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Desalination 209 (2007) 238–243
DESALINATION
www.elsevier.com/locate/desal

Exergy analysis of evaporative cooling for reducing energy use in a Malaysian building

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Abstract

To reduce energy consumption in the buildings and minimize negative environmental impacts, it is necessary to determine the operating condition that provides optimum system performance. Entropy or exergy analysis can be used as a reliable tool for analyzing energy consumption and environmental impact. This paper describes the modelling and optimization analysis for cooling system in the building. Exergy technique has been used to evaluate overall and component efficiencies and to identify thermodynamic losses. The method is well suited for analyzing thermodynamic model and identified exergy losses of air conditioning application in a building.

Keywords: Energy consumption; Building; Exergy; Optimization; Air conditioning

1. Introduction

The main contributor to increasing atmospheric carbon dioxide (CO_2) concentration is the combustion of fossil fuels from electricity generation, commercial and domestic uses. The demand for energy is expected to grow rapidly in developed countries as well as in the developing countries as they attempt to obtain a higher standard living. This increase energy demand and consequently increase carbon dioxide concentration in the atmosphere.

Energy consumed in HVAC accounts for approximately 20% of the total energy consumption nowadays. Effective use of energy is important. Evaporative cooling uses recovered energy for air conditioning. Evaluation of evaporative cooling performance is very important in improving the use of energy and the indoor air quality [1].

Like other developing countries with hot and humid climates, Malaysia has been experiencing

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The Ninth Arab International Conference on Solar Energy (AICSE-9), Kingdom of Bahrain

0011-9164/06/$– See front matter
doi:10.1016/j.desal.2007.04.033

dramatic growth in the number of use of air conditioners, and the usage will be higher in the future. In the HVAC applications, evaporative cooling may be utilized to reduce energy consumption or to replace conventional refrigeration system.

Evaporative cooling is a technology that can substantially reduce the cooling energy requirement in the building. There are three types of evaporative cooling process: direct, indirect and indirect/direct. In direct evaporative cooling processes, the air is brought into direct contact with water in the direct evaporative cooler. Indirect evaporative cooling is achieved by sensibly cooling a primary air stream through heat exchanger. Heat is transferred to a secondary fluid on the cold side of the heat exchanger, which ultimately rejects heat to the atmosphere by evaporation effect. The cold-side fluid may be air, water, or in the case of a heat pipe-refrigerant [2].

Energy and exergy methods are usually used to study energy conversion processes. The exergy method, known as the second law analysis, calculates the exergy loss caused by irreversibility, which is an important thermodynamic property which measures the useful work that can be produced by a substance or the amount of work needed to complete a process [3]. 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 in a system lie. The second law of thermodynamics uses an exergy balance for the analysis and design of thermal systems.

In this paper, the use of the concept of exergy in the assessment of air-conditioning applications will be applied to optimize the system. The concepts of physical exergy and chemical exergy are an important role in assessing the true thermodynamic merit of air conditioning applications.

2. Data input

Malaysia, being an equatorial country, has a uniform temperature throughout the year. There was no large variation in temperature throughout the country. Several studies show that ambient temperature has major contribution of energy consumption of air conditioning system. The data represent the average humidity and temperature for 10 years from 1972 to 1998 in Malaysia is collected for this study. However, because of commercial building is occupied from 8 p.m. to 5 a.m., therefore only the temperatures when the building is occupied are used for this study. The average hourly temperature and relative humidity in Malaysia show in Table 1 [4].

For the purpose of selecting the temperature of air entering indoor side, the comfort range and the effective temperature for the population in the particular country and region were considered. The classification was made on the effective temperature and comfort range for a hot climate country (population) like Malaysia. In fact, to set an effective temperature for all human being is impossible because an optimum and acceptable level of comfort range for acclimatized Asian Africans was found to be higher compared to the

Table 1
Records of daily average temperature and relative humidity of Malaysia [3]

Hour	Temperature (°C)	RH (%)
8	25.63	92.2
9	27.52	82.0
10	29.21	74.6
11	30.39	70.1
12	30.01	67.5
13	31.23	67.0
14	30.98	68.5
15	30.21	71.8
16	29.2	75.6
17	28.09	79.3
Average	29.25	74.86

Table 2
Comfort range and effective temperature for hot climate

Comfort range	Effective temperature °F (°C)
Above acceptable	Above 76 (above 24.5)
Upper acceptable	73–76 (22.8–24.5)
Optimum	69–73 (20.6–22.8)
Lower acceptable	66–69 (18.9–20.6)
Below acceptable	Below 66 (below 18.9)

higher population of North Amaerica and Europe [5]. The comfort range and effective temperature for hot climate have been discussed in the User manual fro the ASEAN climatic atlas and the compendium of climatic statistics. The result is tabulated in Table 2 [6].

3. Methodology

A reversible thermodynamic process can be reserved without leaving any trace on the surroundings. That is, both the system and the surroundings are returned to their initial states at the end of the reverse process. This is possible only if the net heat and network exchange between the system and surrounding is zero. All real processes in nature are irreversible.

Exergy measures the ability of energy to work. Exergy can be transferred by three means: exergy transfer associated with work, exergy transfer associated with heat transfer, and exergy transfer associated with the matter entering and exiting a control volume. All such exergy transfers are evaluated relative to the environment used to define exergy. Exergy is also destroyed by irreversibilities within the system or the control volume [7]. For fluid flow, the exergy represents the work that can be produced in a reversible process that is designed to bring it in a state of equilibrium with the environment. The exergy balance for the control volume may be represented as follows:

$$\dot{m}_{\mathrm{a}} e_{\mathrm{t,a}} + \dot{m}_{\mathrm{w}} e_{\mathrm{t,w}} = \dot{m}_{\mathrm{a}} e_{\mathrm{t}} + \dot{S} T_{0\mathrm{gen}} \tag{1}$$

The physical exergy is the work obtainable by taking the substance through reversible process from its initial state to the state of the environment. The specific exergy is written as:

$$e_{\mathrm{ph}} = (h - h_0) - T_0 (s - s_0) \tag{2}$$

where h_0 and s_0, respectively, the specific enthalpy and entropy at the restricted dead state. The moist air encountered in air conditioning applications may assumed from the definition of the physical flow exergy applied to an ideal mixture and its specific total flow exergy per mole of humid air mixture may be represented as follows:

$$e_{\mathrm{t}} = (c_{\mathrm{p,a}} + \omega c_{\mathrm{p,v}}) T_0 \left[\frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right] + (1 + \bar{\omega}) R_{\mathrm{a}} T_0 \ln \frac{P}{P_0} + R_{\mathrm{a}} T_0 \left[(1 + \bar{\omega}) \ln \frac{1 + \bar{\omega}_o}{1 + \bar{\omega}} + \bar{\omega} \ln \frac{\bar{\omega}}{\bar{\omega}_0} \right] \tag{3}$$

where the mass ratio called specific humidity or humidity ratio, ω, and the mole fraction ratio, $\bar{\omega}$, are defined as follows:

$$\omega = \frac{m_{\mathrm{v}}}{m_{\mathrm{a}}} \tag{4}$$

$$\bar{\omega} = \frac{x_{\mathrm{v}}}{x_{\mathrm{a}}} \tag{5}$$

The specific total flow of dry air can be calculated as follows:

$$e_{\mathrm{t,a}} = c_{\mathrm{p,a}} T_0 \left[\frac{T}{T_0} - 1 - \ln \frac{T}{T_0} \right] + R_{\mathrm{a}} T_0 \ \ln \frac{P}{P_0} + R_{\mathrm{a}} T_0 \ \ln \left[1 + \bar{\omega}_0 \right] \tag{6}$$

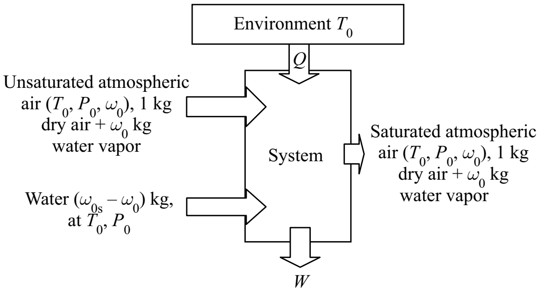

Fig. 1. Schematic of an ideal process.

The total flow exergy of liquid water can be approximated by using the properties of respective neighboring states on the two-phase dome of mollier chart [8]:

$$e_{\mathrm{t,w}} \cong h_{\mathrm{f}}(T) - h_{\mathrm{g}}(T_0) - T_0(s_{\mathrm{f}}(T) - s_{\mathrm{g}}(T_0)) + \left[P - P_{\mathrm{sat}}(T)\right] v_{\mathrm{f}}(T) - R_{\mathrm{v}} T_0 \ \ln\phi_0 \tag{7}$$

The schematic diagram of an ideal process of evaporative cooling is presented in Fig. 1. Such process will allow the water to diffuse into the unsaturated air reversibly and will reach the saturated state. Usually, the atmospheric state (T_0, p_0, ω) will be considered as the dead state. The exergy for water is

$$e_{\mathrm{t,w}} = -R_{\mathrm{v}} T_0 \ \ln\phi_0 \tag{8}$$

$$\phi = \frac{P_{\mathrm{w,0}}}{P_{\mathrm{w,0s}}} \tag{9}$$

where $P_{\mathrm{w,0}}$ is the water vapor pressure of the unsaturated atmospheric air and $P_{\mathrm{w,0s}}$ is the saturated water vapor pressure at T_0.

The exergetic efficiency provides a true measure of the performance of a system from the thermodynamic viewpoint. For a control volume at steady state whose exergy rate balances can be estimated by:

$$\dot{E}_{\mathrm{F}} = \dot{E}_{\mathrm{P}} + \dot{E}_{\mathrm{D}} + \dot{E}_{\mathrm{L}} \tag{10}$$

The exergetic efficiency can be represented as follow:

$$\varepsilon = \frac{\dot{E}_{\mathrm{P}}}{\dot{E}_{\mathrm{F}}} = 1 - \frac{\dot{E}_{\mathrm{D}} + \dot{E}_{\mathrm{L}}}{\dot{E}_{\mathrm{F}}} \tag{11}$$

where $\dot{E}_{\mathrm{F}}$ is the rates at which the fuel is supplied and $\dot{E}_{\mathrm{P}}$ denotes the product is generated. $\dot{E}_{\mathrm{D}}$ and $\dot{E}_{\mathrm{L}}$ denotes the rates of exergy destruction and exergy loss, respectively. The rate of exergy destruction per kg of dry air is, therefore

$$\frac{T_0 \dot{S}_{\mathrm{gen}}}{\dot{m}_{\mathrm{a}}} = e_{\mathrm{t,a}} + \omega e_{\mathrm{t,w}} - e_{\mathrm{t}} \tag{12}$$

Then, the exergy efficiency of the evaporative cooler can be defined in the term of:

$$\varepsilon = \frac{e_{\mathrm{t}}}{e_{\mathrm{t,a}} + \omega e_{\mathrm{t,w}}} \tag{13}$$

In HVAC, the energy flows also need to be properly classified in order to get a proper evaluation of exergy product and exergy supply. The input electricity or mechanical work is obviously classified into exergy supply. The reduction of exergy of the secondary flow streams that is used to heat or cool, or humidity the primary flow streams should also be classified into exergy supply. The relevant energy flow can be regarded as the source energy flow. While the increase of exergy of primary flow streams is classified into exergy product, the relevant energy flow is regarded as service energy flow because it is provided to serve the need for other systems [9].

4. Results and discussion

The conventional air conditioning is usually used to cool or dehumidify the hot moist air. However, in evaporative cooling, air is cooled by

Table 3
Ideal gas constants of dry air and water vapor

Dry air	Water vapor
$R_a = 0.287$ kJ/(kg K)	$R_v = 0.4615$ kJ/(kg K)
$C_{p,a} = 1.003$ kJ/(kg K)	$C_{p,a} = 1.872$ kJ/(kg K)
$M_a = 28.97$ kg/kmol	$M_a = 18.015$ kg/kmol
$\bar{R}_a = 8.314$ kJ/(kmol K)	$\bar{R}_a = 8.314$ kJ/(kmol K)
$\bar{c}_{p,a} = 29.057$ kJ/kmol K)	$\bar{c}_{p,v} = 33.724$ kJ/(kmol K)

humidifying the primary or secondary air. The direct evaporative cooling process is used as an example in this study. The atmospheric state is selected as the dead state for calculating the exergy of moist air. The choice of $P_0 = 1$ atm is quite obvious, however there is a lack of a convention for the selection of T_0 and ϕ_0. The properties of humid air as the a perfect gas mixture of dry air and water vapor is tabulated in Table 3 [8].

Fig. 2 shows the correlation between relative humidity and exergy efficiency. The study found that typically, as the relative humidity is increased, exergy efficiency will be increased. In direct evaporative cooling process, the mixing of fresh and return air causes the destruction of the exergy of fluid stream. However, the enthalpy of the moist air approximately remains constant because of the adiabatic evaporation.

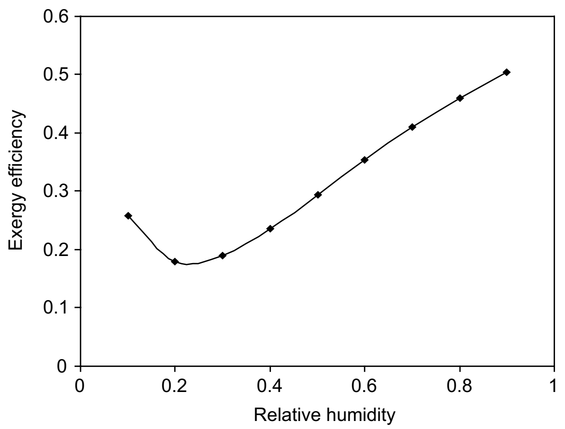

Fig. 2. Exergy efficiency of the evaporative cooling process as function of relative humidity with $T_0 = 29.25$°C.

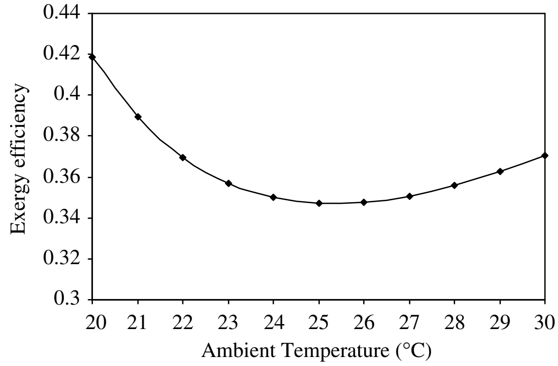

Fig. 3. Exergy efficiency of the evaporative cooling process as function of ambient temperature with RH = 70%.

And, the pressure of the air decrease because of the flow resistance. The correlation between ambient temperature and exergy efficiency is presented in Fig. 3.

This study also has shown that an effectiveness of evaporative cooling heat exchanges has great importance in improving the performance of evaporative cooling that applied in cooling system.

5. Conclusions

The exergy analysis of an evaporative cooling applied in Malaysian building has been presented through the exergy balance of an open system. The evaporative cooling is a feasible technology that can reduce mechanical cooling and energy requirement in air conditioning application that will effect to decrease emissions from electricity generation in Malaysia. Thus, further work should be conducted to improve the effectiveness of the evaporative cooling.

Nomenclature

c_p	specific isobaric heat capacity (kJ/kg K)
e	specific exergy (kJ/kg)
E	exergy (kJ)

h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
Q	heat load (kJ)
R	specific ideal gas constant (kJ/kg K)
S	entropy (kJ/kg K)
s	specific entropy (kJ/kg K)
T	temperature (°C, K)
W	work (kJ/kg)
ϕ	relative humidity (%)
ε	exergy efficiency
ω	specific humidity (%)
$\bar{\omega}$	mole fraction ratio

Subscripts

0	ambient state, dead state
a	dry air
ch	chemical
f	saturated liquid
g	saturated vapor
gen	generation
i	input
o	output
p	potential
ph	physical or thermochemical
t	total
v	water vapor
w	water

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