Sustainable Development Research; Vol. 7, No. 4; 2025
ISSN 2690-9898 E-ISSN 2690-9901
https://doi.org/10.30560/sdr.v7n4p73

Influence of Outer Zone Water Distribution Density on Anti-Freezing Performance of Cooling Towers

Haijun Wang[1], Zhonggui Guo[1], Hongwei Wang[1], Chiyuan Ma[1], Jiangang Xiao[1], Bin Yu[2], Yunsong Du[2] & Luozhong Li[2]

[1] Inner Mongolia GuohuaJungar Power Generation Co., Ltd., Inner Mongolia, China

[2] Changzhou Jintan Plastic Factory, Changzhou, China

Correspondence: Haijun Wang, Xuejiawan Town Jungar Banner, Ordos 010300 Inner Mongolia, China. Tel: 86-1-774-771-1106. E-mail:16080334@ceic.com

Received: July 24, 2025 Accepted: November 22, 2025 Online Published: November 26, 2025

Abstract

This research mechanistically probes boundary-layer flow distribution effects on freeze-risk mitigation in cooling towers via FLUENT-based CFD simulations for a 300MW coal-fired unit. Thermodynamic analysis of effluent temperatures across varying loads (50%/75%/100%) and circulating flow rates confirms that modulating water spray density effectively enhances freeze resistance. Critically, maintaining 11.26 kg/(m²·s) at full load ensures temperatures ≥15°C,inhibiting extensive ice formation. These findings establish a viable operational strategy for cold-region power plants.

Keywords: cooling towers, water distribution density, peripheral distribution, freeze protection

1. Introduction

Natural draft hyperbolic counterflow cooling towers, widely used in power plant circulating water systems, frequently experience icing during winter operation in cold regions due to subfreezing temperatures. Severe ice accumulation can cause concrete spalling on diagonal support columns (exposing reinforcement steel) or tear away fill media, compromising structural integrity. Consequently, implementing freeze protection measures is critical to ensuring the cooling tower's safe, stable, efficient, and economical operation (Song. 1996).

Based on the thermal equilibrium principle in the cooling process, the heat dissipated by circulating water equals the heat absorbed and carried away by incoming air. To meet economic operation requirements, the circulating water flow in winter is typically maintained at approximately 60% of the design flow rate. This reduced flow decreases water distribution density, forming an ultra-thin water film on the fill media that lowers ventilation resistance and increases air volume. Consequently, under cold winter air exposure, the circulating water undergoes rapid cooling, resulting in ice formation near the air inlets of cooling towers—a phenomenon that may cause structural hazards (Bi et al., 2002).

Adjusting water distribution patterns in outer zones by regulating spray density provides a key methodology for upgrading cooling tower anti-freezing performance. Different water distribution schemes in inner/outer zones were compared, demonstrating that high-density water distribution in outer zones reduces cooling tower airflow while elevating water temperature, consequently significantly mitigating icing risks in the air intake zone (Yuan et al., 2025).An anti-freezing solution for cooling towers was developed through synergistic integration of outer zone spray density regulation and drift eliminator angle optimization, elevating temperatures in icing-prone zones by 3–5°C (Zhang et al., 2025).The impact of spray density on anti-freezing capability was investigated, revealing that maintaining outer zone spray density ≥1.5 kg/(m²·s) ensures water temperature remains >2°C at the packing base, thereby effectively suppressing ice formation (Wang et al., 2024).It was demonstrated that elevating outer zone spray density to 1.3 times the design value enhances rain zone temperature uniformity by 18%, effectively mitigating localized overcooling phenomena (Yang et al., 2025).

Numerical simulation serves as a proven effective approach for investigating anti-freezing in cooling towers. A 3D numerical model under constant heat load was established, revealing that allocating 60% of water flow to outer zones optimizes airflow uniformity, reducing air inlet velocity by 27% and restricting cold air intrusion (Wang et al., 2024).Non-uniform exit-water temperature profiles in dry cooling towers were experimentally identified as inducing localized radiator icing, while outer zone water distribution improved temperature uniformity by elevating the coldest point by 4.2°C (Li et al., 2019).Louver angles and water distribution strategies were optimized, maintaining stable system ventilation at -15°C while reducing anti-freezing energy consumption by 8.7% (Wei et al., 2019).

Dynamic control enhance the effectiveness of outer zone water distribution. A dynamic monitoring system for closed cooling towers was developed, which adjusts spray density and activates electric tracing within 5 seconds by detecting real-time outer zone water temperature and flow rates (Liu et al., 2023).A steam-traced preheating network for outer-zone pipelines was engineered, ensuring initial spray temperatures >5°C to prevent icing during cold starts (Jin et al., 2022).Windbreak panels were integrated with outer zone water distribution systems for 600 MW units to assess anti-freezing and wind resistance efficiency (Yang et al., 2023).Adjustable air deflectors coupled with outer zone distribution were demonstrated to balance ventilation and anti-freezing demands, lowering winter operation energy consumption by 14% (Yang et al., 2021).

Current research focuses on three synergistic domains: intelligent system integration, partitioned water distribution optimization andspray density regulation. These collectively boost anti-freezing capability through enhanced outer-zone thermal homogeneity, cold-air infiltration suppression, and dynamic frost-risk mitigation. However, mechanistic analysis of how spray density dynamics dictate anti-freezing efficacy remains underdeveloped, constituting a critical barrier to winter-operational optimization.

2. Project Description

The cooling facility employs a natural draft cooling tower with the following specifications:

Water Drenching Area: 4,500 m² per tower

Tower Top Elevation: 102.6 m

Inlet Air Height：7.185m

Bottom Shell Diameter：76.8m

Datum Plane Diameter (at 0m EL)：87.646m

Throat Height：76.6m

Throat Diameter：45.67m

Outlet Diameter：51.94m

Fill Pack Specifications: 1,500 mm (L) × 500 mm (W) × 500 mm (H)

Total Fill Volume: 4,500 m³

The water distribution system is seasonally adjusted. Key operational parameters include:

Summer Design Maximum Circulating Water Flow: 9.94 m³/s

Average Water Spray density: 7.96 m³/(s·m²)

For winter anti-freezing analysis, calculations are based on winter-average weather conditions (Table 1) to ensure the outlet water temperature remains ≥15°C.

Table 1. Related Value for Atmosphere Conditions

Dry-Bulb Temperature(°C)	Relative Humidity	Atmospheric Pressure(hPa)	Circulating Water Flow Rate(t/h)	Temperature Approach(°C)
-6.1	0.59	903	35928	9.38
-6.1	0.59	903	30528	11.04
-6.1	0.59	903	21564	15.63
-6.1	0.59	903	35928	7.04
-6.1	0.59	903	30528	8.28
-6.1	0.59	903	21564	11.72
-6.1	0.59	903	35928	4.69
-6.1	0.59	903	30528	5.52
-6.1	0.59	903	21564	7.82

3. Mathematical Model and Calculation Method

The atmosphere condition and the quantity of circulating water all keep unchanged; the steady three dimensions model can be used for the analysis of the flow around the natural draft cooling tower.

3.1 Air Flow Field Governing Equation

As the unit load, the atmosphere condition and the quantity of circulating water all keep unchanged; the steady three dimensions model can be used for the analysis of the flow around the natural draft cooling tower. The governing equation can be expressed as follows.

$$\frac{\partial(\rho\Phi)}{\partial t} + \nabla \cdot (\rho\vec{v}\phi) = \nabla \cdot \Gamma_\phi \nabla\phi + S_\phi \quad (1)$$

In these equations, ρ is the gas density (kg/m3), $\vec{V}$ is the velocity vector (m/s). The variables ϕ, diffusion coefficient term Γ_ϕ, and source term S for each governing equation are shown in Table 1 (Li et al,2013).

Table 1. Model constant

Governing equation	Continuity equation	Momentum equation	κ-equation	ε-equation
ϕ	1	u, v, ω	κ	ε
Γ_ϕ	0	$\mu + \mu_t$	$\mu + \mu_t/\sigma_k$	$\mu + \mu_t/\sigma_\varepsilon$
S_ϕ	0	$-\frac{\partial p}{\partial x_i}$	$G_k - \rho\varepsilon$	$\frac{C_1 G_k \varepsilon - C_2 \rho\varepsilon^2}{\kappa}$

3.2 Resistance Models

There are two kinds of resistance models, one is used to analyze the fill zone resistance, the other is used to analyze the rain zone resistance. The fill zone employs a porous media model, while the rain zone adopts the Discrete Phase Model (DPM).

3.3 Heat And Mass Transfer Model

The Merkel model was used to analyze the heat and mass transfer process in the fill zone and the rain zone.

Relevant equations and model constants are detailed in references (Zhao et al, 2017).

3.4 Boundary Conditions

The computational domain was partitioned into two distinct zones: the interior space enclosed by the cooling tower structure and the external atmospheric environment surrounding it. For the outside region, the bottom was adiabatic boundary, the other sides of the border was the pressure outlet boundary. The wall of the tower shell was defined as adiabatic boundary. By using UDF, K and ε boundaries could be given:

$$\frac{\partial K}{\partial n} = 0, \quad \frac{\partial \varepsilon}{\partial n} = 0 \quad (2)$$

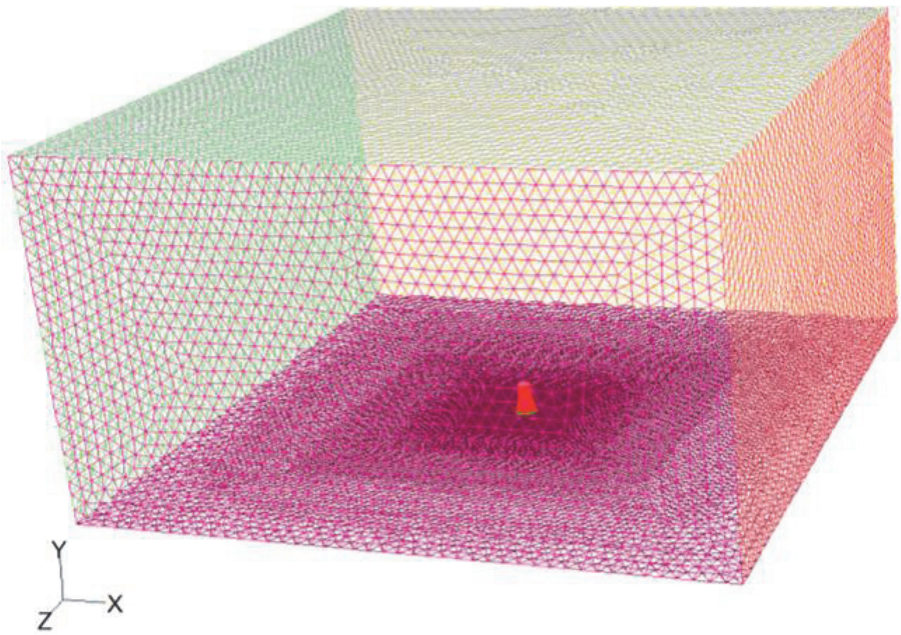
Where n was the normal to the boundary surface.

4. Calculation and Analysis

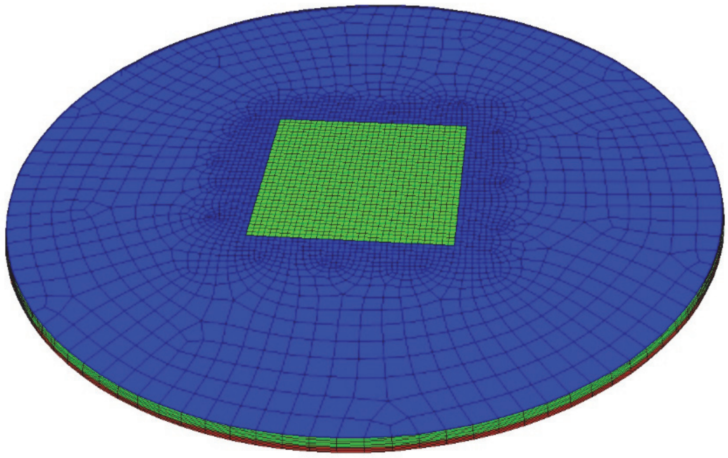
4.1 Modeling And Meshing

Based on the cooling tower with a water drenching area of 4500 m² in this study, a three-dimensional model comprising approximately 2.2 million mesh elements was developed. The computational domain dimensions of 600 m × 600 m × 600 m are shown in Figure 1. Environmental parameters under standard operating conditions were configured in the simulation. The pressure-velocity coupling algorithm and second-order upwind discretization scheme were employed, with all residuals converging below 10^{-6} to ensure computational accuracy.

(a) The cooling tower mesh



(b) The overall mesh



(c) The fill zone mesh

Figure 1. The global graph of the computing grid

The characteristics of the fill employed in this simulation are mathematically defined by Equations (3) and (4), quantifying its heat transfer efficiency and aerodynamic resistance, respectively.

$$N = 1.812\lambda^{0.667} \tag{3}$$

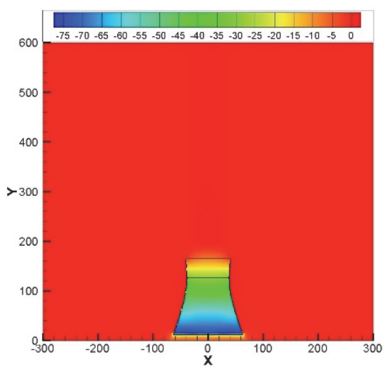
$$\frac{\Delta P}{\gamma_a} = Av^M \tag{4}$$

Where: $A = 4.557\times10^{-4}q^2 + 1.62\times10^{-2}q + 0.728$

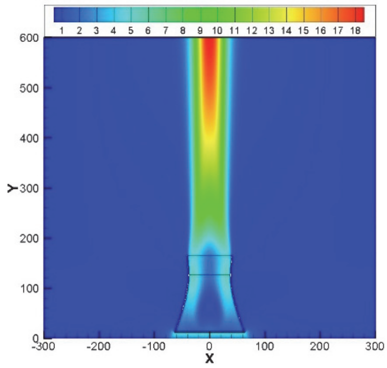
$$M = 3.27\times10^{-6}q^2 - 1.086\times10^{-2}q + 1.92$$

4.2 Result Analysis

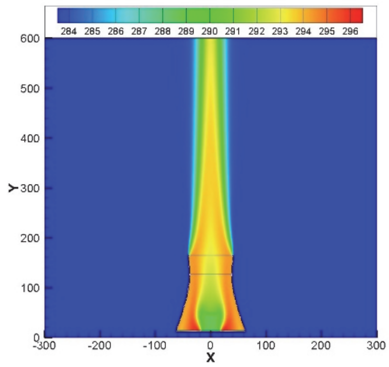
This study evaluates the thermal-hydraulic performance of a 4,500m² cooling tower implementing peripheral water distribution strategies under winter operating conditions with crosswind effects. Three load (50%, 75%, and 100% of design capacity) were evaluated, with corresponding water drenching densities set at 60%, 85%, and 100% of full-load values, to quantify the impact of density variation on outlet water temperature.



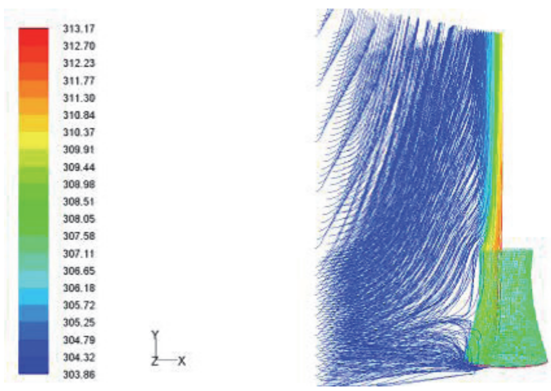
(a) Contours of static pressure



(b) Contours of velocity magnitude



(c) Contours of temperature



(d) Air streamline field

Figure 2. Air flow distribution

As evidenced by the static pressure distribution in (Fig. 2a), in the cooling tower induces localized negative pressure peaking exclusively at the periphery of the packing surface, with pressure demonstrating a vertically ascending gradient until it reaches equilibrium with ambient atmosphere is achieved near the outlet. CFD simulations confirm persistent buoyancy-driven stratification within the fill section, impeding thermal equilibration of countercurrent air streams. Streamline diagnostics verify dual-regime flow in quiescent environments: advection-dominated core inflow penetrates centrally while secondary currents ascend along the containment shell, with peripheral water distribution amplifying wall-jet dominance.

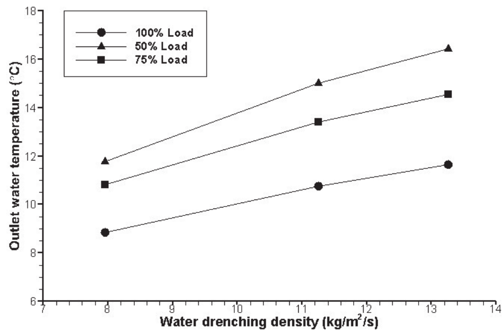


Figure 3. Water Temperature vs. Irrigation Density

Figure 3 quantitatively verifies outlet water temperature (°C) governed by irrigation density across operational spectra. This validates spray density modulation as a viable winter-operation strategy for freeze-risk mitigation, with efficacy confirmed via field-validated peripheral distribution protocols. CFD analysis further substantiates that under rated-load conditions, sustaining 11.26 kg/(m²·s) spray density guarantees ≥15°C, thereby preventing freezing.

5. Conclusion

This study demonstrates that modulating peripheral water distribution density serves as an effective freeze-mitigation strategy for winter-operating cooling towers, with outlet water temperature exhibiting a monotonic increase with spray density elevation under the three distinct load levels studied. Critically, maintaining 11.26 kg/(m²·s) at full load ensures outlet temperatures remain above the freeze protection threshold. Aerodynamic diagnostics reveal peripheral water distribution creates localized negative pressure at packing interfaces and amplifies wall-jet concentration—phenomena that impede thermal homogenization and degrade draft efficiency. These outcomes reconcile the intrinsic thermo-safety trade-off in cold-climate operations, establishing a first-principles design framework for utility-scale cooling system winterization.

References

Bi, Q., & Guo, P. (2002). Research on icing problems in water cooling towers during winter. *Electric Power*, *(10)*, 36-38.

Jin, Q., Song, C., Yang, J., et al. (2022). Control research on preheating anti-freezing system for natural draft cooling tower. *Power Generation Equipment*, *36*(1), 58-65. https://doi.org/10.19806/j.cnki.fdsb.2022.01.012

Li, H., & Zhao, S. (2013). Numerical simulation on the aerodynamic characteristics of the forced draft mechanical cooling tower. *Journal of China Institute of Water Resources and Hydropower Research*, *11*(3), 206-209. https://doi.org/10.13244/j.cnki.jiwhr.2013.03.015

Li, W., Wang, H., Wang, J., et al. (2019). Effect mechanism of exit-water temperature distribution characteristics on the anti-freezing of natural draft dry cooling tower. *Applied Thermal Engineering*, *161*, Article 114078. https://doi.org/10.1016/j.applthermaleng.2019.114078

Liu, B., Zhu, L., Cheng, S., et al. (2023). Anti-freezing scheme and dynamic monitoring system design for closed cooling towers based on northern cold weather. *China Plant Engineering*, *(14)*, 94-96. https://doi.org/10.3969/j.issn.1671-0711.2023.14.042

Liu, J., Chang, K., & Yang, Z. (2025). Research on cooperative control technology of anti-freezing and energy saving for cooling towers during deep peak regulation. *Energy Conservation*, *44*(5), 108-110.

Song, K. (1996). Freeze protection measures for natural draft cooling towers. *Water & Wastewater Engineering*, *(4)*, 29-30. https://doi.org/10.13789/j.cnki.wwe1964.1996.04.012

Wang, Z., Shi, X., Yue, Z., et al. (2024). Three-dimensional numerical study on anti-freezing characteristics of natural draft wet cooling tower under constant heat load. *Thermal Power Generation*, *53*(6), 132-141. https://doi.org/10.19666/j.rlfd.202401025

Wang, Z., Yue, Z., Wang, W., et al. (2024). Study on the influence of circulating water bypass on the thermal and anti-freezing characteristics of high-level wet cooling tower. *Energies*, *17*(9), Article 2073.

https://doi.org/10.3390/en17092073

Wei, H., Ge, Z., Yang, L., et al. (2019). Entransy based optimal adjustment of louvers for anti-freezing of natural draft dry cooling system. *International Journal of Heat and Mass Transfer*, *134*, 468-481. https://doi.org/10.1016/j.ijheatmasstransfer.2019.01.068

Yang, J., Pan, H., Chen, P., et al. (2023). Integrated research on anti-freezing and anti-crosswind for 600 MW unit cooling tower. *Journal of Shenyang Institute of Engineering (Natural Science Edition)*, *19*(3), 34-39+57. https://doi.org/10.13888/j.cnki.jsie(ns).2023.03.007

Yang, L., Li, X., Li, Y., et al. (2025). Numerical study on the influence of local water distribution on anti-freezing and energy-saving characteristics of high-level water collecting cooling towers. *Shandong Electric Power*, *52*(3), 86-96. https://doi.org/10.20097/j.cnki.issn1007-9904.2025.03.010

Yang, S. (2021). *Research on air inlet adjustment device of natural draft cooling tower for 600 MW unit* [Doctoral dissertation, North China Electric Power University]. China National Knowledge Infrastructure. https://doi.org/10.27139/d.cnki.ghbdu.2021.000753

Yuan, W., Zuo, S., Zhou, J., et al. (2025). Freeze protection performance of natural draft wet cooling tower with different partition water distributions. *Applied Thermal Engineering*, *260*, Article 124801. https://doi.org/10.1016/j.applthermaleng.2024.124801

Zhang, L., Zhou, J., Yuan, W., et al. (2025). Local anti-freezing mechanism of large-scale natural draft wet cooling towers based on drift eliminator control. *Case Studies in Thermal Engineering*, *72*, Article 106305. https://doi.org/10.1016/j.csite.2025.106305

Zhao, S., Song, X., et al. (2017). Numerical study on the performance of a natural draft cooling tower with water-cooled collectors. *Heat Transfer Engineering*, *38*(10), 1054-1062. https://doi.org/10.1080/01457632.2016.1216998