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

Review of cooling tower technology applied to nuclear power plants globally

*Changmin Yoon[a], Jeong Ik Lee[a]**
[a]Nuclear Quantum Engineering department, KAIST, Yuseong-gu, Daejeon, 34141
[*]Corresponding author: jeongiklee@kaist.ac.kr

1. Introduction

South Korean industrial consortium was selected as preferred bidders based on the EU-APR model for the new construction of the Dukovany nuclear power plant in the Czech Republic. However, the Czech Republic's geography and environmental conditions presented new technical challenges, which requires a cooling tower [1].

The Korean nuclear power plants (NPP) have been successfully constructed in sites, but there is no experience of constructing cooling tower, since all the projects were based on sites near ocean. Thus, cooling tower design and construction will become new experience for the Korean industrial consortium when taking on the Dukovany NPP project in the Czech Republic [2].

Cooling towers enable heat rejection using less cooling water from environment in nuclear power plants and play a key role in ensuring safe operation. Especially in a geographical environment such as the Dukovany NPP, the design and operation of cooling towers can directly affect the overall performance of the plant. Therefore, this study will present the critical factors for cooling tower design and, based on this, investigate and compare cooling tower design and operation practices around the world. The results can be used as a reference to derive an optimized cooling tower design which will be most suitable to the climatic conditions and geographical characteristics.

2. Methods and Results

2.1 Heat exchange process in cooling tower

The temperature difference between the bottom and the top of the tower creates a density difference in the air, which drives the air flow via natural circulation, or known as the stack effect. This is the core operating principle of Natural Draft Cooling towers.

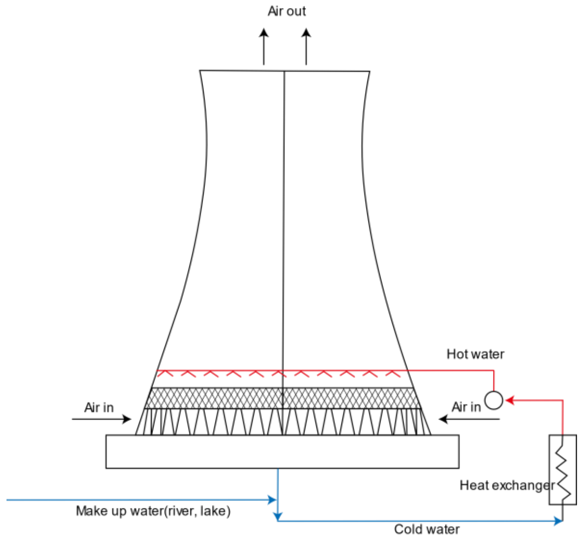

Fig 1. Schematic diagram of a nuclear power plant cooling tower

As shown in Figure 1, the bottom of the tower is sprayed with hot coolant from a nuclear power plant, and the falling droplets come into contact with the cold air coming in from the bottom of the tower, releasing heat. In this process, The heated air rises to the top of the tower, and cooler air from the outside flows into the bottom of the tower.

Heat is removed as water evaporates inside the cooling tower, where some of the water evaporates and is released from the top of the tower as water vapor. The cooled water is collected back at the bottom of the tower and recycled back into the cooling system of the power plant.

The main advantage of Natural Draft Cooling towers is that by using the stack effect, airflow is naturally directed without the need for mechanical fans or additional power sources. This has the effect of increasing energy efficiency and reducing maintenance costs. However, the disadvantages of these cooling towers are that they are very large, require a large footprint, and their cooling efficiency can vary depending on the external weather conditions.

$$\dot{Q} = \dot{m}_a\left(h_{air,out} - h_{air,in}\right) = \dot{m}_w \times C_p \times T_w - (\dot{m}_w - \dot{m}_{w,evaporated}) \times C_p \times T_c \quad (1)$$

$\dot{Q} = Exchanged\ heat\ in\ cooling\ tower$

$\dot{m}_a = mass\ rate\ of\ dry\ air$

$\dot{m}_w = mass\ rate\ of\ circulating\ water$

$\dot{m}_{w,evaporated} = mass\ rate\ of\ evaporated\ water$

$T_w = temperature\ of\ hot\ water\ entering\ tower$

$T_c = temperature\ of\ cold\ water\ leaving\ tower$

$h_{air,in} = enthalpy\ of\ air\ entering$

$h_{air,out} = enthalpy\ of\ air\ leaving$

$C_p = specific\ heat\ of\ water$

Equation (1) shows the heat exchange process inside the cooling tower. From this equation, it can be seen that $\dot{Q}$ determines the amount of heat cooled with respect to the capacity of the power plant, and $\dot{m}_a$ is determined by the stack effect, so it is determined by the size of the cooling tower. In addition, $h_{air,in}$ is determined by the temperature and humidity of the air around the power plant. Therefore, the higher the capacity of the power plant and the temperature and humidity of the surrounding air, the size of the cooling tower will become larger.

2.2 Cooling tower around the world

Table 1 presents data of cooling towers for major nuclear power plants in selected countries as a reference for deriving cooling tower design options. The table shows that the tower differs by capacity and environmental characteristics. Table 1 includes information of the name of the plant, site location, height of the cooling tower, generating capacity (MWe), average temperature, and relative humidity. The data in the table shows that the height of the cooling towers is determined by different climatic conditions and geographical features.

Table 1. List of pressurized water nuclear reactor cooling towers worldwide[2]

Name	**Country**	**Location**	**Height**	**Capacity (MWe)**	**Temperature range (°C)**	**Relative humidity (%)**
Vogtle Electric Generating Plant Unit 3 & 4	United States	Burke County, Georgia	180	1150	7.8 ~ 27.6	61 ~75
Civaux Nuclear Power Plant, cooling tower 1	France	Civaux	180	1561	0~27	71 ~ 84
Cooling towers of Golfech Nuclear Power Plant	France	Golfech	179	1363	3~29	66 ~ 85
Cooling towers of Chooz Nuclear Power Plant	France	Chooz	172	1560	0 ~ 22	79.98 ~ 90.27
Novovoronezsh Nuclear power plant, Unit II-1	Russia	Voronezh Oblast	170	1150	-6.4 ~ 22	85 ~ 59
Doel Nuclear Power Station, cooling tower 1	Belgium	Beveren	169	1056	5.8 ~ 23.19	87.13 ~ 74.35

Callaway Nuclear Generating Station	United States	Fulton, MO	169	1215	-0.5 ~ 26.1	64 ~ 68
Vogtle Electric Generating Plant Unit #1	United States	Burke County, Georgia	167	1150	7 ~ 27	67.1 ~ 89
Leningrad Nuclear Power Plant Unit II-2	Russia	Leningrad oblast	167	1188	-6.15 ~ 22.05	70.45~ 93.54
Nine Mile Point Nuclear Generating Station	United States	Scriba, NY	166	1375	-6 ~ 18.3	55 ~ 64
Cooling towers of Belleville Nuclear Power Plant	France	Belleville-sur-Loire	165	1300	4.54 ~ 21.6	71.51 ~ 86.05
Cooling towers of Cattenom Nuclear Power Plant	France	Cattenom	165	1300	3.3 ~ 19.7	71 ~ 87
Cooling towers of Nogent Nuclear Power Plant	France	Nogent-sur-Seine	165	1300	3.64 ~ 21.66	70.02 ~ 87.62
Gundremmingen Nuclear Power Plant, cooling tower 1	Germany	Gundremmingen	160	1284	2 ~ 23.5	77.4 ~ 89.46
Torre de refrigeración de Central nuclear de Ascó	Spain	Ascó	160	1033	8.9 ~23.6[3]	69 ~ 75
Temelín Nuclear power plant	Czech Republic	Temelin (using two towers)	160	1080	1 ~ 23.25[3]	74.08 ~ 87.6
Cooling towers of Cruas Nuclear Power Plant	France	Cruas	155	956	3.91 ~ 23.77	64.55 ~ 83.98
Watts Bar Nuclear Plant, cooling tower 1	United States	Rhea County, TN	154	1165	4.2 ~ 26	72 ~ 80
Dukovany Nuclear Power Station	Czech Republic	Dukovany (using two towers)	125	510	-0.39 ~ 21.2	72 ~ 86

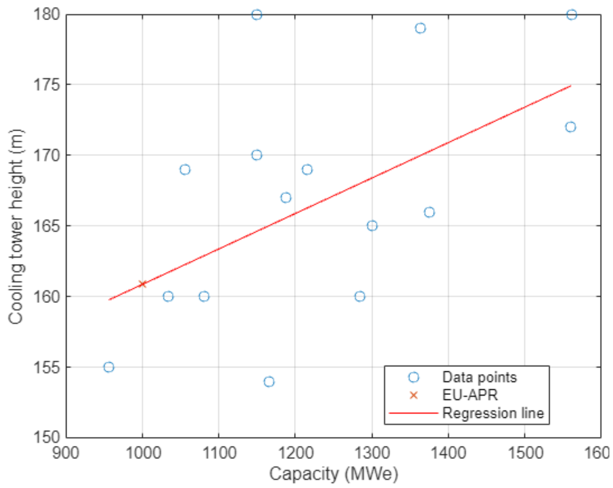

Fig 2. Cooling tower height by capacity

Using the EU-APR's capacity of 1000 MWe as an input of the regression model, it is approximately 161 meters. This value was derived by substituting the capacity of the EU-APR into a model that linearly regressed the examples in Table 1.

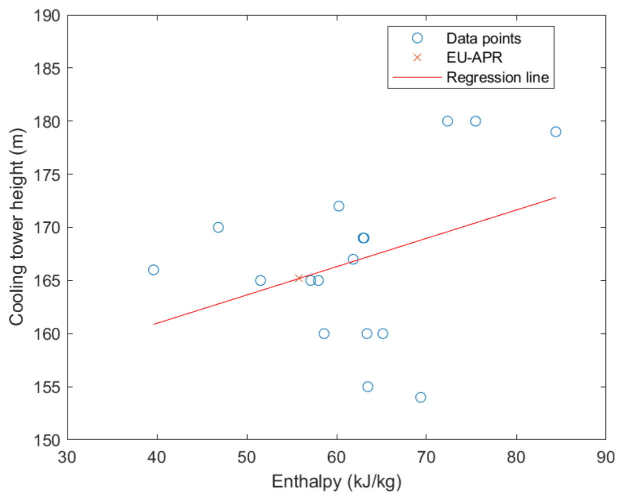

Fig 3. Cooling tower height by enthalpy of inlet air

As previously mentioned, the higher the temperature and relative humidity, the larger the cooling tower is required. Therefore, Figure 3 shows how height relates to the maximum value over the range of temperatures and relative humidity listed in Table 1.

From the temperature and relative humidity information in Table 1, it is possible to find the enthalpy of the air entering from the bottom of the cooling tower. Figure 3 shows the height of the cooling tower as a function of the enthalpy of the air. As the enthalpy increases, the height of the cooling tower tends to increase. Using the enthalpy of the air as a function of temperature and humidity in Ducovany in a regression model, the height of the cooling tower is about 165 meters. This value was derived by substituting the height of the EU-APR into a model that linearly regressed the examples in Table 1.

3. Summary and Further Works

This study collected the characteristics of cooling towers operating around the world. Using data from various nuclear power plants around the world, the authors planned to analyze the cooling tower designs, including design factors such as height, capacity, average temperature, and relative humidity.

The analysis demonstrated how cooling tower designs are optimized based on the specific climatic and geographical conditions of each location.

The collected information will be particularly relevant in light of the recent Dukovany Nuclear Power Plant project in the Czech Republic. In this project, the EU-APR will have to include a cooling tower, and the design should reflect local environmental conditions. This study provides a comprehensive reference for the design of cooling towers.

From the data collected from this study, future research will focus on designing a cooling tower specifically tailored to the environmental conditions of the Dukovany Nuclear Power Plant in the Czech Republic. This will involve the application of the design principles identified in this study, adjusted for the specific climatic conditions at Dukovany, such as its temperature range and relative humidity.

Acknowledgements

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government MOTIE (No. RS-2024-00400615)

REFERENCES

[1] “ KHNP selected to supply new Czech nuclear units”, world nuclear news, last modified 17 July 2024, accessed Aug 14, https://www.world-nuclear-news.org/Articles/KHNP-selected-to-supply-new-Czech-nuclear-units
[2] "climate chart", Weather and climate, accessed Aug 14, https://weatherandclimate.com/
[3] "Catalonia Climate & Temperature",clima Temps, accessed Aug 14, http://www.catalonia.climatemps.com/