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Exergy analysis of cooling towers for optimization of HVAC systems

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ABSTRACT

Exergy analysis is a useful thermodynamic technique for assessing and improving the efficiency of processes and systems. By examining the exergy destruction properties, it is possible to optimize the environmental and economic performance of the systems. This research applies exergy analysis technique to investigate and optimize the performance of evaporative cooling towers in HVAC (heating, ventilating and air conditioning) systems. The analysis is carried out in two steps. The first step considers the physical exergy of each component and process within a whole HVAC system for a typical office building. The building's cooling load and cooling energy requirements are determined by building energy simulation software. Exergy destruction and exergy efficiency of the system are calculated from theoretical models. The result indicates that the exergy loss of cooling tower is quite significant, and the loss is affected by outdoor environment and condensing water temperature. The second step considers the chemical exergy of condensing water and outdoor air. A counter-flow wet cooling tower is investigated by experiments and theoretical models. The dry-bulb temperature and relative humidity of outdoor air are studied by an exergy approach in order to maximize the cooling tower performance. The distribution of exergy loss within the system has been shown and information to minimize exergy destruction and optimize the system efficiency can be determined.

Keywords: Exergy analysis, cooling towers, optimization of HVAC systems.

冷卻塔的火用分析應用在暖通空調系統的優化

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摘要: 火用分析是一種很有用的熱力學評估技術來提高系統和流程的效率。通過檢查火用破壞性能，可以優化系統的環境和經濟性能。本研究採用火用分析技術來研究和優化蒸發冷卻塔在暖通空調系統的性能。該分析有兩個步驟。第一步考慮火用物理過程的每一個組成部分，以典型辦公大樓的空調系統為例。該建築的冷負荷和冷卻能源需求是由建築能耗模擬軟件計算。火用效率的破壞和對系統的計算則採用理論模型。結果表明，冷卻塔的火用損失是相當顯著，它會受到室外環境和冷凝水溫度所影響。第二步考慮冷凝水和室外空氣的化學火用值。通過實驗和理論模型來研究一個逆流濕式冷卻塔。以火用的方法，探討室外空氣的幹球溫度和相對濕度如何用來以最大限度地提高冷卻塔的性能。通過分析在系統內火用損失的分配，可以確定資料以盡量減少火用破壞和優化系統的火用效率。

關鍵詞: 火用分析，冷卻塔，暖通空調系統的優化。

1. Introduction

Heating, ventilation and air conditioning (HVAC) systems account for a significant portion of the energy consumption in buildings. For the commercial buildings in Hong Kong, the air-conditioning systems could constitute 30% to 50% of the energy end-use (EMSD, 2009). Therefore, efficiency of HVAC systems is a major concern for energy saving nowadays.

Exergy analysis is a useful thermodynamic technique for assessing and improving the efficiency of processes and systems (Ahern, 1980; Kotas, 1985). It can be applied for studying the performance of evaporative cooling towers which are heat rejection devices in HVAC systems (Muangnoi, Asvapoositkul and Wongwises, 2007 & 2008). By examining the exergy and exergy destruction properties, it is possible to optimize the environmental and economic performance of the systems (Qureshi and Zubair, 2007; Ren, Li and Tang, 2002; Sayyaadi and Nejatolahi, 2011). Also, the exergy method can provide a benchmark for the analysis of air conditioning systems in buildings (Alpuche, *et al.*, 2005).

This research applies exergy analysis technique to investigate and optimize the performance of cooling towers in HVAC systems. The analysis is carried out in two steps: exergy analysis of HVAC systems and exergy analysis of cooling tower performance. The first step considers the physical exergy of each component and process within the whole HVAC system for a typical office building. The second step considers the chemical exergy of condensing water and outdoor air. By carrying out exergy analysis, distribution of exergy loss within the system can be indicated and essential information to minimize exergy destruction can be obtained.

2. Basic Principles

Exergy is defined as the work that is available in a gas, fluid, or mass as a result of its non-equilibrium condition relative to some reference condition, or simply the available energy (Ahern, 1980). The exergy method of energy system analysis is based on the second law of thermodynamics and the concept of irreversible production of entropy (Kotas, 1985). In general, the steady-state condition of surrounding environment will be used as a base to which work can be referenced for all systems. Exergy can show the real quantities and locations of the losses in energy resources.

Exergy technique has been used to evaluate overall and component efficiencies and to identify thermodynamic losses (Taufiq, *et al.*, 2007). The method is well suited for analyzing thermodynamic model and identifying exergy losses of air conditioning application. Unlike energy, exergy is a measure of the quality or grade of energy and it can be destroyed in the thermal system. Analysis of exergy losses provides information as to where the real inefficiencies of a system lie.

2.1 Exergy Analysis

Energy consists of useful work and waste energy. Exergy is the available work which determines the useful work potential of a given amount of energy at specified state, or simply the maximum useful work that can be obtained from a system (Cengel and Boles, 2007). Available work is maximized when the process between two specified states is reversible. To maximize the work output, a system must go to the dead state at the end of the process. Dead state is the state which the system is in thermodynamic equilibrium with the environment where the system is in. In general, the dead-state temperature and pressure are taken as T_0 = 25 ℃ and P_0 = 1 atm., respectively. Available work at a final state can be calculated with reference to the dead state as shown below.

Available work = $(h - h_0) - T_0 (s - s_0)$ (1)

where h = enthalpy at final state
h_0 = enthalpy at dead state
T_0 = temperature at dead state
s = entropy at final state
s_0 = entropy at dead state

Change in available work can be calculated from point 1 to point 2 in a given process. It is a loss if no useful work is done in the process (Ahern, 1980).

Available work change = $(h_2 - h_1) - T_0 (s_2 - s_1)$ (2)

(a) Balance of mass, energy and entropy

The balance equations of mass, energy and entropy can be expressed as follows:

$$\sum_i m_i - \sum_e m_e = m_2 - m_1 \quad (3)$$

$$\sum_i (e + P\nu)_i m_i - \sum_e (e + P\nu)_e m_e + \sum_r (Q_r)_{1,2} - (W')_{1,2} = E_2 - E_1 \quad (4)$$

$$\sum_i s_i m_i - \sum_e s_e m_e + \sum_r (Q_r/T_r)_{1,2} + \Pi_{1,2} = S_2 - S_1 \quad (5)$$

where m = mass
e = u + ke + pe (specific internal, kinetic and potential energy)
P = absolute pressure
ν = specific volume
$(Qr)_{1,2}$ = amount of heat transferred into the control volume across region r
$(W')_{1,2}$ = amount of work transferred out of the control volume
E = energy
s = specific entropy
S = entropy
T = absolute temperature
$\Pi_{1,2}$ = amount of entropy created in the control volume (also refers as S_{gen})
subscript i = state at inlet
subscript e = state at exit

(b) Exergy of flows

Exergy of matter flows: $\Delta x = (e_2 - e_1) + P_0 (\nu_2 - \nu_1) - T_0 (s_2 - s_1)$ (6)

Exergy by heat transfer: $X_{heat} = (1 - T_0/T) Q$, where Q = heat transfer at a location (7)

Exergy of work is equal to the net work done by the system (Cengel & Boles, 2007); exergy of electricity is just equal to the electrical energy (Dincer and Rosen, 2007).

Exergy destruction (lost of work potential): $X_{destroyed} = T_0 S_{gen} \geq 0$ (8)

2.2 Cooling Towers

Cooling tower is a “wet-bub” driven heat rejection device and its main function is to extract waste heat from warm water to the atmosphere. The heat rejection process involves heat and mass transfer as there is direct contact between ambient air and warm water (ASHRAE, 2008). Figure 1 shows the structure of a counterflow wet cooling tower. The cooling tower’s heat rejection performance depends very much on how close the condenser water leaving temperature reaches the wet-bulb temperature of outdoor air (Hill, Pring and Osborn, 1990).

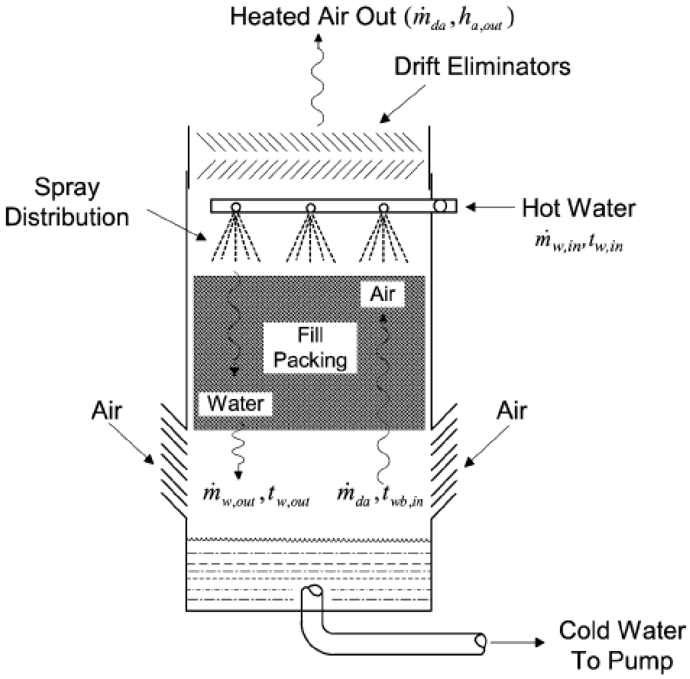

Figure 1. Counterflow wet cooling tower (Qureshi and Zubair, 2007)

Muangnoi, Asvapoositkul and Wongwises (2007) have developed a mathematical model for predicting the properties of water and air along the counterflow wet cooling tower based on heat and mass transfer principles. They have presented a method for the prediction cooling tower performance by using exergy analysis. According to their findings, the following equation is used for the calculation of air exergy in the cooling tower.

$$X_{air} = G\left[(C_{pa} + \omega C_{pv})\left(T - T_0 - T_0 \ln\frac{T}{T_0}\right) + R_a T_0 \left((1 + 1.608\omega) \ln\frac{1 + 1.608\omega_{00}}{1 + 1.608\omega} + 1.608\omega \ln\frac{\omega}{\omega_{00}}\right]\right. \tag{9}$$

where G = dry air mass flow rate in kg/s
C_{pa} = specific heat capacity of air = 1.004 kJ/kg.K
C_{pv} = specific heat capacity of water vapour = 1.872 kJ/kg.K
R_a = gas constant of air = 0.287 kJ/kg K
ω = humidity ratio of dry air (kg/kg)
T = temperature in K
subscript 0 = reference state (dead state)
subscript 00 = environment

3. Research Methods

The research is carried out in three ways: (a) building energy simulation, (b) energy and exergy analysis, and (c) experiment on cooling tower unit.

3.1 Building Energy Simulation

The cooling load and energy consumption of a typical office building are simulated using TRACE700 (Trane, 2005). The modelling assumptions and simulation data are based the local conditions in Hong Kong, with reference to the performance-based building energy code (EMSD, 2007). There are five important data obtained from the simulation results:

- Design cooling capacity
- Energy consumption in compressors
- Energy consumption in chilled water pumps
- Energy consumption in condensing water pumps
- Energy consumption in cooling tower fans

3.2 Energy and Exergy Analysis

A HVAC system cycle is constructed to demonstrate the relationship among different components and processes (see Figure 2). Energy consumption of the equipment is estimated from the building energy simulation results. Mass flow rates of refrigerant, chilled water, condensing water and outdoor air are calculated based on the first law of thermodynamics, with typical values assumed for the properties of chilled water and refrigerant.

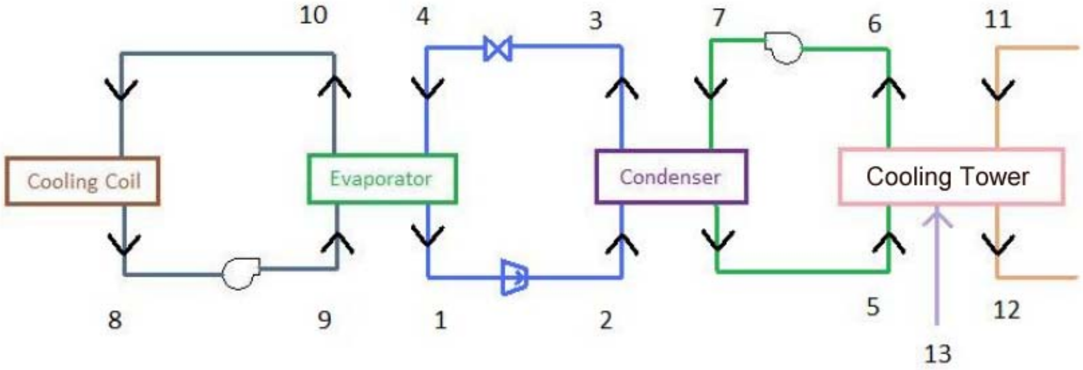

Figure 2. HVAC system cycle

The second law of thermodynamics uses an exergy balance for the analysis and design of thermal systems. Qureshi and Zubair (2007) has presented thermodynamic analysis of counter flow wet cooling towers and evaporative heat exchangers using both the first and second laws of thermodynamics. Irreversible losses are determined by applying an exergy balance on the systems. In this research, properties of moist air are obtained from an equation solver with built-in thermodynamic functions via the software Engineering Equation Solver (EES).

3.3 Experiments on Cooling Tower Unit

Experimental apparatus was used by Lemouari, Boumaza and Mujtaba (2007) to investigate the thermal performances of a wet cooling tower. Naphon (2005) studied the heat transfer characteristics of an evaporative cooling tower using a similar setup. In this research, experiment was carried out to examine the assumptions made for the energy and exergy analysis. Figure 3 the equipment used in the experiments. It imitates the operation of an open cooling tower for heat rejection purpose. The following two assumptions have been verified in the experiments: (a) leaving outdoor air is saturated after heat rejection process and (b) wet-bulb temperature of leaving outdoor air equals leaving condenser water temperature.

Figure 3. Cooling tower experiment unit

4. Exergy Analysis of HVAC System

Exergy analysis was carried out by considering the amount of exergy input and exergy output of the HVAC system. The exergy input is the electricity input for each equipment; the exergy output is the exergy remained after the deduction of exergy destruction. The exergy destruction for each process and component within the system is determined using the block method as suggested in Ahern (1980). The equations are shown in Table 1.

Table 1. Equations for calculating exergy destruction

Component	**Process**	**Exergy destruction***
Chilled water pump	Pumping	$E_8 - E_9 + W_{chw\ pump}$
Evaporator	Evaporation	$(E_4 - E_1) - (E_{10} - E_9)$
Compressor	Compression	$(E_1 - E_2) + W_{comp}$
Expansion valve	Expansion	$(E_3 - E_4)$
Condenser	Condensation	$(E_7 - E_5) - (E_3 - E_2)$
Condenser water pump	Pumping	$(E_6 - E_7) + W_{cond\ pump}$
Cooling tower	Heat rejection	$(E_{11} - E_{12}) - (E_6 - E_5 - E_{14}) + W_{fan}$
Heat sink (surrounding)	Heat exchange	$-Q \times (24 - 25)/(273.15 + 24)$

Note: * Please refer to Figure 2 for the state point numbers.

Table 2 gives a summary of the results of monthly exergy calculations for the whole HVAC system (based on the climate of Hong Kong and the assumptions for a typical office building). It can be seen that the maximum exergy efficiency (25.2%) occurs in May and the minimum (5.2%) in January. The exergy efficiency depends much on the wet-bulb temperature of outdoor air because cooling tower is a wet-bulb driven heat rejection equipment. Further examination of the data indicated that the cooling tower contributed 12.8% to 26.7% of the total exergy destruction (among all the components as shown in Table 1, it is the highest one for many months). The cooling tower performance also indirectly affected the compressor and condenser.

Table 2. Results of monthly exergy calculations

Month	**Exergy input (kW)**	**Exergy output (kW)**	**Exergy efficiency (%)**	**Exergy destruction (kW)**	**Cooling tower contributed to* (%)**
Jan	913.1	47.5	5.2	865.6	13.5
Feb	971.4	87.4	9.0	884.0	15.1
Mar	1121.7	134.0	12.0	987.7	18.2
Apr	1374.7	330.4	24.0	1044.3	12.8
May	1603.1	404.2	25.2	1198.9	16.3
Jun	1781.3	396.4	22.3	1384.9	23.4
Jul	1742.9	332.6	19.1	1410.3	24.9
Aug	1757.0	329.4	18.8	1427.6	26.7
Sep	1669.6	301.9	18.1	1367.7	22.1
Oct	1306.4	154.4	11.1	1242.0	22.8
Nov	1116.9	72.8	6.5	1044.1	19.4
Dec	958.6	50.3	5.3	908.3	17.3

Note: * Cooling tower contributed to total exergy destruction of the system.

5. Exergy Analysis of Cooling Tower

The exergy analysis of HVAC system in the previous section indicated that May is the month with highest exergy efficiency. Thus, the general weather data of May is taken in the exergy analysis of cooling tower. The focus here is how the change in outdoor air wet-bulb temperature affects the exergy efficiency. Six different scenarios of outdoor dry-bulb and wet-bulb temperatures were taken to represent regular steps of change in relative humidity from 50% to 100% which is common in the month of May in Hong Kong. Calculations of six different scenarios were carried out and the results are shown in Table 3.

Table 3. Six different scenarios for the exergy analysis of cooling tower

Ref.	**Outdoor air dry-bulb (°C)**	**Outdoor air wet-bulb (°C)**	**Relative humidity (%)**	**Exergy Efficiency (%)**
1	28.44	20.71	50	28.7
2	28.44	22.45	60	24.0
3	28.44	24.08	70	20.1
4	28.44	25.62	80	26.9
5	28.44	27.07	90	25.7
6	28.44	28.44	100	23.7

From Table 3, the maximum exergy efficiency occurs with relative humidity 50%. After that, the efficiency drops until reaches the lowest efficiency for relative humidity 70%. The efficiency rises again for relative humidity 80%, but decreases again with an increase in relative humidity. Since cooling tower rejects heat by sensible and latent heat losses, with lowest outdoor humidity, the water evaporation rate will increase and the latent heat loss will become more significant for the heat rejection.

The exergy of cooling tower can be divided into two parts: (a) air exergy and (b) water (condensing water) exergy (Muangnoi, Asvapoositkul and Wongwises, 2008). Table 4 shows the data calculated for them for the six different scenarios.

Table 4. Comparison of air and water exergy for the six scenarios

Ref.	Relative humidity (%)	Air Exergy (kW)	Air Energy (kW)	Water Exergy (kW)	Water Energy (kW)
1	50	146.8	7678.1	51.1	7540.5
2	60	70.8	7678.1	119.2	7540.5
3	70	7.7	7678.1	128.9	7540.5
4	80	117.6	7678.1	177.6	7540.5
5	90	97.9	7678.1	206.7	7540.5
6	100	65.7	7678.1	245.7	7540.5

From Table 4, the total energy of air and water are the same regardless of the change in relative humidity. It is because energy value is calculated by the change of enthalpy only. With the change in outdoor air temperature, the amount of entropy generated also varies. Therefore, exergy analysis can better show the relationship between outdoor environment and cooling tower performance. In general, water exergy increases with the increase in leaving water temperature. To minimize exergy destruction, the amount of air exergy should be sufficient to recover that of water exergy. Muangnoi, Asvapoositkul and Wongwises (2007) also obtained similar results from their research analysis in Thailand.

6. System Optimization

Optimization of HVAC system should consider how well the energy is being used and the quality of the energy resources. It is believed that the energy concept alone is insufficient to describe some important viewpoints on energy utilization (Muangnoi, Asvapoositkul and Wongwises, 2007). Therefore, exergy analysis was applied to indicate exergy and exergy destruction of water and air flowing through the cooling tower. A cooling tower assisted vapor compression refrigeration machine has been considered for optimization with multiple criteria by Sayyaadi and Nejatolahi (2011). A thermodynamic model based on energy and exergy analyses and an economic model have been developed.

In order to evaluate the exergy performance of cooling tower and compressor which are the most important components of HVAC system, the exergy destruction of these two components were identified as shown in Figure 4 for the six different scenarios described in the previous section. It is found that cooling tower and compressor contribute the major part of total exergy destruction within the whole HVAC system. With the change in relative humidity, exergy destruction by compressor does not change, but that of cooling tower varies a lot. In order to optimize the efficiency of the whole HVAC system, analyses can be carried out to investigate and reduce the entropy generation of each component or process.

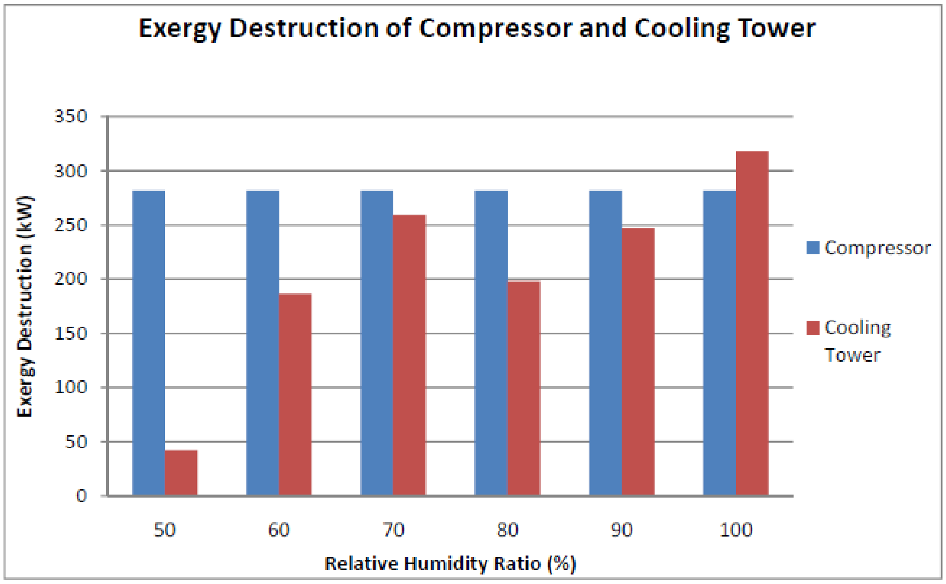

Figure 4. Exergy destruction of cooling tower and compressor

7. Conclusions

In this research, the technique of exergy analysis has been applied to study the performance of cooling towers in HVAC systems. The exergy method, also known as the second law analysis, calculates the exergy destruction caused by irreversibility and indicates the useful work that can be produced by a substance or the amount of work needed to complete a process. Exergy destruction and exergy efficiency of the system were calculated from theoretical models for a typical office building under Hong Kong climate. The result indicates that the exergy loss of cooling tower is quite significant for the HVAC system. This loss is affected by outdoor environment and condensing water temperature.

By considering the chemical exergy of condensing water and outdoor air at the cooling tower, it is possible to evaluate the distribution of exergy loss within the HVAC system and identify the important factors needed to optimize the overall system efficiency. The data from building energy simulation provided the basis for the energy and exergy analyses; whereas the experiment on cooling tower unit help to examine the assumptions made for the analyses.

It should be noted that exergy analysis is not a substitute for first law energy analysis, rather a supplement. It can indicate possibilities for improvement of a process but cannot indicate the practicality of any possibility. Further efforts are needed to examine the practical situation and develop strategy for optimization of real HVAC systems.

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