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Investigating the thermodynamics and economics of operating the thermal power plant under uncertain conditions

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ABSTRACT

The effects of variation of process streams' temperatures and flowrates in an operating Natural Gas Fired Thermal Power Plant (NGFTPP) were investigated using Mathematical Modeling approach. The results showed that with an increase in supply temperatures, the total exchanger area increased from 85874.1 m^2 in the base case to 88255.8 m^2, heat input reduced from 528.1 MW to 496.4 MW, condenser duty increased from 284.4 MW to 306.8 MW, the cycle efficiency reduced from 46% to 38.2%. The reduction in inlet temperatures increased the area, heat input and efficiency to 92443.9 m^2, 543.9 MW and 51.8%, respectively. The condenser duty reduced to 262.0 MW. An increase in the flow rates increased the area, heat input, condenser duty to 90699.7 m^2, 530.1 MW and 298.6 MW, respectively. The cycle efficiency was 43.7%. Reduction in flow rates reduced the area, heat input and condenser duty to 81089.9 m^2, 506.1 MW and 270.2 MW, respectively. The cycle efficiency increased to 46.6%. The study concluded that any variation in the process streams parameters affects thermodynamics and economic performances of thermal power plant.

1. Introduction

The effects of changes of process streams' temperatures and flow rates on the thermodynamics and economics performances of a Heat Exchanger Network (HEN) could be so significant. In fact, more investment and cost expenditure in industry could be due to over design and or under design of heat exchanger network to accommodate any possible changes in temperature and or flow rates during the plant operation. Furthermore, harmful emissions, i.e. CO_2, NO_x, SO_x, etc. were released to the environment during combustion of fossil fuel in a power plant, as such more costs were spent to construct control technologies for such emissions. The environmental impacts of these anthropogenic activities call for efficient operation of an electricity generating system in an economical and environmentally friendly manner. Process integration, especially pinch analysis hasbeen applied as a tool for identifying and selecting optimum technical solutions for improving efficiencies and providing optimum manufacturing solutions [1,2].

Extensive efforts have been made in the fields of energy-efficiency improvement and energy recovery technologies using the pinch concept. The idea was first applied in process industries and significant savings in energy cost were achieved [3–6]. Methodologies for design of optimal HEN have been accomplished using Pinch Analysis or Mathematical Programming [7–9]. Heat exchanger network retrofits by heat transfer improvement was studied by Wang et al. [10], and the method saved energy without any topology modification. Mathematical modeling approach using MINLP model was developed for analyzing investments and the long-term operation of Combined Heat and Power (CHP) plants in a district heating network with long-term thermal storage. The model takes into account thenon-linear off-design behavior of the CHP plants as well as a generic mathematical model of the thermal storage, without the need to fix temperatures and pressure [11].

Recently, applications of pinch technology were extended to power plants with tremendous success in terms of process improvement and energy cost savings. The application of pinch technology to power plants was studied by Linnhoff and Alanis [12]. Their research model and many other works were based on modification of an existing site but neglected the possibility of uncertainty in the fluctuation of process parameters. Combined pinch and exergy analysis, as a second model was introduced by Dhole and Zheng [13]. This model used exergy concept in addition to pure pinch method for targeting and analysis of a thermal power plant.

The problem of synthesizing heat recovery networks by allowing variation of the flow rate and inlet temperature within a predefined lower and upper bound have been addressed. However, some of these approaches were based on heuristics or adoption of different models for utility, energy and area targets, which led to decomposition of HEN problem into separate targeting procedures. The

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Nomenclature

ΔT	temperature range (°C)
Q	exchanger duty (MW)
Q_u	duty of utility, U (MW)
C_u	unit cost of utility, U (\$/kW yr)
r	interest rate (%)
$\sum$	cost summation for all utilities used
ΔT_{min}	minimum approach temperature (°C)
W	mass flow rate of the fluid (kg/s)
H	enthalpy of the fluid (kJ/kg)
H_{m}	enthalpy of stream, m (kJ/kg)
W_{m}	flowrate of stream, m (kg/h)
n	number of mixing streams

Subscripts

S	shell
T	tube
i	inlet
o	outlet

Indices

i	hot process or utility stream
j	cold process or utility stream
k	index for stage, 1,...,NOK and temperature location, 1,...,NOK + 1

Sets

H	$\{i/i$ is a hot process stream$\}$
C	$\{j/j$ is a cold process stream$\}$
HU	hot utility
CU	cold utility
K	$\{k/k$ is a stage in the superstructure, $k = 1,\ldots,$NOK$\}$

Parameters

AF	annualization factor (\$/yr)

T^{S}	inlet temperature of stream (°C)
T^{T}	outlet temperature of stream (°C)
CCU	cost per unit of cold utility (\$/kW yr)
CHU	cost per unit of hot utility (\$/kW yr)
C	area cost coefficient
CF	fixed charge for the exchangers
$\mathrm{MC_P}$	heat capacity flow rate (MW/°C)
NOK	total number of stages
U	overall heat transfer coefficient (MW/m^2 °C)
β	exponent for area cost
Ω	an upper bound for heat exchange
Γ	an upper bound for temperature difference

Binary variables

z_{ijk}	variable indicating the existence of match ij at stage, k, in optimal network
$z_{i,CU}$	variable indicating the existence of match between hot stream i and cold utility
$z_{HU,j}$	variable indicating the existence of match between hot utility and cold stream j

Variables

dt_{ijk}	driving force for match ij in interval k
$dt_{i,CU}$	temperature approach for the match of hot stream i and cold utility, CU
$dt_{HU,j}$	temperature approach for the match of hot utility HU and cold stream, j
q_{ijk}	heat exchanged between hot stream i and cold stream j at stage, k
$q_{i,CU}$	heat exchanged between hot stream i and cold utility, CU
$q_{HU,j}$	heat exchanged between hot utility, HU, and cold stream j
t_{ik}	temperature of hot stream i at hot end of stage, k
t_{jk}	temperature of cold stream j at hot end of stage, k

shortcoming is that none of these approaches could guarantee a feasible network that ensures minimum total cost [14,15].

In this study, simultaneous Mixed Integer Nonlinear Programming (MINLP) optimization model, which is capable of capturing the general features of the HEN and guaranteed minimization of total cost, was used. The model followed the formulation of Yee and Grossmann [16]. The isothermal heat transfer, which could arise from latent heat of condensation and vaporization, was neglected. This is because the implications of sensible heat transfer due to variations of temperatures and flow rates were the interests of this study. An optimization approach was developed. Variations were allowed between upper and lower bounds for both temperatures and flow rates and General Algebraic Modeling System (GAMS) was used to solve the MINLP problem using DIscrete and Continuous OPTimizer (DICOPT) solver. Schematic arrangement of the plant's cycle showing the heat exchanger network was shown in Fig. 1 and detailed description given [17].

2. Problem statements

Given a number of hot process streams, N_H, that needed to be cooled and a number, N_C, of the cold process streams that needed to be heated. Furthermore, provided were the process streams' supply temperature, T^S, target temperature T^T and heat capacity flow rate MC_p. Available for use were heating and cooling utilities, Q_{HU}, and Q_{CU}, respectively, whose costs, supply temperatures, and target temperatures were given. The effect of changes of process streams' inlet temperatures and flow rates on the process heat recovery and total annual cost will be investigated.

3. Methodology

3.1. Process simulation and stream data extraction

Operating data were used as input to the HYSYS [18] process simulator to provide heat and mass balances data of the plant. The data generated from HYSYS were used to validate the process operating data. The process stream identification step led to specification of nine hot streams and two cold streams. Two utility streams were used as shown in Table 1.

3.2. Estimation of exchanger heat load and process stream heat capacity flow rate

The duty of each shell and tubes heat exchanger in the network was estimated by Eq. (1) [19,20].

$$Q = W_s(H_{si} - H_{so}) = W_T(H_{To} - H_{Ti}) \tag{1}$$

For the mixing of streams inlets to the shell side of the heat exchanger, the effective enthalpy is as given in Eq. (2) [21].

$$\text{Effective Enthalpy} = \frac{\sum_0^n H_m W_m}{\sum_0^n W_m} \tag{2}$$