14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

Heat pump application approach to abate plume generation from a cooling tower

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Abstract

In Korea, white plume generated by cooling tower is a one of major social conflicts due to its visual pollution. Various methods have been developed to abate plume generation, such as outdoor air condensing, dry/wet hybrid cooling, membrane method, etc. However when cooling towers operate in cold climate without plume generation, both humidity ration and relative humidity have to be reduced with effective methods. Dehumidification and regeneration using heat pump cycle can be a good technical solution for this since it condense water vapor and then reheat the air with condensation heat and compressor power input. The required energy of a heat pump method is 3 to 4 times less than a direct heating method. For further energy reduction, an outdoor air mixing is introduced before heat pump stage and the power input can be reduced up to 10% compared to a direct heating.

Keywords: Cooling Tower; Heat Pump; Plume; Plume Prevention

1. Introduction

Stacks or cooling towers tend to exhaust plume when the outdoor temperature is low and relative humidity is high. The plume is literally water vapor and not environmentally harmful. However it may cause social conflicts due to visual pollution and misperception as fire or smoke [1, 2]. In addition, when the white smoke does not rise and spreads on the road, it may cause icing problems and sometimes cause traffic problems. For this reason, cooling tower plume abatement is one of the biggest technical issues in the related industry.

2. Plume abatement by applying a heat pump cycle

One of the most widely used methods to reduce plume generation from cooling towers is outdoor air mixing method in which exhaust wet air is firstly dry-cooled by lower temperature outdoor air while discharging thermal energy to the outdoor air and reducing water vapor intake. Then the two air streams are mixed together and the humidity ratio and relative humidity of the discharged air of cooling tower are decreased [3]. By adopting this method, it is possible to reduce the absolute discharge of water vapor and reduce water consumption through condensate recovery. This method can be applied with small design changes in existing cooling towers while minimizing additional input energy, but it is difficult to ensure plume abatement in low temperature outdoor condition such as winter morning with high relative humidity or high relative humidity condition such as foggy or snowy weather.

Condensing and removing water vapor using a heat pump can also be another method for reducing plume generation. By applying a more active cooling/heating device, heat pump, it becomes possible to efficiently prevent plume even in sub-zero climate conditions [3]. The heat pump recovers sensible and latent heat from the humid discharged air of cooling tower in the evaporator and the recovered heats is then transferred to the

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discharge stream passing through the condenser. Therefore the relative humidity can be lowered much more than the outdoor air mixing method (Fig.1). Since air in cooling tower is at high relative state, heat transfer in the evaporator is increased due to condensation, and energy consumption can be reduced by the factor of COP of the heat pump compared to the electric heaters.

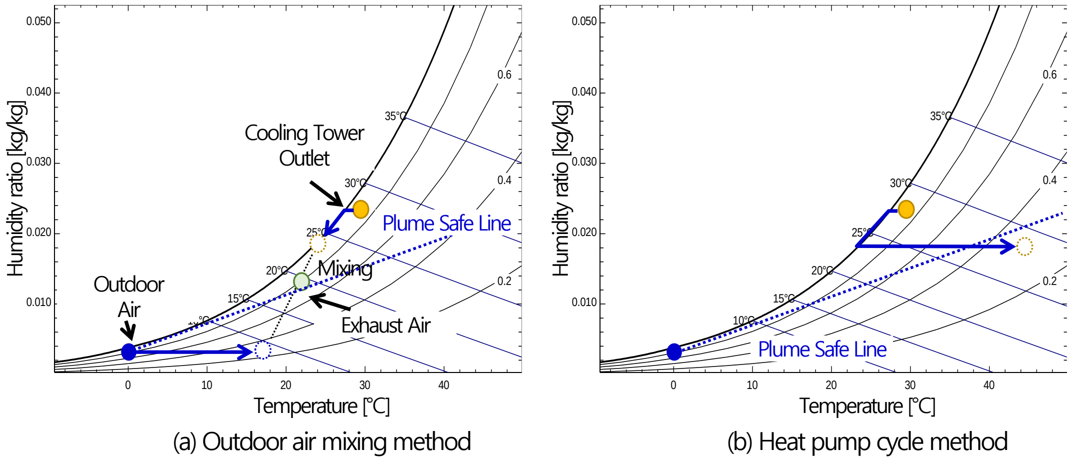

Fig. 1. Plume abatement approaches – outdoor air mixing and heat pump

Fig. 2 shows a reference case of heat pump cycle analysis under typical cooling tower flow conditions. The cycle characteristics in the cooling tower flow condition are the high latent heat ratio in the evaporator (latent heat transfer is more than 95% of the total heat transfer) and the high condenser pressure approaching the compressor operating limit. The high latent heat ratio is due to the high relative humidity, and as the evaporator and the condenser operate at the same air volume rate, the condensation pressure has to increase more compared to the general heat pump system. Under the suggested operating conditions in the figure, the air at the exit of the condenser is heated up to 51.5°C, and plume prevention can be expected to about 0°C outdoor air temperature. The estimated COP obtained by the heat pump is 4.0.

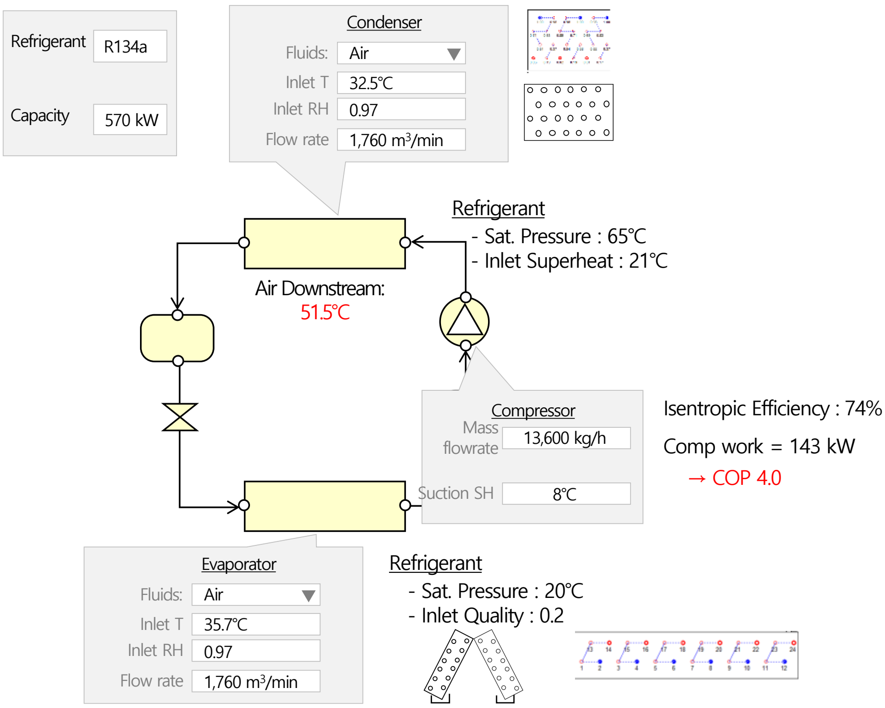

Fig. 2. Heat pump cycle analysis under typical cooling tower flow conditions

3. Plume Prediction based on Psychrometric Chart

From a thermodynamic point of view, plume is generated when condensation occurs in the mixing process between exhaust air of cooling tower discharge and low-temperature outdoor air. The occurrence of condensation means that the humidity ratio of the two mixed stream is higher than the value of saturated condition at the mixed temperature. So the saturated humidity ratio to the mixed temperature and the current humidity ratio were selected as the criterion for plume generation. In order to prevent plume generation in certain outdoor conditions and cooling tower outlet conditions, either the outlet air temperature must be raised or the humidity ratio value must be reduced. The figure below shows the process of estimating the minimum value of outlet air temperature increase on a psychrometirc chart, and the determination process is briefly presented too.

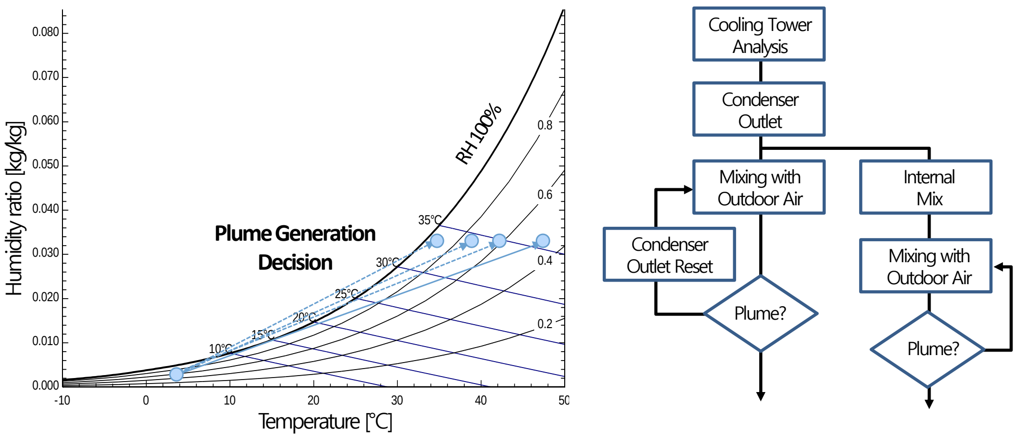

Fig. 3. Process of finding operation conditions for the prevention of plume generation

The plume generation prediction method based on the psychrometic chart can be used for following cases

- (Analysis of outdoor temperature effect) The result of analyzing the temperature required for plume prevention according to the different outdoor temperature with fixed cooling tower outlet condition of 33℃ and RH99% is shown in the below figure and table. When the outdoor temperature is lower than a certain point, the temperature required for plume prevention tends to increase rapidly. For example, for the outdoor temperature of 20ºC, only 1.4 ºC temperature increase is required. However the required values are increased to 9.9ºC at 10ºC outdoor and 37.4ºC at 0ºC outdoor. Reheating temperature prediction tool with outdoor temperature changes makes it possible to derive operational limits for plume prevention in currently constructed facilities.

T_old(℃)	Outdoor T(℃) (RH 75%)	T_new(℃)	h_old(kJ/kg)	h_new(kJ/kg)	Delta T(℃) (Heating)
33	20	34.4	115.6	117.1	1.4
33	19	34.8	115.6	117.5	1.8
33	18	35.2	115.6	118	2.2
33	17	35.8	115.6	118.6	2.8
33	16	36.4	115.6	119.2	3.4
33	15	37.2	115.6	120.1	4.2
33	14	38	115.6	120.9	5
33	13	39	115.6	122	6
33	12	40.2	115.6	123.3	7.2
33	11	41.5	115.6	124.7	8.5
33	10	42.9	115.6	126.2	9.9
33	9	44.6	115.6	128	11.6
33	8	46.4	115.6	129.9	13.4
33	7	48.4	115.6	132	15.4
33	6	50.7	115.6	134.5	17.7
33	5	53.2	115.6	137.1	20.2
33	4	56	115.6	140.1	23
33	3	59.1	115.6	143.4	26.1
33	2	62.5	115.6	147.1	29.5
33	1	66.3	115.6	151.1	33.3
33	0	70.4	115.6	155.5	37.4

T_old/h_old : air temperature/enthalpy exiting base cooling tower
T_new/h_new : air temperature/enthalpy after condenser to prevent plume generation

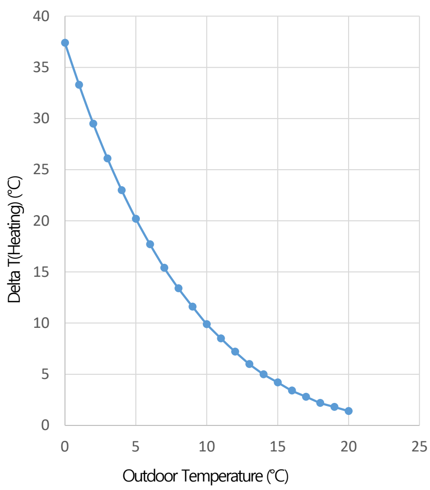

Fig. 4. Analysis of outdoor air temperature effect on plume prevention

- (Analysis of outlet temperature effect) In order to analyze the cooling tower operating conditions for plume prevention in low-temperature outdoor condition, an outdoor plume reduction temperature analysis was performed at −5℃/RH75%. Considering the fact that the heating temperature rapidly increases as the outdoor temperature decreases in the previous case, the cooling tower outlet temperature was arbitrarily lowered in this case, and the plume prevention temperature increase characteristics were analyzed for 20-29°C outlet temperature. The results are presented in the figure and table below, and compared to the case of 15.1°C heating requirement a 20°C outlet temperature, 42.2°C heating is required at 29°C outlet (2.86 times more heat required). Therefore, in order to effectively prevent plume, it is necessary to design a control logic that lowers the outlet air temperature and a system in which the output of the heat pump for plume removal is inter-connected with each other.

T_old(℃)	Outdoor T(℃) (RH 75%)	T_new(℃)	h_old(kJ/kg)	h_new(kJ/kg)
20	-5	35.1	57.01	72.59
21	-5	38.2	60.45	78.23
22	-5	41.5	64.04	84.23
23	-5	45	67.78	90.61
24	-5	48.6	71.68	97.26
25	-5	52.6	75.75	104.5
26	-5	56.9	79.99	112.3
27	-5	61.3	84.43	120.4
28	-5	65.8	89.06	128.8
29	-5	71.2	93.91	138.4

T_old/h_old : air temperature/enthalpy exiting base cooling tower
T_new/h_new : air temperature/enthalpy after condenser to prevent plume generation

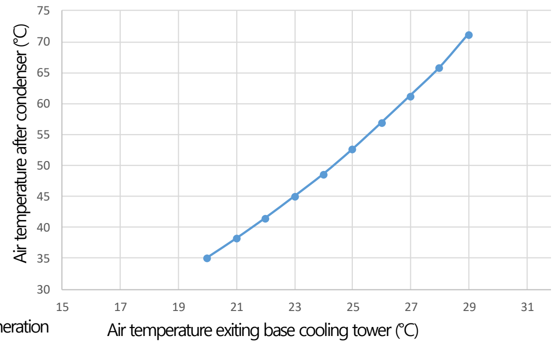

Fig. 5. Analysis of outlet temperature effect on plume prevention

- (New operation proposal and operation characteristic analysis) As the outdoor temperature decreases, the heating temperature required for plume prevention increases rapidly due to the nonlinearity of the humidity curve. In order to reduce the energy required for plume prevention, a new operating mode was suggested. The new operating concept was designed considering the cooling tower operating boundaries for a power plant. Even if the outdoor temperature is lowered, the turbine back pressure must be maintained constantly. Therefore the temperature change of the cooling tower circulation water should be maintained. In order to maintain the same temperature change, the cooling tower air volume flow rate must be reduced. If the outside air is taken as the amount of the difference between design air flow rate and operation air flow rate and then mixed with cooling tower outlet air, the mixed air becomes supersaturated. Assuming that the supersaturated liquid droplets generated inside the cooling tower can be removed relatively easily by methods such as drift eliminator and fog collector, wet air entering the pump can be assumed to be saturated with low temperature. This mixing and droplet elimination process is represented as “Internal Mix” in fig. 3. Then plume reduction temperature after mixing the excess of the design air volume as above was calculated. The result is as follows. From the table, it can be seen that less energy is required for mixed heating compared to direct heat pump application.

Outdoor RH 75%

T_out	Air flow	Heat Pump Output	Output with Mixing	Evap. In Temp.(°C)	Mixed Air Temp.(°C)
-5	488.1	655.9	39.36	34.31	6.954
-4	494.9	604.8	39.38	34.36	7.83
-3	502.1	557.5	39.41	34.42	8.704
-2	509.5	515.1	36.41	34.47	9.577
-1	517.3	474.6	36.44	34.52	10.45
0	525.5	438.2	36.48	34.57	11.32
1	533.7	398.3	36.51	34.62	12.18
2	543.2	362.1	33.5	34.67	13.06
3	552.3	327.6	33.54	34.72	13.92
4	561.8	296.3	30.52	34.77	14.77
5	571.9	267.5	30.55	34.82	15.62
6	582.5	241.2	27.53	34.86	16.47
7	593.6	216.3	27.56	34.91	17.32
8	605.4	192.9	27.6	34.95	18.17
9	618	172.3	27.64	34.99	19.01
10	631.3	152.1	24.6	35.04	19.85

Outdoor Temperature 0°C

RH_out	Air flow	Heat Pump Output	Output with Mixing	Evap. In Temp.(°C)	Mixed Air Temp.(°C)
0.75	525.5	438.2	36.48	34.57	11.32
0.76	525.9	446.9	39.52	34.57	11.33
0.77	526.4	455.7	39.52	34.57	11.34
0.78	526.8	465.5	42.56	34.57	11.35
0.79	527.3	476.4	45.6	34.57	11.36
0.8	527.7	487.3	45.6	34.56	11.36
0.81	528.2	498.3	48.64	34.56	11.37
0.82	528.6	510.3	51.68	34.56	11.38
0.83	529.1	523.4	54.72	34.56	11.39
0.84	529.5	537.6	57.76	34.56	11.4
0.85	530	552.8	60.8	34.56	11.41
0.86	530.4	569.2	66.88	34.56	11.42
0.87	530.9	587.7	69.92	34.56	11.43
0.88	531.3	606.2	76	34.56	11.44
0.89	531.8	630.1	82.09	34.56	11.45
0.9	532.2	654	91.21	34.56	11.46

Fig. 6. Heat pump output reduction effect with suggested operation proposal

4. Conclusion

The characteristics of the heat pump cycle in the cooling tower flow are as follows.

- Since air flow rate is fixed as the cooling tower operating value, the operation conditions of evaporator and condenser are restricted.
- When reheating air flow in condenser with the recovered heat from evaporator, a high condensing temperature is particularly required due to the low heat capacity of air.
- About 50°C discharge air, COP around 4 are expected under typical cooling tower rated conditions

The input energy characteristics for plume reduction are as follows.

- As the outdoor temperature decreases, the input energy needed increases rapidly. (Unsuitable operating conditions even for the heat pump cycle with sub-zero outdoor conditions)
- A design approach that lowers the discharge air temperature of the cooling tower while maintaining the circulating water temperature range is preferred.
- Operation that utilizes the flow rate margin between the design air volume and the operating air volume to take outside air is suggested to reduce the heat pump input energy further.

Heat pump cycle can control the evaporation temperature and condensation temperature. The low temperature heat recovered by heat pump can be upgraded and used for other high temperature purposes. Through this, it is possible to expand heat pump application not only to prevent plume generation, but also to recover and reused waste energy in exhaust gas in energy intense industries such as power generation, petrochemical, and paper manufacturing. The suggested approach will be able to expand its application to cooling towers for building air conditioning, cooling towers for subway heat treatment along with plume prevention for large cooling towers of power generation, petrochemical plants, etc.

Acknowledgements

This work was supported by the Technology Innovation Program (20018456, Development of a 160°C steam generation heat pump with thermal capacity of 350kW using oil-free centrifugal compressor) funded By the Ministry of Trade, Industry & Energy(MOTIE, Korea).

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