Preliminary study on the effect of dry/wet cooling combinations for the sustainable management of water of cooling tower

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Abstract

Recently, sustainable management of water has received a lot of interest since the shortage of it are one of the major environmental issues. Power plants eject tremendous amount of condensation heat while generating electricity. Water is the most commonly used heat transfer materials. During the heat transfer process, large amount of water is evaporated into the atmosphere. This may cause a severe water management problem. Dry cooling is an alternative cooling method, but it may cause efficiency degrade. In this article, a preliminary strategy for the combination of dry/wet cooling methods was derived.

Keywords: power plant; wet cooling; dry cooling; water saving; NTU analysis

Received 7 September 2017; revised 12 November 2017; editorial decision 13 November 2017; accepted 30 November 2017

1 INTRODUCTION

The power plant of close-loop cycle like steam turbine requires a cooling process in which the remaining thermal energy is ejected outside the system after electricity conversion. One-through, wet cooling (or recirculating cooling) and dry cooling are the most widely used cooling methods for heat rejection. Water is commonly used for one-through method and wet cooling method due to its easy accessibility and high performance in heat transfer. Since a large amount of water withdrawals is required for once-through method, the power plant is usually located nearby adequate water source such as ocean or river. The withdrawn water is discharged downstream and the temperature usually rises ~10°C. The temperature rise is strictly controlled under the environmental regulations. Wet cooling method utilizes the evaporation heat transfer process to cool down circulation water. About 1% of circulation water is consumed as evaporation to cool down the circulation water by 7°C [1]. This also needs affluent water resources and consumes far more amount of water than once-through method. Dry cooling method does not require water for cooling as its name implies. It uses mostly air as heat transfer media. Dry cooling is preferred in a region where water is scarce or the government practices strict environmental regulation on water resource. However, its poor heat transfer performance makes the cooling system much bulkier and requires more investment cost. Table 1 shows schematic diagrams and features of three cooling methods [2].

Securing sustainable water resources is an important environmental issue. In the future energy system, renewable energies such as wind power and solar power will take large portion in the electricity generation. These energies do not generate exhaust heat, thus requiring small water consumption. However, even in the future energy society, it is predicted that the conventional ways of electricity generation through the combustion of fossil fuels still play important roles. Because distributed power generation system will play a key role in future energy system, the penetration rate of wet cooling system is expected to increase. Therefore, reducing water consumption in power plant cooling is likely to become an important environmental issue in the future since the heat loads left after electricity production must be treated. In this study, a preliminary study on the design of power plant cooling system to reduce water consumption was conducted.
WATER CONSUMPTION CHARACTERISTICS FOR POWER PLANT COOLING

Water withdrawal is the amount of water taken outside of power plant. The once-through method discharge all the water withdrawn, so it seems to have high withdrawal but low consumption level. According to a water usage report of National Renewable Energy Laboratory (NREL) in early 2000 [2], power plants accounted for nearly 40% of total water withdrawals, but they occupied only 3% in total water consumption, implying that most of power plants in USA adopt once-through cooling method (Figure 1).

Other report of NREL in 2011 [3] claimed that wet cooling consumes 2000–3000 l water per MWh while once-through cooling needs ~800 l water per MWh. This implies that even though once-through method rejects all of the withdrawn water, considerable amount of water is consumed somewhere. Amit and Karen [4] insisted that fossil-fuel plant with wet-cooling was assumed to consume 2000 l per MWh while that with once-through consumed 1000 l per MWh (Table 2). The authors explained that the reason why one-through method had relatively high level of water consumption was the secondary thermal pollution. As the temperature of discharge water is higher than that of main water stream, evaporation occurs while it cools down to ambient temperature.

Although dry cooling does not need any water for cooling process, it also consumes water for boiler make-up and utility needs such as office, toilets, etc. [5]. According to EPRI (Electric Power Research Institute)'s analysis of coal-fired power plant water balance [6], 19801 water/MWh are used for wet-cooling cooling, 337 l/MWh for boiler make-up water and 30 l/MWh for flue-gas desulfurization (FGD) in a 500 MW power plant. The amount of boiler make-up water is ~1.5% of water consumed by wet cooling. While wet cooling uses temperature potential to wet bulb temperature, dry cooling uses temperature difference between circulation water and dry bulb temperature. In most atmospheric conditions, dry bulb temperature of air is higher than wet bulb temperature. This means dry cooling has smaller temperature potential than wet cooling. Dry cooling requires five to eight times more initial cost than wet cooling. The performance may be extremely decreased or limited as the ambient temperature rises in summer peak season. This causes additional cost penalty in operation. Therefore, operation cost (or penalty cost) as well as initial capital cost must be considered in designing the dry cooling system. The increase of system size will require higher initial capital cost. However, it will save operation cost since the approaching temperature decreases. The total cost may have an optimum point as shown in Figure 2, which schematically shows above trend [5]. The increase of ambient temperature will also result in higher back pressure of turbine. Above certain point, the turbine may have to stop its operation. Operation range of back pressure of turbine, ambient temperature trend, operation schedules of power plant are also considered in case of dry cooling.

WET/DRY HYBRID COOLING FOR WATER SAVING

Once-through method does not directly consume water. But the thermal pollution after discharge causes considerable amount of...
water evaporation. Wet-cooling method may be the most efficient methods of cooling in the view point of compactness. However, it also has the highest water consumption level. If only wet cooling method is applied to a 500 MW power plant, cooling alone consumes more than the water consumption of 50,000 persons. (The average water consumption in Korea: 285 l/day [7].) Dry cooling is the most preferable one to save water, but its cost and limitation in operation hinder the application of dry cooling. In this article, a preliminary study on the system construction plan for the water saving of wet cooling system was conducted among various installation scenarios. The basic mechanism of wet cooling is heat transfer between latent (evaporation) and sensible processes. The ratio of sensible heat to latent heat determines water consumption ratio. For example, it consumes ~1% of circulation water evaporation to cool down by 7°C. Improvement of heat and mass transfer will contribute minor effect in reducing water consumption in cooling tower. To reduce water consumption, dry cooling must be accompanied with wet cooling. There are two approaches in combining wet cooling and dry cooling; serial layout and parallel layout [8]. Since the back pressure of the turbine must be ensured, the final cooling of the circulating water should be made with a potential difference between wet bulb temperature and process water. This means wet cooling should be placed at the end stage of cooling. Therefore, parallel layout was selected and a simple design strategy for the parallel type was derived. Figure 3 schematically illustrates the cooling process of circulating water in a parallel layout. When the cooling water passes through the dry heat transfer method, the counter flow method is used to derive the heat transfer level, and the heat transfer level is calculated using Baker and Shyrock’s method, which is the most commonly used approach for wet cooling analysis [1, 9]. The target water saving level was set as 30%.

The heat transfer efficiency is effected by wet bulb temperature and dry bulb temperature of ambient air. Therefore, annual climate data must be considered in the analysis of heat transfer requirement. Cooling range is also important since a low design point of approaching temperature causes unnecessary increase of heat transfer area. Figure 4 shows trends of air temperature (daily maximum) and relative humidity of Daejeon, Korea. For 100 kW power plant with efficiency of 0.4, the dry cooling NTUs and wet cooling NTUs in case of 30% water reduction are plotted in Figure 5 with different cooling ranges. For cooling range of 37–30°C, the flat zone in the graph of NTU_dry represents that dry cooling cannot deal with 30% of total cooling demand. When the range is changed to 47–40°C, there is

Table 2. Approximate withdrawals and consumptions, without accounting for ambient temperature or plant efficiency (Amit and Karen [4]).

| Plant and cooling system type water | Withdrawal (l/MWh) | Consumption (l/MWh) |
|-----------------------------------|--------------------|---------------------|
| Fossil fuel/biomass/waste, once-through cooling | 76 000–190 000 | 1000 |
| Fossil fuel/biomass/waste, wet cooling | 2000–2300 | 2000 |

Figure 2. Schematics of trade-off of cooling system (redraw the graph in reference [5]).

Figure 3. Cooling process of circulating water in a parallel layout.

Figure 4. Trends of air temperature (daily maximum) and relative humidity of Daejeon, Korea.

Figure 5. Heat transfer efficiency with different cooling ranges.

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no such a flat zone in graphs. However, the maximum NTU value of dry cooling is 1 and it is more than 20 times of the maximum NTU of wet-cooling.

Fixing water consumption target for all days and then designing cooling system is not an economical approach. Figure 6 shows the requirement of NUT of wet cooling when NTU of dry cooling is fixed. The year-averaged portions of dry cooling are displayed in each chart when the cooling range is from 37 to 30°C. For 0.5 of NTU_dry, up to 40% of total cooling demand can be treated through dry cooling around a year. The portion drops down to 10% in summer season. When NTU_dry is increased to 1.0, the portion of dry cooling in summer does not have significant improvement. In winter time, the portion is increased more than 60%. Therefore, the year-average portion of NTU_dry is increased from 24 to 38%. The almost same contribution of dry cooling in summer makes little change in the maximum value of NTU_wet. In an actual cooling tower design, the capacity should be determined to be able to deal with the maximum load condition. In the selected city for analysis, the NTU difference of wet cooling requirements between maximum load in the summer and minimum load in the winter was more than 10 times. Since the contribution of dry cooling in summer was insufficient, the design value of wet cooling did not change much even if the given NTU_dry cooling increased four times. If the NTU_dry was 2.0, it will be able to handle almost 90% load in one winter. It was not meaningful to increase the design capacity beyond this point.

Other major operation parameter for dry cooling system design is cooling range. For different cooling ranges, performance analysis procedure of Figure 6 is applied to obtain year-averaged portions of dry cooling (Figure 7a). The increase of cooling range gives extended temperature potential in the heat exchanger of dry cooling system. In achieving the same contribution of dry cooling, the required value of NTU of dry cooling is reduced for higher cooling range. The sensitivity of dry cooling portion to NTU also increases about two times as cooling range increase by 10°C. Figure 7b is the year-round trends of dry cooling portion when the year-average values are similar (0.27, 0.26, 0.25) with different NTUs. Lower cooling range demands higher NTU to obtain similar year-average dry cooling effect. In this case, the enlargement of NTU begins to compensate the disadvantage in temperature potential when the ambient temperature becomes lower than 20°C.

![Figure 4. Year-round trends of ambient temperature and relative humidity in Daejeon City, Korea.](image)

![Figure 5. Trend of NTU_wet and NTU_dry with different cooling ranges and fixed dry cooling contribution of 30%. (a) Cooling range: 37–30°C. (b) Cooling range: 47–40°C.](image)
CONCLUSION

In this article, water consumption features of different cooling methods of power plant were examined. Once-through method discharges all of the water withdrawals and does not consume water directly. However, the downstream evaporation such as thermal pollution contributes certain amount of indirect water consumptions. Dry cooling method which does not require water for cooling has disadvantage in performance. It also demands more initial investment cost. Wet cooling is the most compact and efficient heat transfer method. The feature that evaporation is the dominant heat transfer process makes wet cooling consume the most amount of water among the three cooling methods. To ensure both performance and water savings, parallel wet/dry cooling layout would be a solution. With annual climate data of a city of Korea, NTU requirements were analysed for both wet cooling and dry cooling. The results shows that varying the portion of dry cooling would be economical approach compared to fixed target approach. The approaches of this study will be used to make commencing plan for cooling system design.

ACKNOWLEDGEMENTS

This work was jointly supported by the National Research Council of Science & Technology (NST) grant by the Korea government (MSIP) (No. CRC-15-07-KIER) and the Energy Efficiency & Resources Core Technology Program of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20132010101780).

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