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Model based approach to synthesize spare-supported cleaning schedules for existing heat exchanger networks

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ABSTRACT

Almost every modern chemical process is equipped with a heat-exchanger network (HEN) for optimal energy recovery. However, as time goes on after startup, fouling on the heat-transfer surface in an industrial environment is unavoidable. If the heat exchangers in an operating plant are not cleaned regularly, the targeted thermal efficiency of HEN can only be sustained for a short period of time. To address this practical issue, several mathematical programming models have already been developed to synthesize online cleaning schedules. Although the total utility cost of a HEN could be effectively reduced accordingly, any defouling operation still results in unnecessary energy loss due to the obvious need to temporarily take the unit to be cleaned out of service. The objective of the present study is thus to modify the available model so as to appropriately assign spares to replace them. Specifically, two binary variables are adopted to respectively represent distinct decisions concerning each online exchanger in a particular time interval, i.e., whether it should be cleaned and, if so, whether it should be substituted with a spare. The optimal solution thus includes not only the cleaning schedule but also the total number of spares, their capacities and the substitution schedule. Finally, the optimization results of a series of case studies are also presented to verify the feasibility of the proposed approach.

1. Introduction

In a chemical manufacturing process, efficient energy recovery and reuse is usually the key to minimizing the total operating cost, while the heat exchanger network (HEN) is a viable vehicle for achieving such a purpose. After putting the units in a HEN in service, the solid impurities in process streams may be deposited continuously on the heat-transfer surfaces and, thus, the overall performance of HEN tends to deteriorate over time. This fouling problem can be abated by cleaning all heat exchangers as a part of the overall maintenance (or checkup) program during plant shutdown. However, if it is also possible to clean at least a portion of the online units when the normal production is still in progress, then a proper schedule must be stipulated to maximize the implied cost saving.

A programming approach has often been adopted in the past to produce the aforementioned HEN cleaning schedules for energy conservation. To this end, Smaïli et al. (1999) first constructed a mixed integer nonlinear programming (MINLP) model for the thin-juice preheat train in a sugar refinery. Since the global solution of such a model cannot always be obtained, several additional studies have been carried out to address the related computation issues. Georgiadis et al. (1999) tried to developed a mixed integer linear program (MILP) via linearization of the nonlinear constraints so as to produce the near-optimum schedules efficiently, while Georgiadis and Papageorgiou (2000) later studied solution strategies of the corresponding MINLP models. Alle et al. (2002) then solved a few example problems successfully with the outer approximation algorithm. Smaïli et al. (2002) subsequently applied the simulated annealing, threshold accepting and backtracking threshold accepting algorithms to solve the models they first developed. Again for the same objective of achieving an approximate global optimum efficiently, Lavaja and Bagajewicz (2004) formulated a new MILP model via linearization to synthesize the cleaning schedules. Their solutions were compared with those obtained in Smaïli et al. (2002) and it was found that both yielded similar schedules and roughly the same total annual costs. On the other hand, Markowski and Urbaniec (2005) suggested using a graphic method to analyze the effects of fouling on the exit temperatures of every unit in a HEN and to manipulate the cleaning schedules accordingly.

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Nomenclature

Sets

E The set of all exchanger labels in the given HEN
I The set of all hot-stream labels in the given HEN
J The set of all cold-stream labels in the given HEN
P_k The set of all period labels in year k of the time horizon

Variables

A_{sp} Heat-transfer area of a spare exchanger (m^2)
$a_{i,j,k,p}^{fm,tp}$ The overall heat-transfer coefficient determined according to fouling model fm $\in \{L, E\}$ at time point tp $\in \{bcp, ecp, bop, eop\}$ during period p ($p \geq 2$) in scenario (i) if exchanger $(i, j) \in$ E is last cleaned during period k and $1 \leq k < p$ (kW/m^2 K)
$c_{i,j,p}^{fm,tp}$ The overall heat-transfer coefficient determined according to fouling model fm $\in \{L, E\}$ at time point tp $\in \{bcp, ecp, bop, eop\}$ during period p in scenario (iii) (kW/m^2 K)
$Eu_{j,p}^H$, $Eu_{i,p}^C$ Estimates of the total hot and cold utility consumption levels needed respectively by cold stream j $\in$ J and hot stream i $\in$ I in period p (kW-mon)
N_{sp} Total number of spares
$Qu_{j,p}^{H,tp}$, $Qu_{i,p}^{C,tp}$ The hot and cold utility consumption rates needed respectively by cold stream j $\in$ J and hot stream i $\in$ I at time point tp $\in \{bcp, ecp, bop, eop\}$ in period p (kW)
$r_{i,j}$ The fouling resistance of heat exchanger $(i, j) \in$ E (m^2 K/kW)
$T_{in,i,p}^{H,tp}$, $T_{out,i,p}^{H,tp}$ The inlet and outlet temperatures of hot stream i $\in$ I of exchanger $(i, j) \in$ E at time point tp $\in \{bcp, ecp, bop, eop\}$ in period p (K)
$T_{in,j,p}^{C,tp}$, $T_{out,j,p}^{C,tp}$ The inlet and outlet temperatures of cold stream j $\in$ J of exchanger$(i, j) \in$ E at time point tp $\in \{bcp, ecp, bop, eop\}$ in period p (K)
$TL_{i,p}^{H,tp}$, $TL_{j,p}^{C,tp}$ The outlet temperatures of hot and cold streams respectively from the last heat exchangers on streams i $\in$ I and j $\in$ J at time point tp $\in \{bcp, ecp, bop, eop\}$ in period p (K)
$U_{i,j,p}^{fm,tp}$ The overall heat-transfer coefficients of exchanger(i, j) at time point tp $\in \{bcp, ecp, bop, eop\}$ in period p determined according to fouling model fm $\in \{L, E\}$ (kW/m^2 K)
$X_{i,j,p}$ A binary variable used to denote whether or not a spare is adopted to replace exchanger $(i, j) \in E$ during period p
$Y_{i,j,p}$ A binary variable used to denote whether or not exchangerer $(i, j) \in E$ is cleaned during period p

Parameters

$A_{i,j}$ The heat-transfer area of exchanger $(i, j) \in$ E (m^2)
$bsp_{i,j,p}^{fm,tp}$ The overall heat-transfer coefficient determined according to fouling model fm $\in \{L, E\}$ at time point tp $\in \{bcp, ecp, bop, eop\}$ during period p in scenario (ii) if a spare is adopted to replace exchanger $(i, j) \in$ E (kW/m^2 K)
C_i^H, C_j^C The heat capacities of hot stream i $\in$ I and cold stream j $\in$ J (kJ/kg-K)
C_p^{HU}, C_p^{CU} The unit costs of heating and cooling utilities in period p ($/kJ)
C_{cl}, C_{cl}^{sp} The cleaning costs of a heat exchanger and a spare ($/cleaning)
C_{sp} Annualized cost coefficient for the capital cost of heat exchanger $\left(\$/m^{1.6}\mathrm{yr}\right)$
f_c The duration of a defouling sub-period (mon)
F_i^H, F_j^C The mass flow rates of hot stream i $\in$ I and cold stream j $\in$ J (kg/s)
$K_{i,j}$ The characteristic fouling speed of exchanger $(i, j) \in$ E (mon^{-1})
$R_{i,j}$ The ratio between the products of mass flow rate and heat capacity of the cold and hot streams in heat exchanger $(i, j) \in$ E
$\dot{r}_{i,j}$ The constant fouling rate of exchanger $(i, j) \in$ E (m^2 K/mon kW)
$r_{i,j}^{\infty}$ The asymptotic maximum fouling resistance of exchanger $(i, j) \in$ E (m^2 K/kW)
t_f The overall time horizon (mon)
TT_i^H, TT_j^C The target temperatures of hot stream i $\in$ I and cold stream j $\in$ J (K)
$U_{i,j}^{cl}$, U_{sp}^{cl} The overall heat-transfer coefficients of exchanger $(i, j) \in$ E and spare exchanger when the heat-transfer surface is clean (kW/m^2 K)
τ_p The length of period p (mon)
η_{cl} Efficiency of cleaning operation
η^H, η^C The heat-transfer efficiencies in heater and cooler respectively