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Optimization model for re-circulating cooling water systems

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ABSTRACT

This paper presents an optimization model for the simultaneous synthesis and detailed design of re-circulating cooling water systems. A cooler network superstructure that embeds all network configurations of practical interest is used as part of the integrated model. Pressure drops in each cooler are treated as optimization variables, and design guidelines and constraints are included in order to provide practical and feasible units. The model is based on a generalized disjunctive programming formulation, which gives rise to a mixed-integer nonlinear programming problem. The objective is to find cooling water systems that minimize the total annual cost. Solution of this mathematical formulation provides the optimal system configuration as well as the optimal operating conditions and design parameters required for each cooler unit in the network and in the cooling tower. Three example problems are presented to show the application of the proposed approach.

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1. Introduction

Re-circulating cooling water systems are widely used to remove waste heat in chemical and petrochemical processes, electric power generating stations, refrigeration and air conditioning plants, pulp and paper mills, and steel mills. As shown in Fig. 1, typical re-circulating cooling water systems are composed of three major components: a cooling water network, a mechanical draft wet-cooling tower, and a pumping system. A cooling water network is an arrangement of heat exchangers that transfer the waste heat from a set of hot process streams to a cooling water utility.

The economic optimization of re-circulating cooling water systems includes the simultaneous selection of the optimal design variables of the cooling tower and each heat exchanger in the cooling network, as well as the optimal structure of the cooling water network. These interactions have not been properly considered. Earlier work on cooling water systems has concentrated on the optimization of stand-alone components. Some of them have dealt with the problem of designing minimum-cost cooling towers for a given heat load that must be dissipated, while others have given special attention on the individual heat exchangers of the cooling water network. On the work related to the cooling towers, Söylemez (2001, 2004) derived simple algebraic equations for estimating iteratively the optimum heat and mass transfer area, as well as the optimum performance point for forced-draft counter-flow cooling towers. Since several major parameters need to be defined when using this approach, only a limited set of design variables is left for optimization. Recently, Serna-González, Ponce-Ortega, and Jiménez-Gutiérrez (submitted for publication) developed a mixed-integer nonlinear programming (MINLP) formulation for minimizing the total annual cost of counter-flow cooling towers, including geometric and velocity constraints that must be met in order to find the most economical and practical solution for a given cooling requirement.

As far as the heat exchanger units are concerned, the economic optimization of shell-and-tube heat exchangers has received a significant deal of attention because this type of exchanger is the most widely used in the process industry (Smith, 2005). Muralikrishna and Shenoy (2000) and Serna-González, Ponce-Ortega, Castro-Montoya, and Jiménez-Gutiérrez (2007) have reported graphical feasibility studies for given sets of geometric and operational constraints; their analysis was based on the Kern (Muralikrishna & Shenoy, 2000) and Bell-Delaware (Serna-González et al., 2007) methods. Serna and Jiménez (2005) formulated two compact expressions that relate the pressure drop for each side of the exchanger with the film heat transfer coefficient and the exchanger area. The combination of the compact relationships with the basic exchanger design equation gave rise to simple design and optimization algorithms for segmentally baffled shell-and-tube heat exchangers. The shell-side compact expression was based on the Bell-Delaware correlations to calculate the film heat transfer coefficient and pressure drop of the fluid. Agarwal and Gupta (2008), Ponce-Ortega, Serna-González, and Jiménez-Gutiérrez (2009), Selbas, Kizilkan, and Reppich (2006), and Wildi-Tremblay

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Nomenclature

$A_{i,k}$ heat transfer area
A_{CT} cross-sectional area for the cooling tower
a^{layout} constants for the layout of the tubes
a_{it}^{Dt} constant for the outer tube diameter
a_{it}^{Dti} constant for the inner tube diameter
a_{it}^{Lpt} constant for the tube pitch
a_n^p constants for Merkel's number for the fill type
b_q^p parameters for the loss coefficient for the cooling tower for a fill type
c_n exponents for Merkel's correlation
C_{AT} constant for the tubes layout
C_o^{CT} installation cost coefficient for the cooling tower
C_G^{CT} mass cost coefficient for the cooling tower
C_V^{CT} volume cost coefficient for the cooling tower
C^{exc} area cost coefficient for exchangers
C^{pump} pressure cost coefficient for pumps
CF^{exc} fixed charge for exchangers
CF^{pump} fixed charge for pumps
Cp heat capacity
Cp_{cw} heat capacity for the cold water
C_{pow} electricity cost
C_{water} unit cost for makeup water
CU cold utility
De equivalent diameter
d_q disaggregated variables for the loss coefficient for the cooling tower
Ds shell diameter
$dtcold_{i,k}$ temperature difference for the cold side in match i,k
$dthot_{i,k}$ temperature difference for the hot side in match i,k
Dti inner tube diameter
Dt outer tube diameter
F_i^h flow for the cold stream i
$F_{cw_{i,k}}$ flow for the cold water in match i,k
FCP_i heat capacity flow rate for hot process stream i
FF_k fresh flow of cooling water to stage k
FO_k deviation flow of the cold water in stage k
F_T correction factor for the *LMTD*
G mass flow rate of air inlet to the cooling tower
h fouling film heat transfer coefficient
ha enthalpy of air in the cooling tower
has enthalpy of saturated air at the local bulk water temperature in the cooling tower
hc clean heat transfer coefficient
HPS $\{i|i$ is a hot process stream$\}$
H_Y yearly operating time
Int_m integrands for Me number
k thermal conductivity
K constant for the pressure drop relationship
Ka constant for Merkel's number
K_{fi} loss coefficient for the cooling tower
Lbc baffle spacing
$LMTD$ logarithmic mean temperatures difference
Lpt tube pitch
L_{TT} total tube length
L_{cw} mean mass flow rate of water in the cooling tower
L_{wi} inlet mass flow rate of water to the cooling tower
L_{fi} fill height for the cooling tower
L_{wo} outlet mass flow rate of water from the cooling tower
L_w^{evap} mass flow rate evaporated in the cooling tower
L_w^{makeup} mass flow rate of makeup water
M mass flow velocity
$M^{property}$ parameters for the Big-M formulations
mav mass flow rate of wet air
Me Merkel's number
n_{cycles} number of cycles for the cooling water in the circuit
NH total number of hot process streams
NOK total number of stages
Ns number of shells in series
N_{TT} number of tubes
N_{tp} number of tubes passes
P thermal effectiveness for multipass exchangers
P_{CT} power consumption in the cooling tower
P_o^{da} vapor pressure of air in outlet of the cooling tower
P_{TOT}^{CT} ambient pressure
P_{12} thermal effectiveness for multipass exchangers of type one shell–two tube passes
ΔP pressure drop
ΔP_{CT} pressure drop for the cooling tower
$\Delta P_{cw_k}^{STAGE}$ pressure drop for cooling water in stage k
ΔP_i^{TOT} total pressure drop for hot stream i
ΔP_{fi} pressure drop for air in the fill of the cooling tower
ΔP_{misc} miscellaneous pressure drop for air in the cooling tower
P^{vap} vapor pressure for air in the cooling tower
$q_{i,k}$ heat exchanged between hot process stream i and cooling water in stage k
Q_{CT} cooling tower heat load
R thermal capacity ratio for multipass exchangers
R_{bs} ratio baffle spacing to shell diameter
Rd fouling factor
ST $\{k|k$ is a stage in the superstructure, $k = 1, \ldots, NOK\}$
T_{ao} outlet temperature of air from the cooling tower
$Tcin_k$ inlet temperature of cooling water in stage k
$Tcout_{i,k}$ outlet temperature of cooling water after match with stream i in stage k
$Tcout_{upper}$ upper limit for the outlet temperature of cooling water
TCH_m temperature for the Chebyshev points
$TCUIN$ inlet temperature of cooling water into the cooling network
$Th_{i,k}$ temperature of hot stream i in stage k
$THIN_i$ inlet temperature for hot process stream i
$THOUT_i$ outlet temperature for hot process stream i
Tl_m water temperature in interval m for the cooling tower
ΔT_{MIN} minimum approach temperature difference
TO_k outlet temperature for cooling water when deviation occurs in stage k
T_{wa} temperature for makeup water
T_{wi} inlet temperature of cooling water to the cooling tower
T_{wo} outlet temperature of cooling water from the cooling tower
U overall heat transfer coefficient
v velocity
V^{da} specific volume for air in the cooling tower
w mass fraction humidity for air in the cooling tower
V_o^{da} specific volume of air at the exit from the cooling tower
y_{CT}^{mfd} binary variable used to denote the mechanical forced-draft in the cooling tower
y_{CT}^{mid} binary variable used to denote the mechanical induced-draft in the cooling tower

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