Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 24-25, 2024

Preliminary Study on Cooling Tower Performance in Czech Climate Conditions for Nuclear Power Plants

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***Keywords :** Cooling towers, Merkel method, Czech Republic, Climate impact, Thermal performance*

1. Introduction

Nuclear power plants have long been a cornerstone of energy production in Korea, with most facilities strategically located along coastal regions. This geographical positioning has traditionally eliminated the need for cooling towers, as seawater provides an efficient means of cooling.

However, the landscape of nuclear energy is evolving. Since Korea may need to construct nuclear power plants in the Czech Republic due to recent success, issues for inland nuclear power generation have to be now addressed. Unlike coastal sites, inland sites necessitate the implementation of cooling towers.

Cooling towers are important components of nuclear power plants (NPPs), particularly those constructed on the inland site. Their primary function is to dissipate waste heat from the power generation process while reducing the cooling water requirement, which is crucial for maintaining plant efficiency and safety.

The performance of cooling towers is not uniform for changing environments; the previous studies have shown that the efficiency of these structures is highly influenced by ambient atmospheric conditions, which can vary significantly depending on the climate [1]. This variability must be considered when designing cooling systems for nuclear power plants.

In light of this, the study focuses on the Czech Republic's unique climate conditions. A preliminary investigation has been conducted to analyze how the local atmospheric characteristics affect the temperature of cooling water after it circulates through a cooling tower. This research aims to provide valuable insights for the operational parameters and design considerations necessary for optimizing cooling tower performance in the Czech environment.

2. Methods

Merkel method [2], e-NTU [3], and Poppe's method [4] are mainly used to model cooling towers [5]. In this paper, in order to simulate a natural draft wet cooling tower, which is mainly used in nuclear power plants, with a simple 1-D code, the authors developed a steady-state analysis code based on the Merkel method [5]. The results are compared to the reference, and the outlet temperature of the cooling water when the Czech climate conditions are applied is calculated.

2.1 Merkel method

Merkel method focuses on the transfer of heat and mass between water and air inside the cooling tower. As hot water flows down the tower, it comes into contact with air moving upwards. This contact allows heat to be transferred from the water to the air, and some of the water evaporates, which cools the remaining water. To simplify calculation, Merkel method assumes the following.

- The water loss due to evaporation is negligible.
- Lewis factor is equal to unity
- Driving potential for the process of heat and mass transfer is the difference in the enthalpy of saturated air at air-water interface and the enthalpy in the bulk air
- Outlet air is assumed to be saturated with water vapor in order to determine air temperature

From above assumptions, the dimensionless parameter Merkel number is proposed that represents the performance of the cooling tower.

$$\mathrm{Me} = \frac{\mathrm{KaV}}{\mathrm{L}} \qquad (\mathrm{eq.}\,1)$$

*Me: Merkel number, K: mass transfer coefficient, a: interface area per unit volume V: cooling volume, L: water flow rate

2.2 Numerical model and governing equations

For Merkel number, the numerical model is shown below. Given equation is derived from experiment from Klopper's work [6]. The height of the fill is 1.2m and the cross-section area is $1m^2$ in the experiment. In this paper, the cooling tower conditions are based on the Klopper's experimental work. This study chooses equation type 3 for the numerical model, which has the highest R^2 value among type 1 to 3.

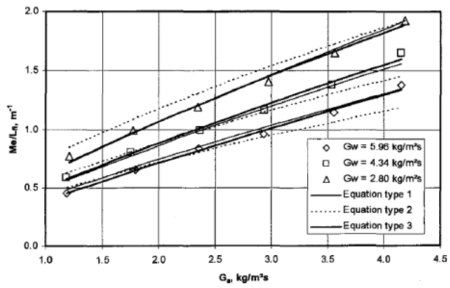

Figure 1 Experimental Result of Merkel number form Klopper (2003) [6]

$$\frac{dMe}{dz} \approx \frac{Me}{H} = 1.380517 * m_w^{0.112753} m_a^{0.698206} - 0.517075 * m_w^{0.461071} m_a^{0.681271} \quad (eq.2)$$

*H: fill height, m_w: mass flow rate of water, m_a: mass flow rate of air

From the assumptions of Merkel method and mass and energy balance equation in cooling tower, governing equation can be simplified to 4 equations with 4 variables.

$$\frac{dm_w}{dz} = -m_w \frac{dMe}{dz}(X_s^w - X) \quad \text{(eq.3)}$$

*X: specific humidity, X_s^w: saturated specific humidity in water temperature

The mass of water evaporated in cooling tower is determined from Merkel number and the difference between specific humidity and saturated specific humidity. The saturation specific humidity follows equation 4.

$$X_s^w = 0.622 \frac{P_s(T_w)}{P - P_s(T_w)} \quad \text{(eq. 4)}$$

*P_s:saturation pressure, P: ambient pressure, T_w: temperature of water

$$\frac{dX}{dz} = \frac{1}{m_a}\frac{dm_w}{dz} \quad \text{(eq. 5)}$$

The mass of water evaporated in cooling tower increase the specific humidity of air in cooling tower.

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$$\frac{dT_a}{dz} = \frac{1}{(c_{pa}^a + X c_{pv}^a)}\left(\frac{dh_a}{dz} - \frac{dX}{dz}(r_0 + c_{pv}^a T_a)\right) \quad \text{(eq. 6)}$$

* T_a :temperature of air, c_{pa}^a :specific heat of air in temperature of air, c_{pv}^a: specific heat of vapor in temperature of air, h_a: enthalpy of air, r_0: latent heat of water in 0C,

The temperature of air is determined by enthalpy of air and latent heat from humidity. The enthalpy of air follows equation 7, which is determined by specific humidity, temperature of air and water.

$$\frac{dh_a}{dz} = \frac{dMe}{dz}\left[(r_0 + c_{pv}^a T_a)(X_s^w - X) + (c_{pa}^a + X c_{pv}^a)(T_w - T_a)\right] \quad \text{(eq. 7)}$$

The temperature of water is determined by enthalpy of air, humidity.

$$\frac{dT_w}{dz} = \left(\frac{1}{c_p^w}\frac{dh_a}{dz} - T_w \frac{dX}{dz}\right) \quad \text{(eq. 8)}$$

*c_p^w:specific heat of water in temperature of water

From the 4 equations; (eq.3), (eq.5), (eq.6), (eq.8), the mass flow rate of water, specific humidity, temperature of air, and water are all obtained.

2.3 1-D code

The 1-D code for cooling tower is described in figure 2. To simulate counter flow wet cooling tower, the temperature of water and air, specific humidity, mass flow rate of water are calculated at dz intervals by dividing the fill height of the cooling tower with n steps. To calculate the four variables for each step, the equations described in Section 2.2 were used. The physical properties of air, water, and steam required for the calculation process were obtained using CoolProp [7], a python-library.

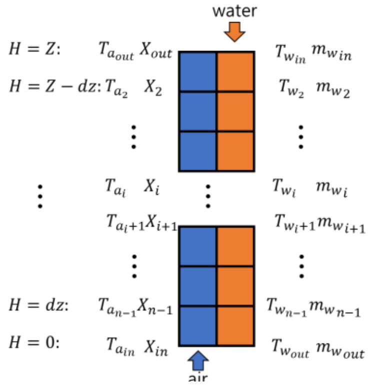

Figure 2 Conceptual diagram of cooling tower 1-D code

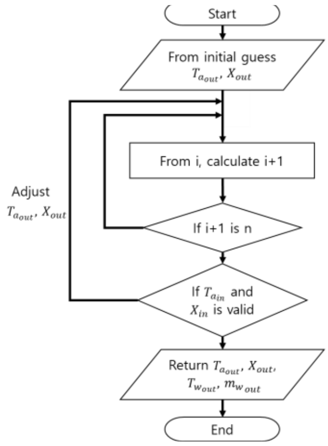

Figure 3 Flowchart of cooling tower 1-D code

Figure 3 illustrates the calculation process, which begins with an initial estimate of the outlet air temperature and specific humidity. The code is provided with known input conditions: the inlet air temperature, inlet water temperature, inlet specific humidity, and the mass flow rates of both water and air. Starting from the assumed outlet conditions, the code then iteratively adjusts these guesses to align with the given inlet conditions. Finally**,** it returns the outlet temperature of the water and air, the outlet mass flow rate of the water, and the outlet specific humidity for the given conditions.

2.4 Code Validation

To validate the code, the results of the 1-D code were compared to the results of the code for the three conditions shown in Klimanek's study. The conditions in each case are shown in table 1.

Table 1 Condition of Numerical example [5]

	Case#1	Case#2	Case#3
$m_{w,in}$, kg/s	3.0	3.0	3.0
$m_{a,in}$, kg/s	3.0	3.0	3.0
X_{in}, kg/kg	0.001	0.002	0.012
$T_{w,in}$, ℃	37.0	37.0	37.0
$T_{a,in}$, ℃	20.0	35.0	20.0

The code calculated the annual change in outlet temperature of cooling water based on climate information for the year 2023 in Dukovany, Czech Republic. The information reflected in the calculation process was the monthly average temperature and average relative humidity, and the specific humidity was calculated based on the input information to determine the approximate behavior of the coolant outlet temperature.

The information reflected in the calculation process was the monthly average high temperature and average relative humidity, and the specific humidity was calculated based on the input information to determine the approximate behavior of the coolant outlet temperature. During the calculation, the mass flow rate of water is 12 kg/s, and the mass flow rate of air is 3 kg/s, due to code convergence.

Table 2 Average High Temperature and Humidity in Dukovany, Czech, 2023 [8]

Month	Average High Temperature	Average Humidity
January	0.8°C	88%
February	2.8°C	84%
March	8.6°C	75%
April	14.9°C	70%
May	18.1°C	76%
June	22.2°C	76 %
July	24.8°C	71%
August	24.9°C	68%
September	19.4°C	72%
October	13°C	79 %
November	7.3°C	85%
December	2.6°C	86%

3. Results

3.1 Validation Result

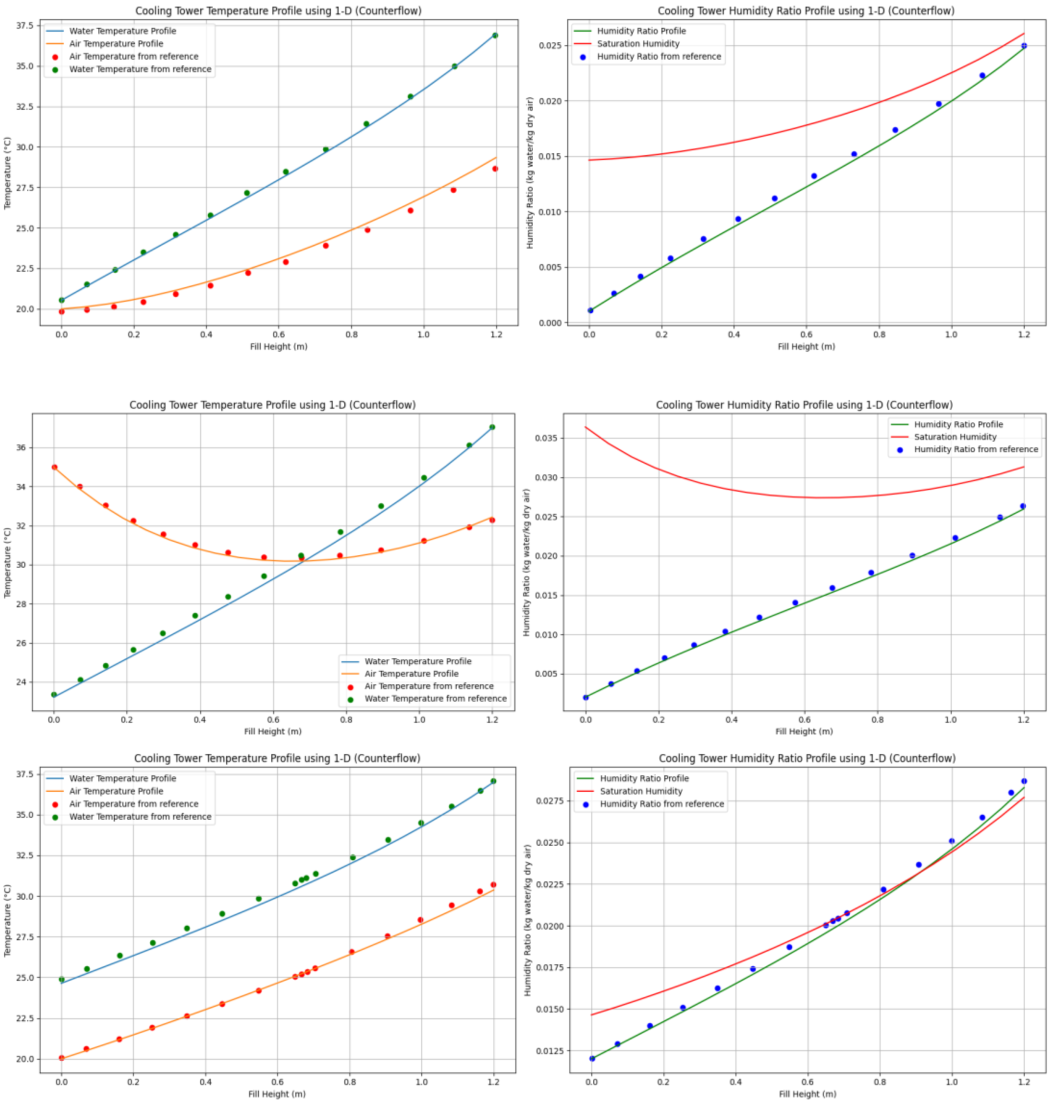

Figure 3 Result of Numerical example; Case#1(top), Case#2(middle), Case#3 (bottom)

Figure 3 illustrates the results of the 1-D code implementation across three distinct scenarios. Analysis of the output reveals a tendency for the code to slightly underestimate both air temperature and humidity. However, relatively accurate predictions are provided for the coolant outlet temperature. Notably, two important phenomena are successfully captured by the code: the temperature crossover between air and coolant in case #2, and the occurrence of humidity supersaturation in case #3. These results suggest that despite minor discrepancies on the air-side predictions, key thermal and moisture interactions within the cooling tower are reasonably modeled by the code.

3.2 Annual Trend of Cooling Water Outlet Temperature

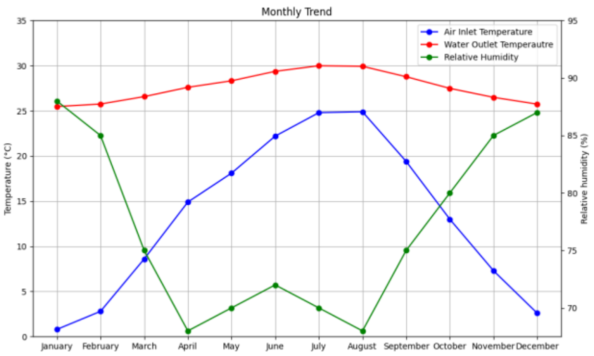

Figure 4 Monthly Trend of Air Inlet Temperature, Water Outlet Temperature, and Relative Humidity

Figure 4 illustrates the monthly trends of cooling tower outlet temperature, air inlet temperature, and relative humidity in Dukovany, Czech Republic, for the year 2023. The cooling tower outlet temperature was calculated using the 1-D code.

As shown from the figure, the cooling tower outlet temperature exhibits relatively minor fluctuations compared to the variations in air inlet temperature. This phenomenon can be attributed to the complementary nature of two key variables affecting the cooling tower outlet temperature. Within the cooling tower, heat is released from the cooling water through heat exchange with air and vaporization. During summer months, when temperatures are relatively high, the lower relative humidity allows for more vaporization, which increases heat release.

Consequently, the increase in cooling water outlet temperature, which would typically be expected to rise with increased air temperature, is comparatively small.

4. Conclusions

The study provides insight into the climatic characteristics of the Czech Republic, indicating that high summer temperatures coupled with low humidity may result in relatively small variations in cooling water outlet temperature from cooling towers. This factor should be considered in future nuclear power plant constructions in the Czech Republic. However, it should be noted that this study was designed to predict general trends using a relatively simple numerical model, and further development is necessary to obtain more definitive results.

It is important to acknowledge that information regarding the cooling requirements of a nuclear power plant's secondary side was not incorporated into this study. The required cooling capacity should determine the size and type of cooling tower. The heat exchange behavior and vaporization process within the cooling tower may vary depending on these cooling tower characteristics, necessitating further investigation for more accurate results.

Despite these limitations, the implementation of a relatively simple numerical model allowed for the prediction that cooling tower performance in the Czech Republic may not fluctuate significantly across seasons. This stability can be attributed to the region's climatic characteristics, particularly the low humidity during summer months. However, more comprehensive studies are required to confirm and refine these preliminary findings.

ACKNOWLEGMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.: RS-2024-00436693).

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