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Exergy Evaluation Of A Central Chilled Water System

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Abstract

This study deals with the performance evaluation of a campus central chilled water system (CCWS) installed in the King Saud University (KSU) using exergy analysis method. The analysis employs actual operational data of the CCWS operated at a load factor of 69%. The system includes a distribution network with three loops at a diameter of 900 mm and is designed for a rated cooling load of 105.5 MW (30,000 refrigeration ton (RT)). This system consists of six centrifugal chillers with a nominal cooling load capacity of 17.58 MW (5,000 RT) each. The design supply (flow) and return temperatures of the chilled water are 5.5 °C and 14.5 °C at a nominal volumetric flow rate of 467 L/s, respectively. The end-user air systems use variable volume/dual duct and variable volume & reheat types capable of delivering 100% outside air. They are designed to satisfy peak-load requirements. A recovery system is also utilized to recover heat/cooling from areas employing exhaust systems requiring high outside make-up air. Exergy analysis method was applied to the refrigeration subsystem (consisting of a compressor, a condenser, an evaporator (cooler), and a throttling valve) of the whole system with two pumps to determine exergy destructions in each of the subsystem components. In this respect, exergy efficiency values for the CCWS unit and whole system on the desired effect (benefit)/fuel basis are calculated to be 33.6% and 27%, respectively. They are obtained to be 74.6% and 73.5% on the product/fuel basis, respectively. This also highlights the importance of the exergy definition used in the analysis. In terms of the relative irreversibities, the compressor was found to have the greatest value, followed by the other components; the condenser, the expansion valve, the evaporator and then the pumps.

Keywords: *Chilled water system, CCWS, exergy evaluation, refrigeration.*

1. Introduction

Energy consumption in the residential sector is one of the main parts of the total energy consumption in most countries. Depending on the countries and their sectoral energy use patterns, 16% to 50% of the total energy consumption worldwide is consumed by HVAC equipment in buildings. In this context, Saudi Arabia has the highest energy consumption due to HVAC applications [1].

As far as the studies on exergetic performance assessment of campus CCWSs are concerned, Harrell [2] studied the CCWS of the Southern Illinois University Carbondale campus, while this system was reported by Harrell and Mathias [3], who also reviewed in detail some studies on various university chiller systems. They also evaluated this system using exergy-based cost accounting to quantify the magnitudes and cost impacts of internal losses with the goals of maximizing chiller capacity utilization and minimizing the unit cost of delivered chilled water. Two independent systems, each comprised of a primary-secondary-tertiary distribution network and cooled by a 12,300 kW (3,500 RT) steam-turbine driven centrifugal chiller, were modeled as control volume networks using steady-state rate balances for energy, exergy, and cost. The overall chiller system exergetic efficiency increased with the cooling rate but remained quite low, ranging from only 3% to 13%.

Boonnsa et al. [4] analyzed chilled water storage (CWS) for use in an academic building cooling system in order to find the optimum solution that provides the best economic performance. They also studied several scenarios for the King Mongkut's University of Technology North Bangkok in Thailand air conditioning system. It was concluded that the mechanical chiller capacity and peak demand could be decreased, while it could move the energy consumption from the on peak to the off peak periods by 35.7%.

Exergy is a measure of the maximum capacity a body or an energy system to perform the useful work, as it proceeds to a specified final equilibrium state with its surroundings. Exergy can also identify better than energy the environmental benefits and economics of energy technologies. The results suggest that exergy should be utilized by engineers and scientists, as well as decision and policy makers, involved in green energy and technologies in tandem with other objectives and constraints [5]. An exergy analysis (or second law analysis) has proven to be a powerful tool in the simulation thermodynamic analyses of energy systems. Exergy analysis method is employed to detect and to evaluate quantitatively the causes of the thermodynamic imperfection of the process under consideration. It can, therefore, indicate the possibilities of thermodynamic improvement of the process under consideration, but only an economic analysis can decide the expediency of a possible improvement [6].

Although exergy analysis has been widely used in the design, simulation and performance evaluation of various energy-related systems, the studies performed on exergetic analysis of campus CCWSs appear relatively a few in numbers in the open literature. This was the main reason for conducting this contribution. In this regard, the main objective of the present study is to analyze the CCWS of the King Saud University (KSU), Riyadh, Saudi Arabia using exergy analysis method and to evaluate its performance for possible further improvements.

King Saud University (KSU) was established in Riyadh, Saudi Arabia in 1957. The KSU main campus, located in Diriyah neighborhood, is one of the biggest in the region with a total area of more than 9,000,000 m2. It was built in phases that started more than 35 years ago. The campus consists of 21 collages with 26 main buildings that were served by the CCWS. The campus has serves more than 40,000 students, 2,500 faculty members and 3,000 staff sometimes ago. The total build area covered by this study is about 9,500,000 m2. The CCWS is designed for a maximum load of 60,000 TR. The campus also includes medical facilities and girls campus that are not currently served by the central chiller plant.

2. System Description

Figure 1 illustrates a schematic of the CCWS system studied, which mainly consists of three parts, namely (i) a chiller unit (a compressor, a condenser, an expansion valve and an evaporator) using R-12 as refrigerant, (ii) a cooling tower, and (iii) a cooling distribution system (building chilled water supply/return).

The CCWS has three pronged loops. These loops consist of three pairs of 900 mm diameter supply/return mains, which start from the CCWS Plant and supply the chilled water to the buildings through one pipe and comes back as a return through the other pipe. The CCWS system is designed at a maximum ultimate load of 60,000 RT and serves to academic area and facility of medicine at the time of this study. It is a primary system with a single set of circulating pumps (chilled water pumps), which pump through the chillers, chilled water supply mains to the buildings, through the building systems and back through the return mains to the central plant circulating pump intake. The CCWS is designed at chilled water supply and return temperatures of 5.5 oC and 14.5 oC, respectively, with a volumetric flow rate of 467 L/s , while it is pressurized, so that adequate submergences may be maintained at the highest point of the system in the academic area with the circulating pumps only. The initial capacity is maintained with six centrifugal water chillers, each with a nominal capacity of 5,000 RT.

Each compressor is driven by a synchronous electric motor that is 700 HP, 13.8 kV, 1200 RPM. Seven chilled water pumps (CHWPs), each with a capacity of 472 L/s at a total dynamic head of 84 m, are installed in the CCWS. Each pump is driven by a 800 HP electric motor, while the pumps are matched to the refrigeration machines and an equal number of pumps is operated. One of the pumps serves as a standby unit. An intermediate header between pumps and chillers is equally subdivided. The pumps and chillers are also equally divided into two groups. The expansion tank is tied into the return header in two places with a three-way valve between these, so that it is connected to the group of chillers, that is being operated. Each chiller is provided with an automatically controlled by-pass valve from its discharge to the chilled water pumps suction header, so that chiller start-up and shut-down may be facilitated without a temperature loss in the outgoing chilled water [7].

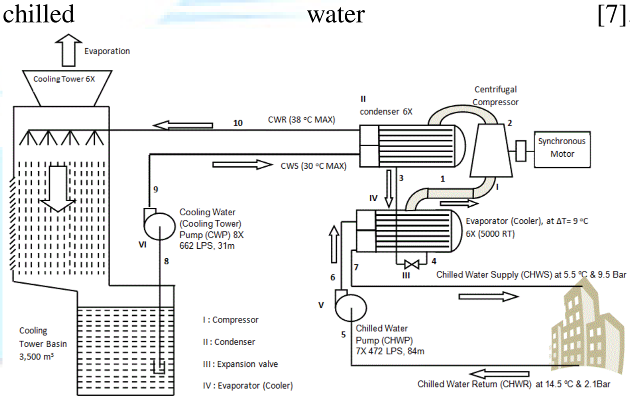

Figure 1. A schematic of the CCWS system studied [7]

3. Analysis

General mass, energy, entropy and exergy balance equations are given in more detail elsewhere [8], while the

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following section covers the relations on the system component basis illustrated in Figure 1. Mass and energy balances as well as exergy destructions obtained from exergy balances for each of the CCWS system components illustrated in Figure 1 are derived as follows:

Compressor (I):

$$\dot{m}_1 = \dot{m}_{2,s} = \dot{m}_{2,act} = \dot{m}_r \quad (1a)$$

$$\dot{W}_{comp} = \dot{m}_r (h_{2,act} - h_1)$$
(1b)

$$\dot{E}x_{dest,comp} = \dot{m}_r (\psi_1 - \psi_{2,act}) + \dot{W}_{comp,elec} \quad (1c)$$

$$\dot{W}_{comp,elec} = \dot{W}_{comp} / (\eta_{comp,elec} \eta_{comp,mech}) \quad (1e)$$

$$\dot{W}_{com,elec} = \sqrt{3}\, V_{comp} I_{comp} Cos\varphi \quad (1f)$$

$$\dot{E}x_{dest,comp,mech,elec} = \dot{W}_{comp,elec} (1 - \eta_{comp,elec} \eta_{comp,mech}) \quad (1g)$$

$$\dot{E}x_{dest,comp,\mathrm{int}} = \dot{E}x_{dest,comp} - \dot{E}x_{dest,comp,mech,elec} \quad (1h)$$

where heat interactions with the environment are neglected.

Condenser (II):

$$\dot{m}_2 = \dot{m}_3 = \dot{m}_r \;; \quad \dot{m}_9 = \dot{m}_{10} = \dot{m}_{w,cw} \quad (2a)$$

$$\dot{Q}_{cond} = \dot{m}_r (h_{2,act} - h_3) \;; \quad \dot{Q}_{cond} = \dot{m}_{cw} C_{cw} (T_{10} - T_9) \quad (2b)$$

$$\dot{E}x_{dest,cond} = \dot{m}_r (\psi_{2,act} - \psi_3) + \dot{m}_{cw} (\psi_9 - \psi_{10}) \quad (2c)$$

Expansion (throttling) valve (III):

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_r \quad (3a)$$

$$h_3 = h_4 \quad (3b)$$

$$\dot{E}x_{dest,exp} = \dot{m}_r (\psi_3 - \psi_4) \quad (3c)$$

Evaporator (Cooler) (IV):

$$\dot{m}_4 = \dot{m}_1 = \dot{m}_r \;\&\; \dot{m}_7 = \dot{m}_6 = \dot{m}_{chw} \quad (4a)$$

$$\dot{Q}_{evaporator} = \dot{m}_{chw} (h_6 - h_7), \dot{Q}_{evaporator} = \dot{m}_{chw} C_{chw} (T_6 - T_7) \quad (4b)$$

$$\dot{E}x_{dest,evaporator} = \dot{m}_r (\psi_4 - \psi_1) + \dot{m}_{chw} (\psi_6 - \psi_7) \quad (4c)$$

Cooling water pump (CWP):

$$\dot{m}_8 = \dot{m}_{9s} = \dot{m}_{9,act} = \dot{m}_{cw} \quad (5a)$$

$$\dot{W}_{cw} = \dot{m}_{cw} (h_{9,act} - h_8) \quad (5b)$$

$$\dot{E}x_{dest,cw} = \dot{m}_{cw} (\psi_8 - \psi_{9,act}) + \dot{W}_{cw,elec} \quad (5c)$$

$$\dot{W}_{cw,elec} = \dot{W}_{cw} / (\eta_{pump,elec} \eta_{pump,mech}) \quad (5d)$$

$$\dot{W}_{cw} = V_{cw} I_{cw} Cos\varphi \quad (5e)$$

Chilled water pump (CHWP):

$$\dot{m}_5 = \dot{m}_{6s} = \dot{m}_{6,act} = \dot{m}_{chw} \quad (6a)$$

$$\dot{W}_{chw} = \dot{m}_{chw} (h_{6,act} - h_5) \quad (6b)$$

$$\dot{E}x_{dest,chw} = \dot{m}_{chw} (\psi_5 - \psi_{6,act}) + \dot{W}_{chw,elec} \quad (6c)$$

$$\dot{W}_{chw,elec} = \dot{W}_{chw} / (\eta_{pump,elec} \eta_{pump,mech}) \quad (6d)$$

$$\dot{W}_{chw} = V_{chw} I_{chw} Cos\varphi \quad (6e)$$

Exergy efficiencies of the CCWS system components and the whole system are evaluated as follows: $\psi = (h - h_0) - T_0 (s - s_0)$

Compressor (I):

$$\varepsilon_{comp} = \frac{\dot{E}x_{2,act} - \dot{E}x_1}{\dot{W}_{comp,elec}} \quad (7)$$

Condenser (II):

$$\varepsilon_{cond} = \frac{\dot{E}x_{10} - \dot{E}x_9}{\dot{E}x_{2,act} - \dot{E}x_3} = \frac{\dot{m}_{cw} (\psi_{10} - \psi_9)}{\dot{m}_r (\psi_{2,act} - \psi_3)} \quad (8)$$

Expansion (throttling) valve (III):

$$\varepsilon_{exp} = \frac{\dot{E}x_4}{\dot{E}x_3} = \frac{\psi_4}{\psi_3} \quad (9)$$

Evaporator (Cooler) (IV):

$$\varepsilon_{evap} = \frac{\dot{E}x_7 - \dot{E}x_2}{\dot{E}x_{13} - \dot{E}x_{11}} = \frac{\dot{m}_s (\psi_7 - \psi_2)}{\dot{m}_{w,gh} (\psi_{13} - \psi_{11})} \quad (10)$$

Chilled water pump (CHWP):

$$\varepsilon_{chwp} = \frac{\dot{E}x_6 - \dot{E}x_5}{\dot{W}_{pump,elec,chw}} = \frac{\dot{m}_{chw} (\psi_6 - \psi_5)}{\dot{W}_{pump,elec,chw}} \quad (11)$$

Cooling water pump (CWP):

$$\varepsilon_{cwp} = \frac{\dot{E}x_9 - \dot{E}x_8}{\dot{W}_{pump,elec,cw}} = \frac{\dot{m}_{cw} (\psi_9 - \psi_8)}{\dot{W}_{pump,elec,cw}} \quad (12)$$

CCWS unit (I-IV):

$$\varepsilon_{CCWS} = \frac{\dot{E}x_{cooling}}{\dot{W}_{comp,elec}} = \frac{\dot{E}x_7 - \dot{E}x_5}{\dot{W}_{comp,elec}} \quad (13)$$

Overall CCWS system (I-IV and pumps):

$$\varepsilon_{CCWS\ ,sys} = \frac{\dot{E}x_7 - \dot{E}x_5}{\dot{W}_{comp\ ,elec} + \Sigma \dot{W}_{pump\ ,elec}} \quad (14)$$

The exergetic coefficients of performance of the CCWS unit and whole system are as follows:

$$COP_{ex,CCWS} = \frac{\dot{Q}_{evaporator}(\frac{T_0}{T_{evaporator}} - 1)}{\dot{W}_{comp,elec}} \quad (15)$$

$$COP_{ex,sys} = \frac{\dot{Q}_{evaporator}(\frac{T_0}{T_{evaporator}} - 1)}{\dot{W}_{comp,elec} + \Sigma \dot{W}_{pump,elec}} \quad (16)$$

Van Gool (1997)'s improvement potential on a rate basis, denoted $I\dot{P}$, is expressible as [9]:

$$I\dot{P} = (1 - \varepsilon)(E\dot{x}_{in} - E\dot{x}_{out}) \quad (17)$$

Relative irreversibility (RI) is given by:

$$RI = \frac{\dot{E}x_{dest,i}}{\dot{E}x_{dest,T}} \quad (18)$$

COP values for the CCWS unit and whole system may be calculated as follows, respectively:

$$COP_{CCWS} = \frac{\dot{E}_{evaporator}}{\dot{W}_{comp\ ,elec}} = \frac{\dot{E}_6 - \dot{E}_7}{\dot{W}_{comp\ ,elec}} \quad (19)$$

$$COP_{CCWS\ ,sys} = \frac{\dot{E}_6 - \dot{E}_7}{\dot{W}_{comp\ ,elec} + \Sigma \dot{W}_{pump\ ,elec}} \quad (20)$$

4. Results and discussion

The following several assumptions are made for the exergy analysis of the system given as an illustrative example.

(a) All processes are steady state and steady flow with negligible potential and kinetic energy effects and no chemical or nuclear reactions.

(b) The directions of heat transfer to the system and work transfer from the system are positive.

(c) The pressure losses in the pipelines connecting the components are ignored, since their lengths are short.

(d) The compressor mechanical ($\eta_{comp,mech}$) and the compressor motor electrical ($\eta_{comp,elec}$) efficiencies are assumed to be 83% and 90%, respectively.

(e) The power values for chilled and cooling water pumps were calculated using their capacity values at a pump efficiency of 75%.

(f) The mass flow rate of the evaporator was determined using a design value of 0.0933 L/s·TR while all the temperature values are based on the actual operational data.

(g) The values for the dead (reference) state temperature and pressure are taken to be 25oC and 101.325 kPa, respectively.

Temperature, pressure and mass flow rate data for the refrigerant R-12 and the water are shown in Table 1 where energy and exergy rates calculated for each state are included in last columns in the same table, following the state numbers specified in Figure 1.

Table 1: Energy and exergy analyses results of CCWS system studied:

State No.	Description	Fluid	Phase	Temp. T (°C)	Pressure, P (kPa)
0	-	(R-12)	Dead state	25	101.325
0''	-	Water	Dead state	25	101.325
1	Evaporator refrigerant outlet/ Compressor inlet	(R-12)	Superheated vapor	6.5	354
2,s	Condenser refrigerant inlet/ Compressor outlet	(R-12)	Superheated vapor	50.58	1004
2,act	Condenser refrigerant inlet/ Compressor outlet	(R-12)	Superheated vapor	56	1004
3	Condenser refrigerant outlet/ Expansion valve inlet	(R-12)	Compressed liquid	40	1004
4	Expansion valve outlet/ Evaporator refrigerant inlet	(R-12)	Mixture	4.5	356.8
5	Chilled water return (CHWR) Chilled water pump (CHWP) inlet	Water	Compressed liquid	11.5	210
6	Chilled water pump (CHWP) outlet Evaporator water inlet	Water	Compressed liquid	11.7	1050
7	Chilled water supply (CHWS)	Water	Compressed liquid	5.5	950

	Evaporator water outlet				
8	Condenser water pump (CWP) inlet	Water	Compressed liquid	21	102
9	Condenser water pump (CWP) outlet Condenser water supply (CWS)	Water	Compressed liquid	21.2	420
10	Condenser water return (CWR)	Water	Compressed liquid	28.5	250

Table 1: Energy and exergy analyses results of CCWS system studied (cont.)

State No.	Specific enthalpy, h (kJ/kg)	Specific Entropy, s (kJ/kg K)	Mass flow rate, $\dot{m}$ (kg/s)	Specific exergy, ψ (kJ/kg)	Energy Rate $\dot{E} = \dot{m}h$ (kW)	Exergy Rate $\dot{E}x = \dot{m}\psi$ (kW)
0	206.9	0.8375	-	-	-	-
0’’	104.8	0.3669	-	-	-	-
1	190.8	0.7	104.34	24.90	19908.1	2597.75
2,s	210.7	0.703	104.34	43.90	21984.4	4580.79
2,act	214.9	0.716	104.34	44.23	22422.7	4614.59
3	74.6	0.272	104.34	36.31	7783.8	3788.53
4	74.6	0.281	104.34	33.63	7783.8	3508.54
5	48.5	0.173	466.34	1.51	22617.5	705.68
6	50.1	0.176	466.34	2.22	23363.6	1034.69
7	24.1	0.084	466.34	3.65	11238.8	1701.89
8	88.1	0.31	460.07	0.27	40532.2	122.06
9	89.2	0.313	460.07	0.47	41038.2	216.61
10	119.6	0.416	460.07	0.16	55024.4	73.77

Using the values given in Table 1 and relations derived, exergy destruction rates are calculated for the major CCWS components and presented in Table 2. As can be seen in this table, the compressor has the highest exergy destruction value, accounting for about 39% of the whole CCWS components. This is followed by the condenser, expansion valve, evaporator and then pumps.

Table 2: Exergy analysis results for the CCWS components

Components	Exergy destruct. Rate kW	Exergy efficiency %	Exergetic improve. potential rate kW	Relative irrevers. %
Compressor	951.17	67.95	304.82	39.09
Condenser	683.21	17.29	565.07	28.08
Expansion valve	279.99	92.61	20.69	11.51
Evaporator (Cooler)	243.59	73.26	65.15	10.01
Chilled water pump	182.99	64.26	65.40	7.52
Cooling water pump	92.45	50.56	45.70	3.80
Total	2433.39	73.53	644.16	100

The mechanical-electrical losses are calculated using Equation (1g) and are found to account for 25.3% of the system input. The mechanical-electrical losses are due to imperfect electrical, mechanical and isentropic efficiencies and emphasize the need for paying close attention to the selection of this equipment, since components of lower performance can considerably reduce overall system performance. Since compressor power depends strongly on the inlet and outlet pressures, any heat exchanging improvements that reduce the temperature difference will reduce compressor power by bringing the condensing and evaporating temperatures closer together. Recent advances in the market have led to the use of scroll compressors.

Irreversibilities in the evaporator and the condenser occur due to the temperature differences between the two heat exchanger fluids, pressure losses, flow imbalances and heat exchange with the environment. The irreversibility associated with the expansion valve (capillary tube) due to the pressure drop of the refrigerant passing through it. To eliminate the throttling loss it is recommended to replace the capillary tube with an isentropic turbine (an isentropic expander) and to recover some shaft work from the pressure drop.

Exergy efficiency values for the CCWS unit and whole system on the desired effect (benefit)/fuel basis are calculated to be 33.6% and 27% using Equations (13) and (14), respectively. They are also obtained to be 74.6% and 73.5% on the product/fuel basis, respectively. This clearly indicates that the exergy efficiency values differ from each other because of the definition used.

The exergetic COP values for the CCWS unit and whole system are calculated to be 0.30 and 0.24 using Equations (15) and (16), while energetic COP values for those are calculated to be 4.09 and 3.31, respectively.

4. Conclusions

In this study, a CCWS with a cooling capacity of 12124 kW (3447 RT) was modeled using exergy analysis method and its performance was evaluated based on the actual operational data. The exergy destructions in the overall CCWS system components were quantified, while the exergy efficiency values of the system components and the whole system were determined.

Some concluding remarks drawn from the results of this study may be listed as follows:

a) The exergy efficiency values on a product/fuel basis were found to be 74.6% for the CCWS unit and 73.5% for the whole system at a dead (reference) state temperature of 25°C.
b) According to Van Gool's improvement potential rate ($I\dot{P}$), the condenser had the highest $I\dot{P}$ value, followed by the compressor, chilled water pump, evaporator, cooling water pump and expansion valve.
c) Based on the relative irreversibility values of the CCWS operated at a load factor of nearly 69%, the compressor had the greatest value, followed by the condenser, the expansion valve, the evaporator and then the pumps.

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