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Coordination of Bypass Control and Economic Optimisation for Heat Exchanger Network with Stream Splits

Lin Sun*, Xin-Lang Zha, Xiong-Lin Luo

Department of Automation, China University of Petroleum, Beijing, 102249, China
sunlin@cup.edu.cn

The bypass control is an online adjustment strategy widely used on heat exchanger network (HEN) to maintain the operating requirements. Once the operating conditions are varied, the controllers will adjust the fractions of bypass until satisfying control objective and keep the value until the next varying. The designed margin has to be increased thus economic efficiency becomes poor obviously. It is essential to take both control performance and economic efficiency into account during the process of operation. Several researchers have put forward coordinate control or coordinate optimization in chemical processes. However, these researches mainly studied on the coordination of different variables for controlling or optimization without considering the relationship between control performance and economic optimization. In this work, firstly we proposed a methodology for coordination of control and economic optimization for the HEN with stream splits. Usually the number of operating variables equals to controlled variables. The fractions of bypass are selected as operating variables and adjusted for achieving the control targets. In addition, the splits as available degrees of freedom have greater adverse effects on pressure drop, so only can be regulated within a tiny range and may suitable as optimization variables for economic optimization. Then a coordination scheme of bypass control and economic optimization for HEN with stream splits is designed on the basic of previous research. In this case, the control objective is to keep outlet stream temperature at the set point and the optimization objective is to release margin minimum which can make cost lower. The fractions of bypass are adjusted for controlling and the split ratios are regulated for economic optimization simultaneously, so adequate control and optimal economic can be achieved at the same time. The simulation results on a HEN with stream splits confirm the superiority of coordination method between bypass control and economic optimization, which ensure economic optimal meanwhile control performance promising though a certain control performance is sacrificed.

1. Introduction

As a component links the process flowsheet with the utility system, heat exchanger network (HEN) transfers energy in form of heat from a set of hot streams to a set of cold streams. HEN is a frequently of utmost importance part and consumes a substantial proportion of energy in chemical process industry. Nevertheless, a great deal of energy still can be saved by heat recovery if appropriate measures are taken (Klemeš and Varbanov, 2012). The potential of heat exchanger networks for saving energy and costs has led to an enormous amount of research, and years ago the literature have fallen into optimal operation of heat exchanger networks (Glemmestad et al., 1999).

The category of optimal operation based on the control viewpoint study how the available degrees of freedom, such as valves, bypasses, split ratios and utility heaters. But it also represents full of challenges due to system nonlinearities, varying process parameters, internal and external disturbances, measurement noise and so on. A number of control strategies that in order to overcome some of above difficulties have been proposed. Bakošová and Oravec (2014) and later Vasickaninova and Bakošová (2015) have reported some advanced control algorithms for better set-point tracking and adequate disturbance rejection ability, the manipulated variables in these control strategy are flow rates of streams without exception. However, direct manipulation of the flow rate of either the hot or the cold stream is most often used when that stream is a utility (cooling water, steam, hot oil, or refrigerant). When the flow rates of both streams are set by process requirements, bypassing

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is widely used for effective control of process stream target temperatures. The presence of bypasses increases flexibility of the heat exchanger network, and closed-loop dynamic responses are improved significantly using controllers with dynamic estimation of uncertainties. The linear quadratic regulator (LQR) control technique can be adopted for HEN through bypass manipulation so that achieve control targets (Delatore et al., 2016).

The control strategies of HEN in listed literature only achieve the purpose of control but not the economic optimisation. An approach for optimising the split between the lines of a parallel heat exchanger system is presented in order to reduce the operating cost, but without considering control performance (Jaschke and Skogestad, 2014,). Moreover, it indicates that the split ratio is appropriate as optimisation variable. In fact, an optimal ISE point is found at a certain bypass fraction which does not correspond to the minimal total annualized cost (Masoud et al., 2016). It has obviously illustrated that there is a conflict between bypass control and economic performance.

Unfortunately, it is uneconomical for control of a HEN without economic optimisation. On the other hand, the economic optimisation without considering control performance is unreasonable, because controlling the operation of these heat exchangers is critically important for maintaining system stability and operating efficiency. The authors propose the coordination of bypass control and economic optimisation for HEN with stream splits in this work.

It is rarely to find researches about coordinated optimisation on HEN. New agent named coordinator agent are implemented to achieve inter-process heat integration, which means reduction of the energy usage and the utility costs entire plant, by coordination of the energy usage with the sub processes (Kimura et al, 2015). It just optimises the energy usage only from the perspective of chemical technology and doesn't take the control requirements into account. The open literature which introduces coordination mechanism into HEN to achieve effective control and economic optimisation at the same time isn't found.

Besides the area margin is gradually released via bypass adjustment, thereby resulting in energy consumption (Luo et al, 2013), which provides a good idea of economic optimisation. Consequently, we firstly proposed the Coordination of Bypass Control and Economic Optimisation (CBCEO) for HEN. The control objective is to keep outlet stream temperature at the set point and the optimisation objective is to release margin minimum which can make cost lower. Compare with common bypass control, through bypass adjustment to quickly meet the control requirements but margin is quite large. The fraction of bypasses in CBCEO is adjusted for control at the same time split ratios is regulated for reducing the margin on the premise of effective control, so promising control performance and optimal economic can be achieved simultaneously.

2. Coordination of Bypass Control and Economic Optimisation

2.1 Methodology for CBCEO

In HEN with bypasses and stream splits, bypass control is widely used for satisfying control requirements but without considering the economic optimisation. Therefore, a coordination methodology of bypass control and economic optimisation is put forward for taking control performance and economic benefit into consideration meanwhile.

As shown in Figure 1, the dashed line stands for CBCEO and the dotted line stands for the bypass control. *SR* refers to a vector consisting of the split ratios, *K* refers to a vector consisting of the bypass fractions and *J* refers to the margin of HEN. The margin should be less which means less cost and the economic benefit is better. Assuming that the system is in the initial state *A*, of which the output temperature is T_0, the vector of bypass fractions is K_A, the vector of split ratios is SR_0 and the loss margin is J_A. When the setpoint is changed to T_{sp}, in common bypass control, the fractions of bypass under control algorithm will be adjusted for achieving the target. Finally system reaches a new state that is the point *C*, of which the output temperature is T_{sp}, the vector of bypass fractions is K_C, the vector of split ratios stays at SR_0 and the loss margin is J_C. The fractions of bypass in common bypass control are adjusted but the split ratios are ignored which also may have significant effects on the output temperature. So in CBCEO, when the setpoint is changed to T_{sp}, the fractions of bypass under control algorithm will be adjusted for achieving the target and the split ratios will be regulated at the same time for economic optimal. Finally system reaches a new state that is the point *B*, of which the output temperature is the setpoint T_{sp}, the vector of bypass fractions is K_B, the vector of split ratios is changed to SR_1 and the loss margin is J_B. Notice that J_B is smaller than J_C, that is to say the economic performance used the methodology of coordination design is better than common bypass control. In addition, the output temperatures of state *B* and *C* are just same and the setpoint T_{sp}, which means the control results used both methodologies are effective.

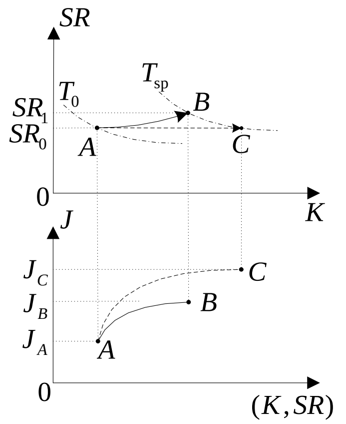


Figure 1: Methodology for coordination of control and economic optimisation

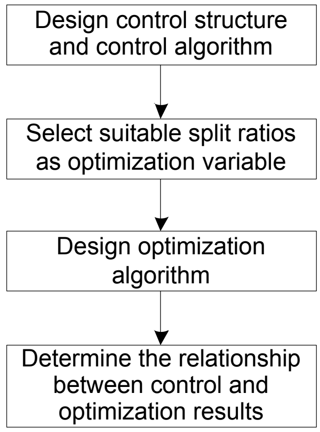


Figure 2: The scheme of coordination between control and economic optimisation.

2.2 Design scheme of CBCEO

When coupling degree is loose in HEN, multi-loop PID is suggested as control strategy and the bypass fractions are the manipulated variables. In order to response faster, usually the fraction of bypass which is nearest to output temperature is as the manipulated variable in one control loop. It's not difficult to obtain the structure of multi-loop PID.

Although the split ratios have effects on the output temperature, it is not logical that all of them are reasonable to be optimisation variables. The steady state gain can be used for estimating and choosing the appropriate optimisation variables. The split of which gain on output value is larger should be selected, so that the effect of shifting on HEN can be smaller. For example, split 1 reduces 1 % and outlet temperature varies 1 K, but split 2 reduces 1 % and outlet temperature varies 5 K. Obviously, in order to reduce the influence of the whole HEN, it is advisable to choose split 1 as optimisation variables. In this work, a more reasonable way of combining optimal control with the conventional control loop proposed by Luo et al. (2013) is adopted in order to take the conventional controller output and optimiser into account together. The control accuracy and reliability of the conventional control loop is ensured by remaining the output of controller unchanged, and then sending the combined conventional controller and optimal controller output values to the adjustment bypass.

Consequently, the scheme of coordination between control and economic optimisation can be concluded as a diagram in Figure 2, there are four main steps for designing.

2.3 Optimisation problem description and solution

The optimisation objective in this work is to release margin of HEN minimum which can make cost lower. In fact, each heat exchanger has its margin, so the margin of HEN refers to the sum of all heat exchanger. Considering the size of the bypass valve and the low flow rate will increase fouling, at the same time in order to maintain a reasonable pressure drop, so flow to heat exchanger can't be too low, there is an upper bound of bypass fraction and can be taken as 0.5. The split ratio should be a value in interval [0, 1]. The split ratios act as optimisation variables and they can be regulated in a tiny range, there are also constraints to reduce the effect of pressure drop.

So the optimisation problem can be described by the following,

$$\min J = \sum_{i=1}^{m} J_i = \sum_{i=1}^{m} \frac{\left|k_{i0} - k_{i1}\right|}{k_{i0}} \times 100\%$$

$$\begin{cases} 0 < k_i < 0.5 \\ 0 < sr_j < 1 \quad j = 1, \cdots, n \\ 0 < \left|\Delta sr_j\right| < delta_j \end{cases} \tag{1}$$

Where m in Eq(1) refers to the total number of heat exchangers and n refers to the total number of split ratios. k_{i0} is the initial fraction of bypass and k_{i1} is the final fraction after controlling. sr_j is the value of split ratio. And it also has a tiny shifting range because of pressure drop, that is $delta_j$. The pattern search method is used for regulating the split ratios between the lines of HEN such that the margin is minimized. Derivatives of the objective function in this method aren't required in the calculation, and it is also named as Hooke-Jeeves method (Hooke and Jeeves, 1961) much later adopted by Chen (2005).

3. Case study

In this paper, the capability of the proposed scheme is demonstrated using a simple case study. A HEN with bypass and split is shown in Figure 3. The streams and heat exchangers data used to control and optimisation the HEN are shown in Table 1. The same case study has been used in earlier studies (Sun et al., 2015).

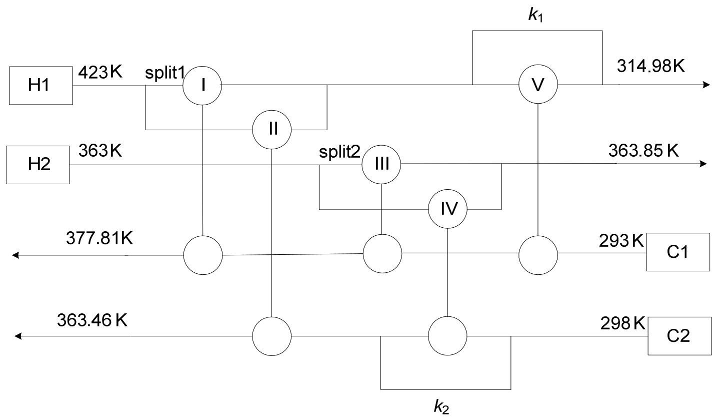


Figure3: Control structure of the HEN with bypass and split.

Table 1: Basic data of streams and heat exchangers

Stream	H1	H2	C1	C2	Heat exchanger	I	II	III	IV	V
Heat capacity / kJ·(kg·K)$^{-1}$	4	4	2.5	2.5	Transfer area / m^2	272.90	291.09	260.12	562.54	109.39
Flowrate / kg·s^{-1}	5	20	10	12	Transfer coefficient / W·m^{-2}·K^{-1}	65.18	62.51	144.27	98.83	184.94
Density / kg·m^{-3}	850	850	995	995						

The ratio of split 1 reduces 1 %, the temperature of H1 stream outlet will increase 0.48 K and the temperature of H2 stream outlet will decrease 0.11 K. Similarly, the ratio of split 2 reduces 1 %, the temperature of H1 stream outlet will increase 0.08 K and the temperature of H2 stream outlet will decrease almost zero. It can be concluded that split 2 can't be as optimisation variable but the split 1 is very appropriate to be optimisation variable. Assume that the fractions of bypass are 0.25 in initial state, and the tiny range of split ratio is [-1 %, 1 %], *J* refers to the margin of HEN which is the less the better of economic, then the optimisation problem can be described by the following,

$$\min J = \sum_{i=1}^{2} J_i = \sum_{i=1}^{2} \frac{|0.25 - k_i|}{0.25} \times 100\%$$

$$\begin{cases} 0 < k_i < 0.5 \\ 0 < sr_1 < 1 \\ 0 < |\Delta sr_1| < 1\% \end{cases} \quad (2)$$

The model of HEN is built in gPROMS, but the control and optimisation algorithms are come true in MATLAB. The energy consumption is measured by the total margin of heat exchangers. The situation for CBCEO and bypass control is presented in Figure 4. Finally the margin using CBCEO is 6.97 % and that using bypass control is 17.81 %, so the margin using CBCEO is designed less. Obviously, it can be stated that the smaller energy consumption is assured by using CBCEO. The economic performance adopting CBCEO scheme is significantly better than that using common bypass control.

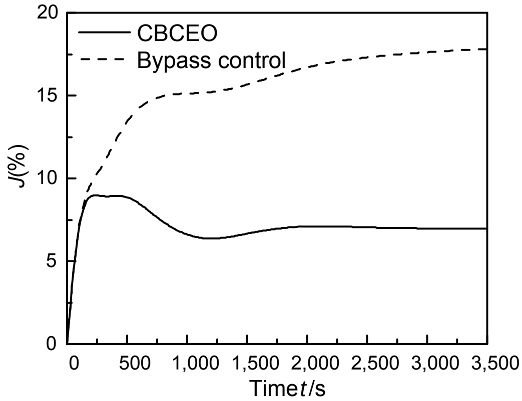
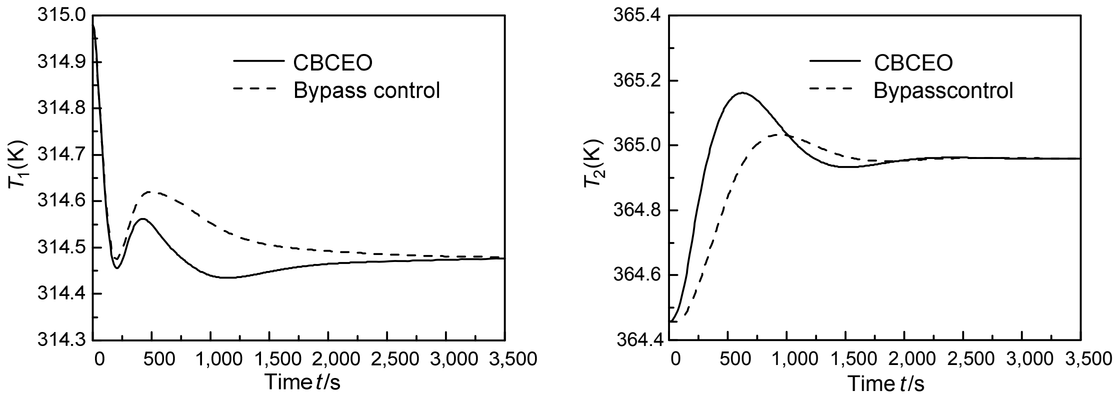


Figure 4: The economic performances of the two control strategies.



(a) The outlet temperature of stream H1 *(b) The outlet temperature of stream C2*

Figure 5: Control performance of streams H1 and C2 outlet temperatures

Figure 5 compares controlled outputs in the task of set point tracking. The set point of stream H1 outlet temperature changes from 314.98 K to 314.48 K at time 0 s, and the set point of stream C2 outlet temperature changes from 364.46 K to 364.96 K at time 0 s. The control response obtained by CBCEO may be not the better one compares with bypass control, but it has the larger overshoots though the faster response. The simulation results of controlling were compared also using IAE (integrated absolute error) and ITAE (integrated time absolute error). And the specific data are provided in Table 2. The value of IAE or ITAE using CBCEO is larger than that using bypass control, which means control performance using CBCEO is not better than that using bypass control. However, the value of IAE or ITAE is not much different and they are on the same order of magnitude respectively. And from Figure 4, the control using CBCEO is also effective and promising. More than anything, the value of J using bypass control is nearly three times as much as it using CBCEO, so it has significant superiority in economic not in control performance and a little control performance is sacrificed because of economic optimisation.

Table 2: Values of IAE, ITAE and J

Control strategies	IAE	ITAE	*J*
Bypass control	116.16	9,559.79	17.81
CBCEO	161.12	10,882.77	6.97

4. Conclusions

In this paper, we proposed the coordination of bypass control and economic optimisation for heat exchanger network with stream splits. The control performances of two control strategies, bypass control and CBCEO, were investigated on the nonlinear HEN wit split. Simulation results obtained using designed controllers were measured calculating integral performance indexes IAE and ITAE. Though the control response obtained by bypass control has smaller value of IAE and ITAE, it is uneconomic because without considering the economic performance.

But in CBCEO, the fractions of bypass are adjusted for controlling similar with bypass control, in addition, the split ratios are regulated for economic optimisation simultaneously. The simulation results confirm that HEN using CBCEO scheme can achieve double purposes of control and optimal economic at the same time though a little control performance is sacrificed.

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Nomenclature

CBCEO	Coordination of Bypass Control and Economic Optimisation	C	cold stream
delta	a tiny shifting range of split	H	hot stream
J	cost function	*K*	bypass openings vector
k	bypass opening	min	minimum
sp	set point	*SR*	split ratios vector
sr	split ratio	*T*	temperature

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