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Multi-period design of heat exchanger networks

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ABSTRACT

Heat exchanger networks are an integral part of chemical processes as they recover available heat and reduce utility consumption, thereby improving the overall economics of an industrial plant. This paper focuses on heat exchanger network design for multi-period operation wherein the operating conditions of a process may vary with time. A typical example is the hydrotreating process in petroleum refineries where the operators increase reactor temperature to compensate for catalyst deactivation. Superstructure based multi-period models for heat exchanger network design have been proposed previously employing deterministic optimisation algorithms, e.g. (Aaltola, 2002; Verheyen and Zhang, 2006). Stochastic optimisation algorithms have also been applied for the design of flexible heat exchanger networks recently (Ma et al., 2007, 2008). The present work develops an optimisation approach using simulated annealing for design of heat exchanger networks for multi-period operation. A comparison of the new optimisation approach with previous deterministic optimisation based design approaches is presented to illustrate the utilisation of simulated annealing in design of optimal heat exchanger network configurations for multi-period operation.

Keywords: Heat exchanger network; Multi-period; Simulated annealing; Design

1. Introduction

Heat exchanger networks are a means of utilising the heat available in a process by exchanging between hot and cold process streams, thereby decreasing energy demand and therefore utility costs, as well as capital investment in auxiliary equipment. Heat exchanger networks thus improve the economics of plant operation. Heat exchanger network design has long been the focus of research studies and remains an area of continuous development due to the current trend of increasing energy costs.

The operating conditions of a plant may vary with time. Firstly, unplanned and/or uncontrolled operational fluctuations in operating conditions around desired values or set points are inevitable. Secondly, planned periodic changes in operating conditions for enhancing performance is inherent to the nature of some processes. For example, the reactor operating temperature in processes such as hydrotreating and hydrocracking in refineries can be changed with time to compensate for catalyst deactivation; distillation column operating pressures can be varied to take advantage of seasonal variations in ambient temperatures. Heat exchanger networks that can remain operable in such varying operating conditions and optimal over the time period of interest are termed flexible heat exchanger networks. Flexible heat exchanger networks are classified as resilient or multi-period respectively, depending on the nature of variation in the plant operating conditions (Verheyen and Zhang, 2006). The aim of this work is to review and analyse multi-period heat exchanger network design and propose a new robust and effective approach using simulated annealing for optimisation.

1.1. Review of design methodologies

This section presents an overview of approaches for design of heat exchanger networks for fixed process operating conditions. A detailed discussion of these design methodologies can be found elsewhere (Nishida et al., 1981; Smith, 2005; Verheyen and Zhang, 2006). Since the pioneering work on

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Nomenclature

A	heat transfer area, m^2
AF	annualisation factor
A_{max}	maximum heat transfer area of a heat exchanger, m^2
B	exponent for area cost
C	area cost coefficient for heat exchangers, €/unit
C_{cu}	per unit cost for cold utility, €/unit
C_f	fixed charge for heat exchanger unit, €/unit
C_{hu}	cost per energy unit for hot utility, €/unit
CP	stream heat capacity flow rate, kW/K
C_{ut}	cost per energy unit cost for utility, €/unit
DOP	duration of period
F_T	logarithmic mean temperature difference correction factor
HU_{up}	upper bound on total hot utility available, kW
N_{CS}	number of cold streams
N_{EQ}	number of equations in the heat exchanger network model
N_{HS}	number of hot streams
N_{ND}	number of nodes in the heat exchanger network
N_{PHX}	number of process heat exchangers
N_{SP}	number of stream splitter-mixer units
N_{ST}	number of process streams
N_{TP}	number of operating periods
N_{UHX}	number of utility heat exchangers
N_{UT}	number of utilities
Q	heat exchanger duty, kW
SF	flow rate splitting fraction in a stream splitter
T	temperature, °C
TC	temperature of the cold stream in a heat exchanger, °C
TH	temperature of the hot stream in a heat exchanger, °C
TMX	temperature of a stream of a mixer, °C
TS	supply temperature of a stream, °C
TSP	temperature of a stream of a splitter, °C
U	overall heat transfer coefficient, $kW/m^2\,K$
XBC	fraction of cold stream bypassed
XBH	fraction of hot stream bypassed
z	existence of process-to-process heat exchanger
zut	existence of utility heat exchanger

Abbreviations

HEN	heat exchanger network
LMTD	logarithmic mean temperature difference
LP	linear programming
MILP	mixed integer linear programming
MINLP	mixed integer nonlinear programming
NLP	nonlinear programming
SA	simulated annealing
TAC	total annualised cost

Indices

cs	cold stream of a heat exchanger
hs	hot stream of a heat exchanger
i	process heat exchanger
j	utility heat exchanger
k	heat exchanger
l	stream splitter
n	hot process stream
nd	temperature node
ndc	temperature node on a cold stream
ndh	temperature node on a hot stream
o	cold process stream
p	period of operation
s	stage number or temperature interval
st	stream of a splitter

Sets

CS	set of cold streams
HS	set of hot streams
HX	set of heat exchangers
PHX	set of process heat exchangers
SP	set of stream splitters
ST	set of streams
TP	set of operating periods
UHX	set of utility heat exchangers
UT	set of utility streams

heat exchanger network synthesis by Masso and Rudd (1969), based on heuristics, different strategies have been explored and developed. Heat exchanger network design methodologies have been classified based on the underlying approach; these are summarised here as background to the extension of conventional approaches to multi-period design.

1.2. *Pinch analysis and heat exchanger network design*

Pinch analysis is a thermodynamic tool for estimating minimum utility consumption, number of units and investment cost of a network for a given minimum approach temperature. Linnhoff and Hindmarsh (1983) proposed heuristic rules for heat exchanger network design based on the concept of the pinch temperature, i.e. the temperature where the net driving force for heat exchange is zero. This technique is developed using the systematic methods introduced by Hohmann (1971) and further refined by Linnhoff and Flower (1978).

Pinch analysis provides estimates for minimum energy and capital costs based on the material and energy balance of process streams. The design of a heat exchanger network is carried out by dividing the problem at pinch temperature. The network is designed above and below the pinch by starting at the pinch and moving away as there is more freedom in the choice of matches away from the pinch. The matches between hot and cold process streams and the heat exchanger duties are determined using heuristics to minimise the number of units and maximise the heat recovery (Smith, 2005).

1.3. *Sequential approaches for heat exchanger network design*

The sequential design approaches using the pinch theory decompose the heat exchanger network design problem into sub-problems for minimising utility costs, number of units and investment costs. The most widely employed models for estimating minimum utility consumption and number of units are the transshipment models of Papoulias and Grossmann (1983). The linear programming (LP) formulation of the transshipment model predicts minimum utility cost for a given system while a mixed integer linear programming (MILP)