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Superstructural approach to the synthesis of free-cooling system through an integrated chilled and cooling water network

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ABSTRACT

Chillers are major energy consumers in industrial facilities. They are indispensable in such industries as semiconductor fabrication, food processing, and plastics manufacturing, among others. Previous studies aimed at improving the energy efficiency of chilled water systems have focused on optimizing the performance of individual chillers. However, an alternative method to recover energy is to perform system-wide water source/sink integration using a superstructural approach. In our previous study, several schemes for chilled and cooling water systems (CCWS) with hub topology were proposed for energy savings. The main contribution of this study is in the development of a methodology to achieve energy savings by introducing free cooling in an integrated superstructure for CCWS. Two examples are used to demonstrate three different scenarios of CCWS with free cooling. It is shown that the integration of free cooling into chilled water system improve the cost and energy saving significantly, and can avoid the need to invest in a new chiller and/or cooling tower to enhance the energy efficiency of CCWS.

1. Introduction

Globalization, economic development and population growth have led to a sustained upward trend in world energy demand. The increasing level of energy demand, especially in the industrial sector, has overdependence on non-renewable energy sources and has strongly affected the environment via carbon emissions. Water chillers, which are used in many applications for heating, ventilating and air conditioning (HVAC) and industrial process cooling, are among the major energy consumers in many industrial facilities. For example, Hu and Chuah (2003) reported that 27.2% of the total power is consumed by chiller plants in semiconductor fabrication. In a typical blow moulding factory (Tangram, 2001), chillers use 14% of the total electricity for plastic processing. Chillers account for 54–67% of the total energy in fresh fruit and vegetable processing plants (Hackett et al., 2005).

Over the last 30 years, the coefficient of performance (COP) of water-cooled chillers has improved from 4 to 7 (Jayamaha, 2006). Many research works have been carried out focusing on the study of individual chiller units. Chang (2004) used Lagrangian method to solve optimal chiller loading (OCL) problem so as to reduce chiller power consumption. Chang (2005) improved the previous studies by using genetic algorithm to solve the problem which produces the results with high accuracy as compared to Lagrangian method. Lee and Lin (2009) proposed particle swarm algorithm to solve OCL problem and compared the developed model with Lagrangian

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Nomenclature

Sets

I	$\left\{i, \ldots, i_{N_{\text{sources}}}\right\}$ is a set of process sources
J	$\left\{j, \ldots, j_{N_{\text{sinks}}}\right\}$ is a set of process sinks
K	$\left\{k, \ldots, k_{N_{\text{plants}}}\right\}$ is a set of plants

Parameters

Ω	parameter to fix the lower and upper limits of the water mass flow rate for determining the existence of pipelines
σ	parameter to fix the lower and upper limits of the inlet water mass flow rate for determining the existence of cooling tower
Γ	parameter to fix the lower and upper limits of the cooling capacity for determining the existence of chiller
α	coefficient of cooling tower performance, dimensionless
β	percent loss of circulating water in cooling tower
γ	parameter to fix the $\text{Fct}_{\text{in}}/Fa$ ratio
η	efficiency
θ	parameter to fix the lower and upper limits of temperature
ρ	water density (kg/m^3)
C_{CHF}	initial cost of chiller (US$)
C_{CHT}	cost of chiller related to cooling capacity (US$/t)
C_{CTA}	cost of cooling tower related to air flow rate (US$/kg)
C_{CTF}	initial cost of cooling tower (US$)
C_{CTV}	cost of cooling tower related to fill volume (US$/m^3)
C_{E}	unit cost of electricity (US$/kW h)
C_{W}	unit cost of make-up water (US$/kg)
H_{Y}	yearly operating time
K_{F}	annualizing factor (1/year)
CC	cycle of concentration, dimensionless
COP	chiller's coefficient of performance, dimensionless
Cp	specific heat of water (kJ/kg °C)
Fd	water flow rate of sink requirement (kg/s)
Fs	available water flow rate of source (kg/s)
H	height (m)
L	distance between the plant and the centralized hub (m)
T_{in}	inlet water temperature of sink (°C)
T_{out}	temperature of source (°C)
g	acceleration due to gravity (m/s^2)
p	variable cost parameter based on the cross sectional area of pipe
q	fixed cost parameter for building one pipeline
v	stream velocity (m/s)
w	Air mass-fraction humidity of cooling tower (kg-water/kg-dry-air)

Continuous variables

a_{ct}	area of cooling tower mass transfer (m^2)
CAPCH	investment cost of chiller (US$/year)
CAPCCH	investment cost of centralized chiller (US$/year)
CAPCT	investment cost of cooling tower (US$/year)
CAPCCT	investment cost of centralized cooling tower (US$/year)
CAPPC	investment cost of the pipeline between the plant and the centralized chiller (US$/year)
CAPPCT	investment cost of the pipeline between the plant and the centralized cooling tower (US$/year)
$F_{i,j}$	flow rate of water from source i to sink j (kg/s)
Fa	air mass flow rate in the cooling tower (kg/s)
Fb	mass flow rate of blow-down water in the cooling tower (kg/s)
Fbc	mass flow rate of blow-down water in the centralized cooling tower (kg/s)
Fch	mass flow rate of water in the chiller (kg/s)
$Fchw$	mass flow rate of regenerated chilled water from an individual plant's chiller (kg/s)
$Fcch$	mass flow rate of water in the centralized chiller (kg/s)
$Fcchw$	mass flow rate of regenerated chilled water from the centralized chiller (kg/s)
$Fcct$	mass flow rate of water in the centralized cooling tower (kg/s)
$Fccw$	mass flow rate of regenerated cooling water from the centralized cooling tower (kg/s)
Fct	mass flow rate of water in the cooling tower (kg/s)
Fcw	mass flow rate of regenerated cooling water from an individual plant's cooling tower (kg/s)
Fe	mass flow rate of evaporated water in the cooling tower (kg/s)
Fm	make-up water flow rate of the cooling tower (kg/s)
Fmc	make-up water flow rate of the centralized cooling tower (kg/s)
Fr	mass flow rate of a free-cooling stream (kg/s)
Frc	mass flow rate of a free-cooling stream from the centralized cooling tower to the centralized chiller (kg/s)
Ft	mass flow rate of drifted water in the cooling tower (kg/s)
Fwh	mass flow rate of a source sent to an individual plant's chiller (kg/s)
$Fwch$	mass flow rate of a source sent to the centralized chiller (kg/s)
$Fwct$	mass flow rate of a source sent to the centralized cooling tower (kg/s)
Fwt	mass flow rate of a source sent to an individual plant's cooling tower (kg/s)
K_{X}	mass transfer coefficient of the cooling tower (kW/m^2 °C)
Me	Merkel's number of the cooling tower (dimensionless)
OPC	operating cost (US$/year)
PC	power consumption (kW)
TAC	total annual cost (US$/year)
TAP	total annual power consumption (kW)
TONS	cooling capacity of the chiller (t)
$Tchw$	temperature of regenerated chilled water supplied by an individual plant's chiller (°C)
$Tcchw$	temperature of regenerated chilled water supplied by the centralized chiller (°C)

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