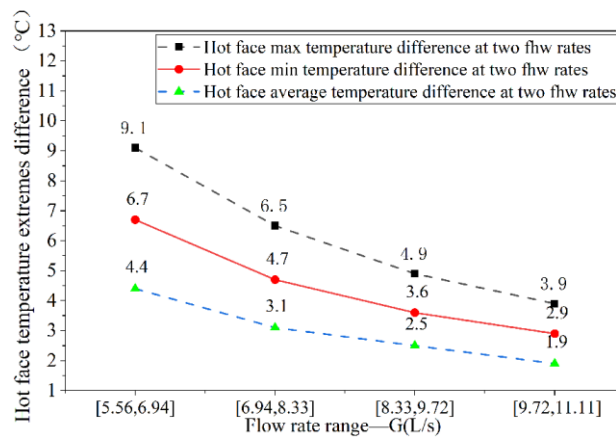


Figure 12. Temperature distribution in the three water channels on one side at $X = 550 - 650$ mm when $G = 8.33$ L/s

Figure 13 further details the effect of flow rate on the hot surface temperature. As the flow rate increases from 5.56 L/s to 11.11 L/s (corresponding to water velocity of 5.56 m/s to 9.29 m/s), and before installing any baffle rods, the following changes occur: (i) maximum temperature drops from 469.55 K to 445.15 K; (ii) minimum temperature drops from 386.55 K to 374.65 K; (iii) average surface temperature drops from 407.95 K to 390.05 K. On average, for every 1 m/s increase in water velocity: the maximum temperature decreases by 6.5 K, the minimum temperature decreases by 3.2 K, and the average temperature decreases by 4.8 K. These results indicate that while increasing the flow rate enhances cooling, the temperature differences (between maximum, minimum, and average) become smaller at higher velocities. This trend suggests that the cooling effect gradually plateaus.



(a)



(b)

Figure 13. Temperature variations on the hot surface under different cooling water flow rates: (a) surface temperature profiles, (b) temperature differences among surface parameters

Figure 14 shows the average Nusselt number (Nu) at the water channel wall under different cooling water flow rates. The Nusselt number, representing the dimensionless temperature gradient at the wall, increases with rising Reynolds number (Re). This indicates that higher flow velocities intensify the temperature gradient near the wall, thereby enhancing fluid mixing and improving heat transfer efficiency between the water and the copper plate.

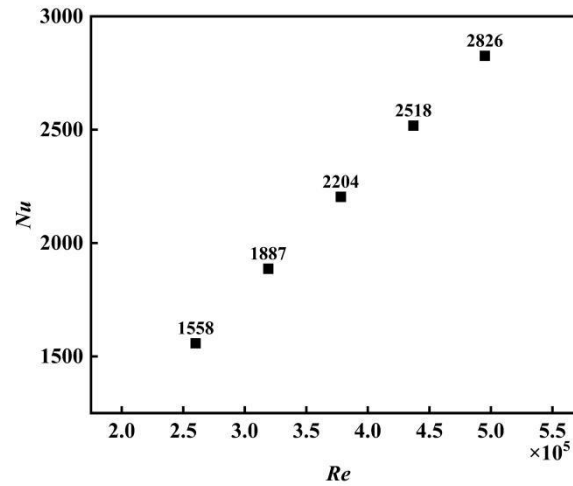


Figure 14. Average Nusselt number at water channel wall surface

To further explore the convective heat transfer mechanism and the relationship between Nu and Re , a correlation was derived based on simulation results at a constant heat flux of 1 MW/m^2 .

In the water channels, the flow is characterized by high-Reynolds-number turbulence, where inertial forces dominate and the effects of viscosity and thermal conductivity are secondary. Under such conditions, the influence of the Prandtl number (Pr) on Nu becomes negligible. Therefore, a fixed Pr value of 0.863—corresponding to the thermophysical properties of water at 300 K—is used and incorporated into the correlation constant. The resulting fitted curve is shown in Figure 15.

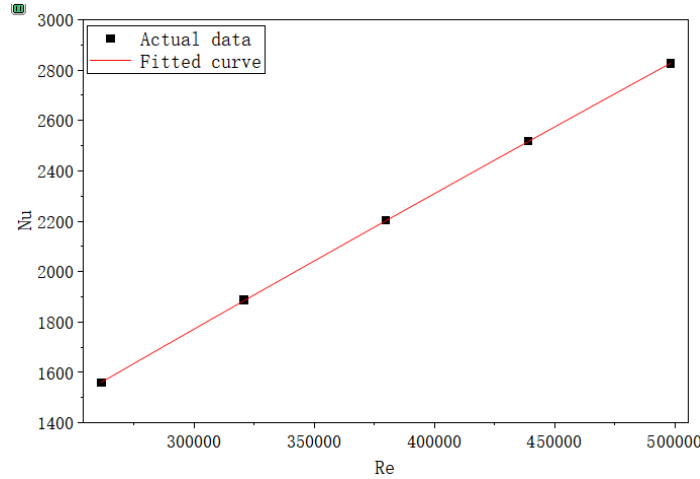


Figure 15. Fitted Nu - Re correlation curve

The resulting empirical correlation is:

$$Nu = 0.0156 Re^{0.9232} \quad (13)$$

5.3. Convective Heat Transfer Coefficient on the Water-channel Wall Surface of the Crystallizer Copper Plate

Figure 16 shows the average convective heat transfer coefficient at the water-channel wall surface of the crystallizer copper plate. Under a constant heat flux of 1 MW/m² on the hot surface and a cooling water flow rate ranging from 5.56 to 11.11 L/s (corresponding to an average flow velocity of 5.56-9.29 m/s), the convective heat transfer coefficient ranges from 27.52 to 49.57 kW/(m² • K). On average, for every 1 m/s increase in cooling water velocity, the convective heat transfer coefficient increases by approximately 3.85 kW/(m² • K). This confirms that increasing the cooling water flow velocity significantly enhances the convective heat transfer performance.

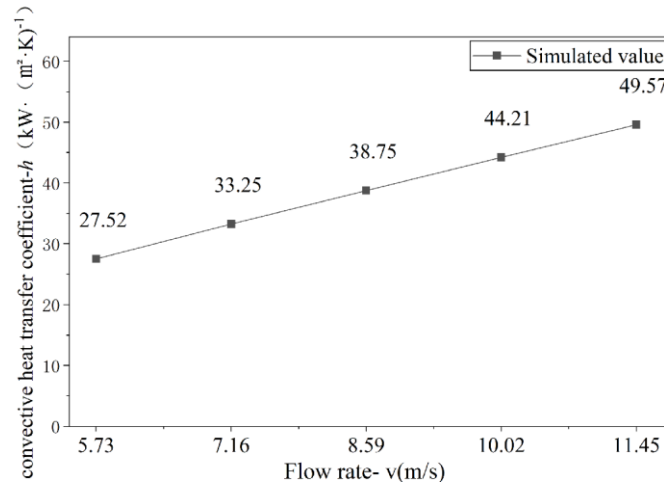


Figure 16. Average convective heat transfer coefficient on the water-channel wall surface

6. Conclusions

(1) Under various flow rates/velocities in the water channel, the relative error between the experimental and simulated values of the average convective heat transfer coefficient of the mold copper plate is always in the range of 7.5% to 7.8%, both of which are lower than 10%, validating the reliability of the numerical simulation method.

(2) Experimental results show that under an average heat flux of 0.2 MW/m² and a cooling water flow rate between 5.39 to 9 L/s, the convective heat transfer coefficient increases by approximately 3.21 kW/(m² • K) for every 1 m/s increase in cooling water velocity. This confirms that cooling water velocity is a key factor in determining the cooling effectiveness of the crystallizer copper plate.

(3) Numerical simulations indicate that under an average heat flux of 1 MW/m² and a cooling water flow rate between 5.56 to 11.11 L/s, the convective heat transfer coefficient increases by approximately 3.85 kW/(m² • K) for every 1 m/s increase in cooling water velocity. However, the effectiveness of increasing cooling water velocity to enhance the cooling performance of the mold copper plate is limited.

(4) The Nusselt number (Nu) correlation derived from the numerical simulation under a heat flux of 1 MW/m² is expressed as: $Nu = 0.0156 Re^{0.9232}$.

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Nomenclature

Symbol	Description	Unit
C_p	Specific heat capacity	J/(kg·K)
\vec{g}	gravitational acceleration	m·s ⁻²
k	Turbulent kinetic energy	m ² /s ²
Nu	Nusselt number	–
p	static pressure	Pa
Pr	Prandtl number	–
Q	Heat source term	W/m ³
q	Heat flux density	W/m ²
Re	Reynolds number	–
T	Temperature	K
t	Time	s
V	Average flow velocity	m/s
ε	turbulent dissipation rate	m ² ·s ⁻³
λ	thermal conductivities	W/(m·K)
μ	dynamic viscosity	Pa · s
ρ	density	kg/m ³

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