Energy and Buildings 67 (2013) 261–266

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Measurable energy savings of installing variable frequency drives for cooling towers' fans, compared to dual speed motors

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ARTICLE INFO

Article history:
Received 20 May 2013
Received in revised form 24 July 2013
Accepted 30 July 2013

Keywords:
Building management system
Dual speed
Cooling towers fans
Variable frequency drive
Water consumption

ABSTRACT

In recent years the building management system (BMS) controllers have been used to control the operation of heating, ventilation, and air conditioning system in addition to lighting and some electrical equipment in order to save energy. In the water cooled system, the BMS controls the operation process of the cooling towers (CTs) fans of dual speed motors to maintain a constant leaving water temperature for different cooling loads and different ambient wet bulb temperature (WBT). This paper presents the effect of installing variable frequency drives (VFDs) for CTs fans in Kuwait during summer season on energy savings compared to dual speed control. The results have shown that with VFD mode, the reduction in water consumption was over 13% compared to the commonly used dual speed mode. More importantly, the combined power for the chillers and the CTs fans for the same amount of cooling produced were reduced by 5.8% in the VFD mode.

1. Introduction

The power production system in Kuwait has recently experienced a dramatic increase in peak load demand specifically during summer due to outdoor weather conditions. The hot weather conditions have a big effect in increasing the energy consumption of air conditioning system. Nowadays, energy conservation has been the core of attention in many countries due to the limited amount of non-renewable energy sources. In addition, the consumption of non-renewable sources has an impact on the environment. Implementation of an energy conservation measures for attenuating electrical demand and mitigating pollution is required. Toward this direction many commercial and governmental buildings have installed energy management system to operate and control an active systems such as heating, ventilation, and air conditioning system in addition to lighting and some electrical equipment in order to save energy [1,2].

Cooling tower (CT) for an air-conditioning (A/C) system with water-cooled (WC) condenser is selected for the maximum cooling load and for the worst design conditions of the place to ensure year round comfort. Thus, for most of the time, it operates under part load and/or favorable weather conditions leading to unwanted electricity and water consumption. Optimization and control techniques in cooling towers are considered a potential source in energy efficiency and water consumption that represent sustainable development [3]. A commonly used control scheme in most countries is to maintain a constant CT leaving water temperature, regardless to variations in the cooling load and the ambient wet bulb temperature (WBT) from the design conditions. This is achieved by regulating the air circulation through the CT [4]. The air circulation reduced with the help of a variable frequency drive (VFD), results in significant reduction in the CT fan power. Theoretically, reduction in fan power of up to 87.5% is likely to be achieved for a 50% reduction in air circulation [5], since the power consumed by the fan drive varies as the cube of the speed according to fan laws [6]. Adams and Stevens [7] established that there is a potential for energy reduction both for the new and the existing CT installation by proper selection of design parameters and operation control for the fans. In addition, the profitability from energy savings for the VFD for a CT fan motor is good as the air flow is likely to vary diurnally and seasonally [8]. Many Mathematical models have been used as an energy savings tools to determine the appropriate control associated with the operation of CT [3,9,10], and water-cooled chiller system with the individual and mixed uses of efficient technologies [11].

In Kuwait and the other countries of the region most of the time during the summer season, the DBT of the incoming ambient air is significantly more than the incoming hot water temperature and the air undergoes sensible cooling. This results in unwanted heat transfer from air to water, demanding increased water vaporization to achieve the required cooling of water. Thus, any reduction in airflow in CT in Kuwait not only reduces energy consumption, it minimizes water consumption as well [12]. This phenomenon,

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http://dx.doi.org/10.1016/j.enbuild.2013.07.081

Nomenclature

CT	cooling tower
WBT	wet bulb temperature
DBT	dry bulb temperature
VFD	variable frequency drive
CTEWT	cooling tower entering water temperature
CTLWT	cooling tower leaving water temperature
θ_{ct}	cooling tower approach
h_{fg}	latent heat of vaporization
Q_h	heat rejection by the condenser water
W_{eo}	water consumption
q_h	condenser water flow rate
c_{pw}	specific heat
ΔW_e	difference of the make up water to the cooling tower and the blow down
W_b	water blowdown
W_m	water make up
W_e	water evaporation
VAF	variable airflow
CAF	constant airflow
$P_{chiller}$	power demand of the chiller compressor
$P_{ctf,r}$	fan power for the reduced air flow
$P_{ctf,d}$	design fan power
q_{ar}	reduced air flow
q_{ad}	design air flow
P_{ctf}	cooling tower fan power
P_{cwp}	condenser water pump power
$PR_{chiller}$	chiller power rating
ρ_w	water production equivalent power
CHEWT	chilled water entering temperature
CHLWT	chilled water leaving temperature
η_m	efficiency of pump water
Q_{muw}	heat of make up water make up water temperature (MUWT)
RT	refrigeration ton
L/s	liter per second
gpm	gallons per minute
°C	degree celsius
CTIAT	incoming air temperature to cooling tower
ΔW_e	water loss for self cooling of air
q_a	air mass flow rate
c_{pa}	air specific heat
CTLAT	leaving air temperature from cooling tower
Q_{cD}	cooling production
cfm	cubic feet per minute
W_{e_D}	daily water consumption
l/RTh	water consumption per unit of cooling production
PR_s	system power rating
WBD	wet bulb depression

defined as the 'self-cooling of air' was highlighted for the first time by the authors Maheshwari and Al-Bassam [13].

The objective of the present work is to verify the technical viability of VFD for the CTs as a water and energy-efficient device using the field data of a site in Kuwait during summer time. CT fans in this site, originally fitted with dual speed motor and operate by BMS control, were retrofitted with VFDs. The site was adequately instrumented to assess energy and water consumption of the cooling production system. Water and power savings in the VFD mode were compared to the dual speed mode.

2. Description of the selected site and its cooling system

Airport Commercial Building at Kuwait International Airport was selected for the study. The cooling production system in this building is comprised of four chillers, each having a rated capacity of 354 RT, and an additional chiller of rated capacity of 490 RT. The five chillers have equal number of primary chilled water pumps, condenser water pumps and CTs; however, their chilled water and condenser water distribution systems are common. A list of major components with their design technical specifications is given in Table 1. Originally every CT fan was to be operated with two speed motors, which is connected to the chiller control panel through a dual speed starter. The chiller control panel has a built in microprocessor-based controller that gives signal to BMS to switch between the fan speeds for automatically maintaining the leaving water temperature from CT. Subsequently, the CT fans were retrofitted with the VFD and controlled by BMS through a manual switch. The VFD capacity for the four CTs was 75 kW and the fifth large CT has VFD capacity of 55 kW as shown in Table 1.

3. Monitoring parameters and instruments

Condenser water flow rate, chilled water flow rate, condenser water temperatures at the inlet and outlet of the CT and chilled water temperatures at the inlet and outlet of the chiller were the parameters monitored for instantaneous performance assessment of the cooling production system. Flow rate of the condenser water and chilled water, were essentially constant, and they were measured on one-time basis periodically. Power transducers were used to measure power consumption of chillers and the CT fan motors. The instantaneous water consumption, make-up water, and blow down water rates were monitored continuously. In addition, parameters included ambient DBT and relative humidity, wind speed and direction were monitored. Full technical specifications of the instruments are given in Table 2 while the control and instrumentation scheme is shown in Fig. 1.

4. Methodology and data analysis

Important power and water demand correlations for a cooling system with water cooled condenser have been developed. In addition, other related issues such as the effect of air–water ratio on CT performance and CT fan power consumption with a VFD have been analyzed. Finally a methodology for data analysis and estimating the energy and water savings of a VFD compared to dual speed modes has been presented.

4.1. Cooling systems with water cooled condenser

Cooling system with water-cooled condenser (WC-cooling system) rejects heat to water in a shell-and-tube heat exchanger, which is eventually transferred to the ambient air through humidification process in a CT.

4.1.1. Water consumption in a cooling tower

The water consumption in a CT is mainly due to the evaporation process. In case of zero sensible cooling transfer between the air and the water, it is the amount of water whose latent heat of vaporization (h_{fg}) is equal to the sensible cooling or the heat rejection by the condenser water (Q_h) in CT. The water consumption (W_{e_0}) and Q_h are calculated as:

$$W_{e_0} = \frac{Q_h}{h_{fg}} \quad (1)$$

$$Q_h = q_h \times \rho \times c_{pw} \times (\text{CTEWT} - \text{CTLWT}) \quad (2)$$

Table 1
Technical specifications of the cooling production system at airport commercial building.

Description	Chillers		Cooling towers		Condenser water pumps		Chilled water pumps	
	1–4	5	1–4	5	1–4	5	1–4	5
Make	Trane		Baltimore		Pullen Pumps		Pullen Pumps	
Model	CVHE-330	CVHE-420	33,458	3648A	HSC 150-380B	HSC 150-380A		
Power (kW)	284	392	18.5[a]	37.5	22	45	15	19
VFD Capacity (kW)	N/A	N/A	75[b]	55	N/A	N/A	N/A	N/A
Water flow (l/s)	54	75	66	95	66	95	54	75
Cooling capacity (kW)	1244	1740	1547	2223	N/A	N/A	N/A	N/A

N/A = not applicable.
[a] For each cooling tower.
[b] For all four cooling towers.

Table 2
Specifications of instruments at airport commercial building.

Performance parameter	Instrument/sensor	Make	Accuracy
Make up water temperature (°C)	RTD	Omega Engineering	±0.01 °C at 0 °C
Inlet/outlet water temperatures for C/T, evaporator and condenser (°C)	Thermister	Trane	±0.2 °C
Make up & blow-down water flow (l/s)	Electromagnetic flow meter	Endress + hauser	±0.5% FS
Chilled & condenser water flow (l/s)	Ultrasonic flow meter		±2% FS
Air entering & leaving C/T temperature (°C)	Combined temperature and relative	Able instruments &	±0.5 °C
Air entering & leaving C/T relative humidity (%)	humidity sensor	control	±2% FS
Wind Speed (m/s) & direction	Combined wind speed/direction sensor	Lastem	±5 °C
Total blow down water consumption (l)	Domestic flow totalizer		N/A

FC = full scale; N/A = not applicable.

where q_h, ρ and c_{pw} are the flow rate, density and specific heat of the condenser water; h_{fg} is the latent of heat of vaporization of water; while CTEWT and CTLWT are the incoming and leaving condenser water temperature to and from the CT, respectively. In Kuwait, for most of the time during the peak summer season, the ambient DBT is higher than CTEWT. In such circumstances, air while cooling the water also gets sensible cooling, and its temperature approaches to CTEWT. This process defined by authors as sensible cooling of the air, results in additional water (ΔW_e) evaporation [14].

Water blow down in CT, the amount of water discharged periodically as waste, so as not to let the salinity of the water in circulation exceed the critical level is also significant. Evaporation process

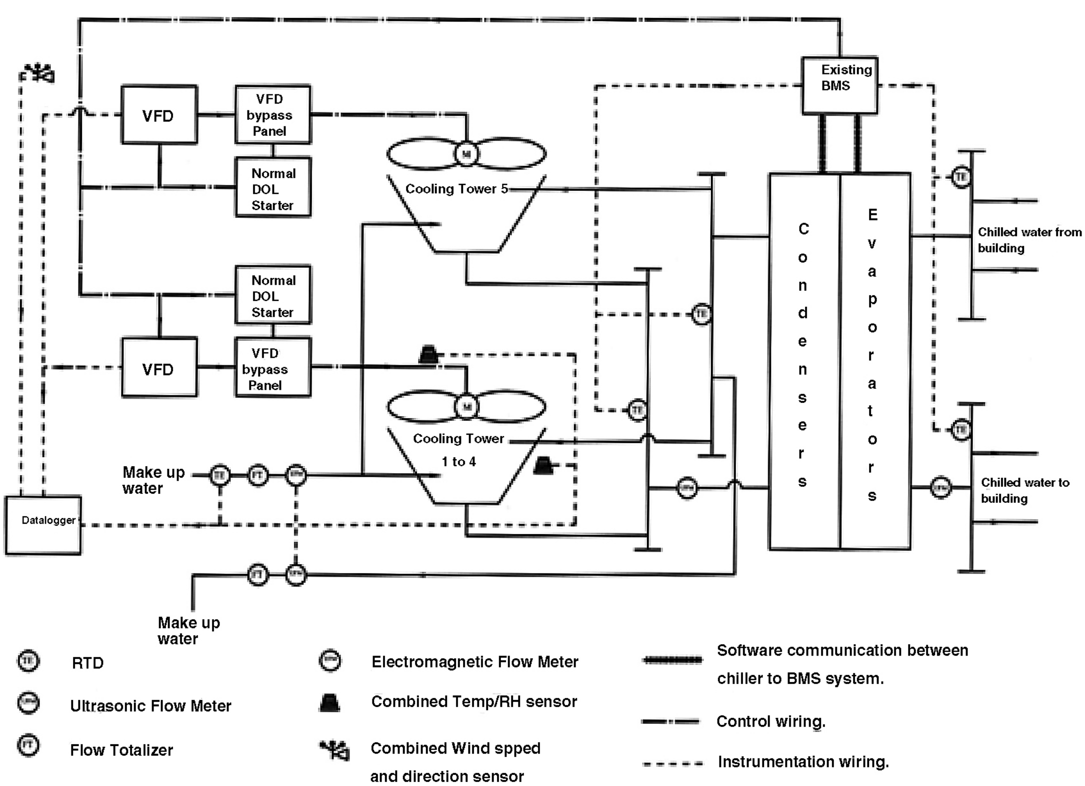

Fig. 1. Control and instrumentation diagram at Airport Commercial building.

(W_e), the sum of W_{e_0} and ΔW_e, is determined as the difference of the make-up water to the CT (W_m) and the blow down (W_b).

$$W_e = W_m - W_b \quad (3)$$

4.1.2. Power demand of a cooling production system

The power demand of a WC-cooling production system (P_s) is determined by combing the power of the chiller compressor ($P_{chiller}$), CT fan (P_{ctf}), condenser water pump (P_{cwp}), and equivalent power to generate desalinated water (P_w).

$$P_s = P_{chiller} + P_{ctf} + P_{cwp} + P_W \quad (4)$$

Energy cost of water production in the desalination plants in Kuwait @ 22 kWh/m^3 [15] is used to estimate P_w as follows:

$$P_w = W_e \times 22\,\text{kW} \quad (5)$$

where P_{cwp} is essentially constant. For a constant airflow (CAF), P_{ctf} and P_w are constant while $P_{chiller}$ reduces gradually with a decrease in CTLWT. It is determined as the product of the chiller power rating ($PR_{chiller}$) and the chiller cooling (Q_c).

$$P_{chiller} = PR_{chiller} \times Q_c \quad (6)$$

where $PR_{chiller}$ is a characteristic of the type, size, and model of the chiller and the CTLWT. Q_c and $P_{chiller}$ are estimated as:

$$Q_c = q_c \times \rho_w \times c_{pw} \times (\text{CHEWT} - \text{CHLWT}) \quad (7)$$

$$P_{chiller} = \sqrt[3]{\frac{V * I * \text{PF}}{1000}}\,\text{kW} \quad (8)$$

where q_c is the chilled water flow rate, and V, I and PF are the voltage, current and power factor of the chiller. Heat rejection in CT, given by Eq. (2) can be alternatively estimated as follows:

$$Q_h = Q_c + P_{Chiller} + P_{cwp} \times \eta_m + Q_{muw} \quad (9)$$

where η_m is the efficiency of pump motor and Q_{muw} is the heat of make-up water. Although not very significant, Q_{muw} is estimated as follows using the make-up water temperature (MUWT)

$$Q_{muw} = W_m \times \rho_w \times c_{pw} \times (\text{MUWT} - \text{CTLWT}) \quad (10)$$

The correlation given in Eq. (9) is helpful for the sites where measurement of condenser water flow is difficult. This was the case for the present study as well.

4.1.3. Chiller power rating

Studying the effect of CTLWT on chiller performance is important to optimize electricity and water consumption of a WC-cooling production system. For a chiller loading of 70 ± 2% and leaving chilled water temperature of 7 ± 0.25 °C, the $PR_{chiller}$ was found to be varying linearly with CTLWT as follows (Fig. 2):

$$PR_{chiller} = 0.0128\,\text{CTLWT} + 0.3886 \quad (11)$$

For the CTLWT range of 24–33 °C, the average increase in $PR_{chiller}$ was 1.7% for every degree Celsius increase in CTLWT. For the present analysis, data with a chiller loading of 70% and above only have been considered to minimize the adverse effect of chiller loading on its performance as the average increase in PR for a 10% reduction in chiller loading is about 1.85% (Fig. 2).

4.2. Application of VFD to regulate air circulation through CT

Presently, most of the CTs have two speed fans, namely the low speed and high speed, although use of single speed fans is not uncommon. Generally, a building management system (BMS) regulates the operating speeds of the fans to ensure CTLWT within a close range. The CTLWT can be controlled more precisely by regulating the airflow through the CT by a VFD driven fan.

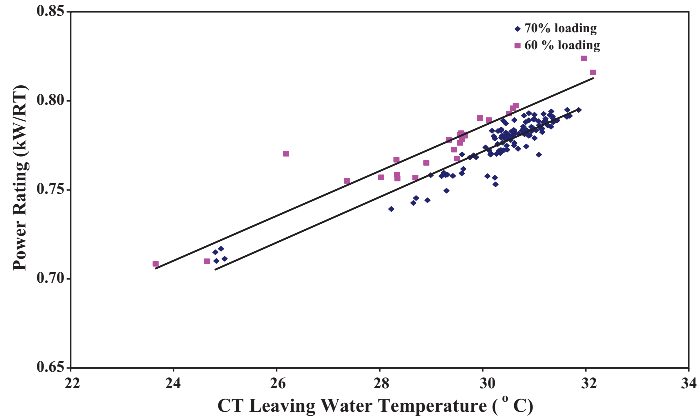

Fig. 2. Effect of cooling tower supply water temperature on chiller power rating.

4.2.1. CT fan power with VFD

The fan power for the reduced air flow ($P_{ctf,r}$) is obtained as follows:

$$P_{ctf,r} = P_{ctf,d}\left(\frac{q_{ar}}{q_{ad}}\right)^3 \quad (12)$$

where $P_{ctf,d}$ is the design power for the CT fan and q_{ad} and q_{ar} are the design and reduced air flow, respectively. Based on the measured fan power under different operational modes, the estimated and measured fan power is shown in Fig. 3. The measured power is slightly higher than the estimated fan power for lower speed. This is likely due to the inefficiencies associated with the mechanical system of the fan and the winding losses in the motor.

4.2.2. Effect of air–water ratio on cooling tower performance during summer season

During the summer season, the DBT of CT incoming air (CTIAT) is more than the CTEWT. This period is characterized with the sensible cooling of air as the DBT of the CT leaving air is less than the CTIAT.Data were collected for a constant water flow rate while the air circulation was regulated under different operation modes. Effect of air–water ratio (G/L) on water consumption for self-cooling of air (ΔW_e) and CT approach (θ_{ct}) were studied.

4.2.2.1. Water loss analysis for self cooling of air. ΔW_e is the product of air mass flow rate (q_a) and drop in its temperature across the CT. It can be expressed as:

$$\Delta W_e = \frac{q_a \times \rho \times c_{pa} \times (\text{CTIAT} - \text{CTLAT})}{h_{fg}} \quad (13)$$

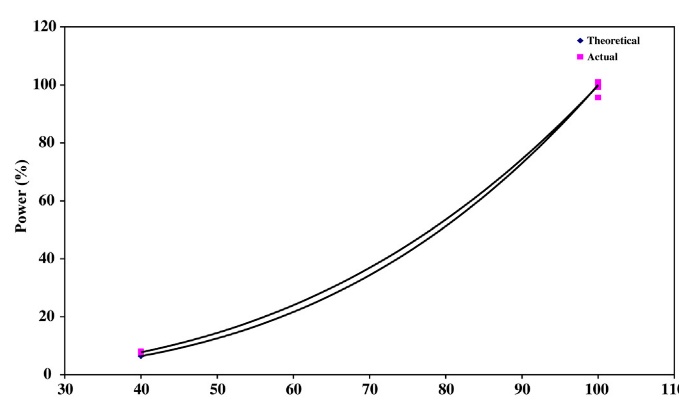

Fig. 3. Fan power variation with variable frequency drive.

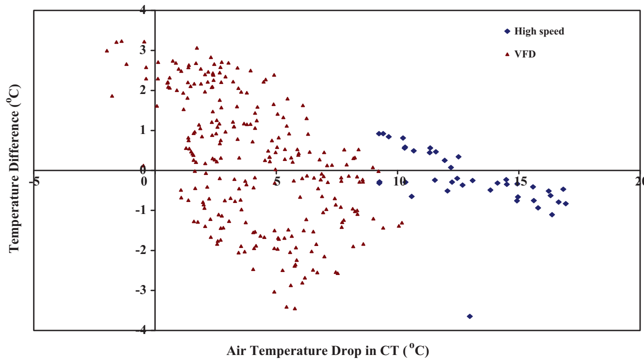

Fig. 4. Incoming water and leaving air temperature difference for different operating conditions.

where ρ and c_{pa} are density and specific heat of air, respectively. According to Eq. (13), the ΔW_e is proportional to the air quantity in circulation. Thus, in the interest of water saving, reduction in air circulation is a key consideration; besides the air temperature drop across the CT. Furthermore, regardless of the incoming temperature of air, or its circulation rate, the CTLAT is very close to CTEWT as shown in Fig. 4. For most of the time it was less than 1 °C, although occasionally reaching as high as 3 °C. Thus, in the interest of water saving, maintaining a high CTEWT, not minding its adverse effect on the chiller performance is advisable.

4.2.2.2. Effect of air–water ratio on the CT approach. CT approach (θ_{ct}) which is the difference between the CTLWT and the ambient WBT is an important characteristic of any CT, besides the heat rejection capacity. G/L controls the θ_{ct} of a given CT for a given duty. This study was designed to operate CTs under different airflows while performing nearly constant heat rejection and keeping a constant water circulation rate. Based on the field data, the effect of G/L on the CT approach was found to be extremely sensitive as shown in Fig. 5.

4.3 Data analysis

Field data have been analyzed on hourly basis for the peak summer days for the electricity and water consumption along with the environmental and operational factors. The results are presented as summary data or average values for different modes of operation for their respective durations. As an example, the accumulative energy consumption (AE) of the cooling production

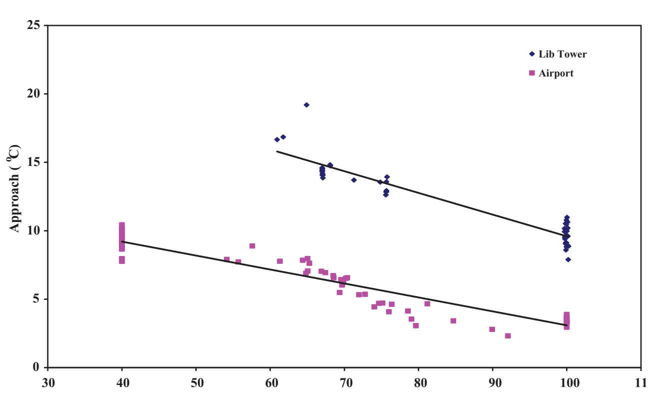

Fig. 5. Effect of airflow rate on θ_{ct} for the Airport.

Table 3
Summary data for different operation modes at summer time at airport site.

Parameters	Operation modes	
	Dual speed	VFD
Operating hours (h)	367	713
Average DBT (°C)	39.69	39.3
Average WBT (°C)	21.98	21.61
Cooling production (RTh*10^3)	279.21	534.2
Chiller energy consumption (kWh*10^3)	220.01	407
Average chiller PR (kW/RT)	0.79	0.76
Average chiller loading (%)	73.2	75.38
Average CT return water temperature (°C)	33.12	33.24
Average CT supply water temperature (°C)	29.92	30.38
Average chilled water supply water temperature (°C)	7.19	7.66
Average fan power (kW)	39.90	17.76
Average CT approach (°C)	8.99	8.82
Average CT PR	0.05	0.0155
Specific Water consumption (L/RTh)	10.77	9.35
Water WASTAGE (%)	48.07	22.48
Average system PR (kW/RT)	1.08	0.98

system is valued as summation of hourly P_s using Eq. (4) over the duration of an operation mode.

$$AE = \sum P_s \tag{14}$$

Likewise, the accumulative cooling production (AQ_c) and accumulative water consumption (AW_e) are estimated using summation of hourly Q_c and W_e. The average specific water consumption (ω_a), the water consumption per unit of cooling production (l/RTh) and the average PR of the WC-cooling production system (PR_a), the two most important parameters for optimization have been valued as follows:

$$\omega_a = \frac{AW_e}{AQ_c} \tag{15}$$

$$PR_a = \frac{AE}{AQ_c} \tag{16}$$

5. Results and discussion

The CT fans were operated alternately with the VFDs, and dual speed motor control through the building management system (BMS). In the ‘dual speed mode’, a fairly common feature in many buildings in Kuwait, the fan speed automatically switches between high and low to maintain the CTLWT close to its set value. Air circulation in the low speed mode is about half as compared to the high speed [16]. The field data collected during the summer season in the two modes was analyzed and the results as the average, for the duration of the mode, are presented in Table 3.

Performance data used for a comparative evaluation are for 367 h in the dual speed mode, and 713 h in the VFD mode. These durations are the summation of the period with steady state conditions extended for a number of days for a specified operation mode. The average DBT for the two operations was nearly identical at 39.5 ± 0.2 °C. Furthermore, the large difference between the DBT and WBT of well over 17 °C, manifests the dryness of weather in Kuwait, particularly during the peak summer season. Average CTLWT for the dual speed and the VFD modes, it was 29.9 °C and 30.4 °C, respectively, although in both the cases, the CTLWT was set at 32 °C, the design temperature for chiller selection. The failure in maintaining the CTLWT at the set temperature in the VFD mode was due to fixing the lowest frequency at 20 Hz as per the recommendation of the CT manufacturer for fan bearing safety, while in the dual speed mode, it was likely due to the poor response of the controlling mechanism.

Chiller PR, the amount of kWh required for unit cooling (RTh) production, a key performance indicator of chiller performance has been calculated using the accumulative cooling production and chiller energy consumption for the two operation modes for their respective durations. Average chillers loading, an important operating parameter that affects the chillers' PR ranged between 73.2 and 75.4%. While the supplied chilled water temperature (CHLWT), an equally important operating parameter ranged between 7.2 °C and 7.7 °C. In the VFD mode, the chillers with an average PR of 0.76 performed better as compared to the dual speed mode with an average PR of 0.79, although the average CTLWT was nearly 0.5 °C lower in the dual speed mode. This is likely due to the merits of the VFD control that can facilitate condenser cooling water at more uniform CTLWT.

The CT fan power and its approach are the main parameters for the performance parameters of a CT. In the VFD mode, the CTLWT was less than the set point of 32 °C, and the fan power was close to 7.5 kW, which was nearly constant for all the time. In fact, this power would have reduced further if the fan operation lower limit was not set for 20 Hz. θ_{ct} with VFD mode ranged between 7.9 and 10.4 °C, and its average value was 8.8 °C. In the dual speed mode that facilitates closure of fans after reaching the set point temperature of the CTLWT, the fan power ranged between 28.6 and 36.4 kW, while the CT approach was between 7.2 and 11.4 °C, and its average value was 9.0 °C.

Specific water consumption (ω) for the two operation modes is shown in Table 3. The dual speed and VFD operation modes, their respective values were 10.77 and 9.35 l/*RTh*. This indicated a 13% reduction in water consumption for VFD as compared to the dual speed mode.

Finally, the average PR of the cooling production system, excluding the condenser water pump power was estimated combining the average chiller and CT fan PR with the PR equivalent of water consumption based on the energy cost of water production (22 kWh/m^3). Average system PR for the dual speed mode was 1.08 kW/RT, which is considered slightly high compared to 0.98 kW/RT at the VFD mode. This shows that the use of VFD through the CT fan is very effective in minimizing the energy cost of cooling production system as compared to the dual speed fan. During the summer season in a country as hot as Kuwait and with non-availability of fresh water, it can lead to reduction of 9.26% by adopting VFD compared to dual speed system.

6. Cost benefit analysis

The cost of VFDs with installation in the airport site for all CTs fans was 9900 kD. The payback period can be calculated as follows:

Considering the hottest months in summer time (peak summer season) from the month of June till the end of August (3 months – 2160 h) and the amount of cooling production of 279.21 $RTh \times 10^3$ for 367 h operating in the dual speed mode (Table 3);

$$\text{The amount of water savings} = \frac{1.42\,\text{l}}{RTh} \times 279.21\, RTh \times 10^3 \times \left(\frac{2160}{367}\right) = 2,333,412.1\,\text{l}$$

The amount of water savings = 616.424 thousands gallon

Considering the cost of water production in Kuwait of 8.418 kD/1000 Gallons, the installed VFD in the airport site will pay for itself in two consecutive peak summer seasons.

7. Conclusions and recommendations

In hot and dry countries, operating CTs with variable airflow is strongly recommended for optimizing water and power consumption. Among the dual speed and the VFD modes, the latter is more effective in maximizing the reductions in water and power consumption besides maintaining a more uniform A/C system performance. For the part load conditions and/or for the ambient wet bulb temperatures lower than the design value, CT leaving water temperature can be maintained at the design level by reducing the airflow. This reduction of airflow can reduce the water wastage considerably. In Kuwait, with the VFD mode, reduction in water consumption was 13% more as compared to dual speed mode during the summer season. Also, fan power for the variable airflow was considerably lower. These reductions would have been likely higher, if the fan speeds of air flow were allowed to go lower than 40% in the VFD mode.

Although the reduction in water consumption was at the cost of higher chiller power, it got over compensated by the reduction in CT fan power. The combined power for the chillers and the CT fans for the same amount of cooling produced were reduced by 5.8% in the VFD mode. More importantly in the countries of Arabian Peninsula, with non-availability for natural fresh water, the respective reduction is 9.26% after accounting for the energy cost of water production.

Acknowledgements

The author would like to thank Kuwait Foundation for Advancement of Sciences and Ministry of Electricity and Water for funding this study. Also, we would like to thank Eng. Gopal Maheshwari for his guidance during this study.

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