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Economic model predictive control of an absorber-stripper CO2 capture process for improving energy cost

Lester Lik Teck Chan, Junghui Chen*

Department of Chemical Engineering, Chung-Yuan Christian University
Chung-Li, Taiwan 320, Republic of China (**e-mail: jason@wavenet.cycu.edu.tw*)

Abstract: Carbon dioxide (CO2) is the major source of greenhouse gas and its capture and recovery is the key to effective reduction of CO2 emissions. Optimization of the CO2 capture plays a critical role in the reduction of energy cost. CO2 concentration in the plant varies with time and a dynamic study of the economic optimization reflects the true cost better when compared to the current strategy of the steady state optimization. The economic model predictive control (EMPC) that combines real-time economic process optimization and feedback control is applied to the optimization of CO2 capture process. The large energy requirement for solvent regeneration is optimized in dynamic settings. Unlike the conventional steady state consideration of the economic optimization, the proposed method allows the cost to be adjusted to the changing condition such as feed composition and utility cost. Case studies are then presented to show the benefits of the EMPC optimization for CO2 capture process.

Keywords: CO2 capture, economic model predictive control, energy cost reduction, optimization

1. INTRODUCTION

Carbon dioxide (CO2) is the major source of greenhouse gas that is a serious issue in the climate change and global warming. The combustion of fossil fuels contributes largely to the emission of CO2. The capture and recovery of CO2 is the key to effective reduction of CO2 emissions. Currently, the absorption is the only commercially attractive option for post combustion capture of CO2 (Aroonwilas and Veawab, 2004, Rochelle, 2009). The optimization of the CO2 capture process plays a critical role for achieving reduction in the energy cost and for meeting safety requirements and environmental regulations. In conventional chemical processes real-time optimization (RTO) has been applied to the optimization of the chemical processes. RTO system analyses process data at steady state to carry out model parameter estimation and update the steady-state process model. The optimization computes the optimal solution based on a process model and the overall decision process involves several levels in the decision hierarchy. The planning and scheduling at the top level addresses long term issues such as production rate targets and raw material allocation. On the other hand, regulatory control of basic flow, pressure, and temperature is implemented at the bottom level in the short term. The CO2 capture process can be handled in the same way where the upper level decides the CO2 capture target and the lower level regulate the process variables. Such a scheme is used to ensure the process operates under optimal condition in order to provide economic benefits (Arce et al., 2012, Chikukwa et al., 2012). Online optimization strategies for CO2 capture have been proposed (Lin et al., 2012, Prölß et al., 2011) but these works mainly focused on the steady state optimization of the objective function. However, the CO2 concentration in the plant varies with time and as a result a dynamic study of the economic optimization reflects the true cost better.

The economic model predictive control (EMPC) that combines real-time economic process optimization and feedback control can be applied to dynamic economic optimization handle such problem. The development of EMPC formulation utilizes general economic cost function replacing the conventional quadratic cost function of the standard model predictive control (MPC) formulations (Ellis et al., 2014). The quadratic cost of conventional MPC allows for tuning of closed-loop response but it may not be an adequate representation of managing real-time process operation with respect to the process economic optimization. EMPC has recently attracted widespread attention given the increasing need to directly account for real-time feed-stock change and demand change during control action calculations. EMPC performs the optimization over specified time horizon and is able to provide better economic optimization since it minimizes the transient cost incurred during transition between different steady-state operations (Angeli et al., 2012, Würth et al., 2011). The economic impact of EMPC becomes even more significant when the best performance is achieved under non-steady-state operation such as periodical and cyclical operation. EMPC has recently been applied to waste water distribution network (Wang et al., 2017) and electric arc furnace (Rashid et al., 2016).

There is a large energy requirement of the CO2 capture process for solvent regeneration (Bui et al., 2014). The heating duty for solvent regeneration reduces significantly when using novel solvents such as ammonia or mixed amines. On the other hand, solvents efficiency can be improved by optimizing the cooling duty or using alternative column configurations (Linnenberg et al., 2012). Nevertheless, from the operation standpoint, the improvement in the dynamic operation of the CO2 capture process can improve the energy cost and the EMPC is a good option to achieve this goal. This work aims to investigate the dynamic optimization of the CO2 capture process using EMPC. Unlike the conventional steady state consideration of the economic optimization, the proposed method allows the cost to be adjusted to the changing condition such as feed composition and utility cost through a dynamic consideration. In this study, the EMPC algorithm is formulated for the CO2 capture process. The advantages of the EMPC method are demonstrated through the simulation studies. The article is arranged as follows. The CO2 capture process and the problem definition are described in the next section. This is followed by the EMPC formulation for the CO2 capture process. Case studies are then presented to show the efficacy of the proposed method and the article concludes with some closing remarks.

2. PROCESS DESCRIPTION AND PROBLEM DEFINITION

The conventional absorber-stripper process is a common CO2 capture process and it requires high energy consumption. By optimizing the operation to capture the CO2 through a balance of the solvent and the regeneration cost due to energy usage, economic benefits can be obtained. As such the EMPC is applied to the optimization of the CO2 capture process. The equipment and the methodology are detailed in the following.

2.1 Absorber-stripper process for CO2 capture

The conventional amine based absorber-stripper pilot equipment that captures CO2 is as shown in Fig. 1. The flue gas (F-gas) flows into the bottom of the packed bed absorber with higher pressure to overcome the pressure drop in the absorber. The lean amine solution (LMEA) is pumped from the storage tank (MEA-TANK) and it enters the upper part of the absorber. The flue gas and lean MEA solution contact counter-currently and react exothermically in the absorber. The CO2 free flue gas (T-GAS) is vented into atmosphere from the top of the absorber. The CO2-rich MEA (RMEA) is pumped to the lean/rich MEA heat exchanger (HEATX). In HEATX, RMEA is heated by exchanging heats with the recycled lean MEA (P-LMEA), and the heated RMEA is called HX-RMEA stream. Then, the HX-RMEA stream enters the upper part of the packed bed stripper. The reboiler under the stripper extracts CO2 from the HX-RMEA stream, and this stream is recovered and it becomes the lean MEA solution (M-LMEA). Most of M-MEA is pumped. It passes through HEATX and becomes HX-LMEA stream. The HX-LMEA stream passes through the cooler (COOLER), where the lean MEA is cooled down by cooling water and then is recycled and mixed with the fresh lean MEA solution (MEA) in the MEA-TANK for further CO2 absorption. The CO2 product and water vapor, which are called VAP1, pass through a reflux condenser (G-L-SEP) at the top of the stripper. Most vapor and the residual MEA absorbent are condensed by cooling water are called REFLUX-L. It flows back to the stripper to desorb CO2 again and the high weight by mass CO2 (HWP-CO2) is collected and discharged.

2.2 Problem Definition

In conventional design the optimization performs the steady state optimization to compute the optimal steady state operation point of the manipulated input. In this case, the inputs considered are the MEA flow and the utility duty, $\mathbf{u} = \left[f_{MEA} \quad C_{util} \right]$. The optimization computes a steady state optimal solution and the optimal solution is in turn supplied to a regulatory layer that consists of controllers that track the required set-points. The two-layer operation of determining the steady-state set point first, followed by tracking is suboptimal compared with a dynamic optimization formulation that directly optimizes the economic objective function (Sildir et al., 2014).

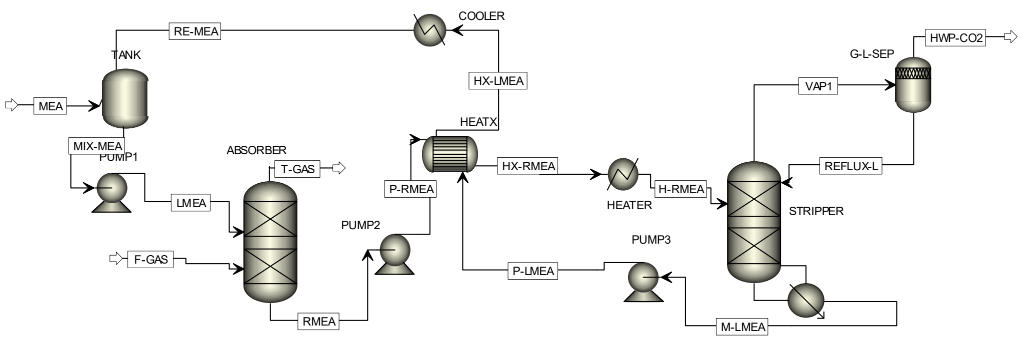

Fig. 1.CO2 capture absorber stripper

In actual operation, the CO2 capture process has to run under economically optimal operating conditions while achieving the operation constraints. Plant disturbances can cause economic impact and optimization is required to respond accordingly. The aim in the economic optimization is to solve the optimal operating condition to minimize the cost of implementation for CO2 capture and recovery in the plant. The equipment cost is regarded as a constant as hardware of the equipment do not change over the course of the plant operation. The reduction of the operating costs is thus the main concern. In such formulation, EMPC converts the open-loop dynamics optimization into a feedback control strategy by performing it at each sample time after updating the measurement. The objective can be expressed as

$$\min_{\mathbf{u}_1,\mathbf{u}_2,\ldots,\mathbf{u}_N} J_{EMPC} = \sum_{k=1}^{N} L\left(f_{MEA,k}, C_{util,k}\right) + C\left(C_{CO_2,N}\right) \tag{1a}$$

s.t.

$$C_{CO_2,k+1} = f_{ss}\left(f_{MEA,k}, C_{util,k}\right) \tag{1b}$$

$$h\left(C_{CO_2,k}, f_{MEA,k}, C_{util,k}\right) \le 0 \tag{1c}$$

$$C_{CO_2,N} = C_{CO_2,SS} \tag{1d}$$

$L\left(C_{CO_2,k}, f_{MEA,k}, C_{util,k}\right)$ is the economic stage cost and $C\left(C_{CO_2,N}\right)$ is the terminal cost. Equation (1b) describes the time evolution of the process whereas Equation (1c) is the inequality constraint of the operation. Equation (1d) represents a compact terminal region that contains the steady-state operating point in its interior. The aim in the economic optimization is to solve the optimal operating condition to minimize the cost of implementation for CO2 capture. The stability criterion using a terminal state constraint, in this case $C_{CO_2,N} = C_{CO_2,SS}$, where $C_{CO_2,SS}$ is the final steady state CO2 concentration, has been proposed (Angeli et al., 2012). Furthermore, in order to allow for more flexibility a terminal region constraint, $C_{CO_2,N} \in C_{CO_2,f}$ can be adopted (Amrit et al., 2011) and eliminating the terminal cost. This relaxes the constraint to a region rather that a definite value. Moreover, weak controllability and dissipativity assumption should be satisfied for stability of the steady state system. As a result the constraint Equation (1d) becomes

$$C_{CO_2,N} \in C_{CO_2,f} \tag{2}$$

The cost of the absorbent MEA is related to the flow of the MEA, f_{MEA} whereas the utility duty is represented by the energy usage for the equipment, including pumps, reboiler, and cooler. The utility duty comes from the operation units including the pumps (PUMP1 to PUMP3 in Fig. 1), the reboilers at the stripper (STRIPPER in Fig. 1) and heater (HEATX in Fig. 1).

In absorber-stripper CO2 capture process the utility cost, C_{util} can be calculated as

$$C_{util,k} = c_{pump,k} + c_{heater,k} + c_{reboiler,k} \tag{3}$$

c_{pump}, c_{heater} and $c_{reboiler}$ are the cost attributed to the pumps, heater and reboiler respectively. The total pump includes individual pumps rating given as

$$c_{pump} = e \times W_{p,k} \tag{4}$$

e is the electrical cost and

$$W_p = \sum_{m=1}^{M} W_{pump,m} \tag{5}$$

where $W_{pump,m}$ is duty of each pump. The heater and the reboiler cost are

$$c_{heater,k} = \frac{C_s Q_{heater,k}}{\lambda_v} \tag{6}$$

$$c_{reboiler,k} = \frac{C_s Q_{reboiler,k}}{\lambda_v} \tag{7}$$

where C_s is the cost of fluid, $Q_{heater,k}$ and $Q_{reboiler,k}$ the respective duty of the heater and reboiler. λ_v is the specific heat of the steam.

3. EMPC FOR CO2 CAPTURE

Economic dynamic optimization performed over a specified time horizon provides better economic optimization as the transient cost is taken into account. The predictive design takes into accounts of the changes in the process and the economic impact of EMPC becomes more significant when the process has to be operated dynamically. EMPC determine the solution to the following optimization problem expressed by (1a) – (1d) and (2). For the CO2 capture process, the objective function can be defined as

$$J_{EMPC} = \sum_{k=1}^{N} f_{\mathrm{MEA,k}} P_{\mathrm{MEA}} + c_{util,k} P_{util} \tag{8}$$

where P represents the price and the subscript indicates the respective prices of the components. In order to ensure that the CO2 composition meets the requirement, constraints are applied to the CO2 concentration such that

$$\begin{aligned} \mathrm{CO2}_{TGAS} &= \mathrm{CO2}_{TGAS}^{spec} \\ \mathrm{CO2}_{HWP} &= \mathrm{CO2}_{HWP}^{spec} \end{aligned} \tag{9}$$

where the superscript *spec* denotes a required specification. It is noted that a relaxed constraint can offer result in larger region of attraction and a guarantee of recursive feasibility but performance guarantees are not as easily obtained (Müller et al., 2013). In addition, the constraints of the manipulated variables are

$$\begin{aligned} f_{MEA}^{l} &\le f_{MEA,k} \le f_{MEA}^{u} \\ c_{util}^{l} &\le c_{util,k} \le c_{util}^{u} \end{aligned} \tag{10}$$

where the superscript u and l denotes the lower and upper bound respectively. Equation (1a) with stage cost represented by (8) is solved at each sample time to obtain the optimal operation of the CO2 capture process. The sampling time for the EMPC and its prediction horizon should be selected appropriately according to the plant dynamics. This can take into account of the computational load as well as the settling time of the process. The constraints represented by (9)-(10) is to ensure that the system remains stable as the process variables are bounded within the constrained interval. The set of the constraints is constructed in such a way that there exist feasible values of the actual plant which can be determined from a steady state calculation of the plant that relates the operation condition to the output. In the implementation of the proposed method, the initialization of the EMPC can be done with the optimization from the estimated output based on a model from the current measurement. In the above formulation, it is assumed that the estimated values are accurate and it can be interpolated. Finally, output conditions are constrained by the physical plant limits as expressed by (10).

4. CASE STUDY

The CO2 capture process by the absorber-stripper system is tested under the EMPC. The process has to run under economically optimal operating conditions while achieving the operation constraints. The CO2 capture process is represented by using the Aspen One. The vector of the calculated manipulated variable is applied to the process simulation and the calculations are repeated at the next interval with the measurement after the current input to the process simulation. In order to demonstrate the effectiveness of the EMPC, disturbances are introduced in the simulation. Plant disturbances can cause economic impact and optimization is required to respond to the changes in the process conditions. In the case study two types of disturbances are considered, namely, the feed quality as well as the utility prices. These disturbances can be considered as fast and slow disturbances (Sildir et al., 2014). Fast disturbances require regulatory action whereas the slow disturbances with high economic impact may initiate a change in the operating conditions.

4.1 Simulation Tools

In order to investigate the application EMPC on the CO2 capture process, the AspenPlus software package is used for simulation. The model is first developed in Aspen Plus V9 and then exported to the Aspen Plus Dynamics for dynamic simulation. The model is adopted from our previous work (Chen and Wang, 2014). After the Aspen Plus Dynamics model is developed it is in turns connected to the Simulink in order to facilitate the optimization using the 'fmincon' in MATLAB. In this study, a prediction horizon of 5 is used but it is noted that increasing prediction horizon usually results in performance improvement (Ellis et al., 2014). The Aspen Plus-Simulink connection is as shown in Fig. 2.

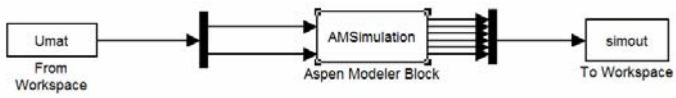

Fig. 2.Aspen Plus-Simulink connection

In order to carry the simulation the input to the process are assigned to the workspace of MATLAB and is ran through the AMS simulation. The result of the operation can then be exported from the Aspen Dynamics to the workspace of MATLAB software.

4.2 Feed Quality

For the absorber-stripper as shown in Fig. 1, the flow of MEA is used to maintain a low concentration of the CO2 in the exit gas of T-GAS. In this investigation, the MEA price is set as $1/kg and the energy price as $0.1/kWh. For the test of feed quality, as the flue gas is considered to come from upstream process and thus the disturbance in the feed quality is a measured disturbance. In this optimization the CO2 concentration at F-GAS is increased after 3 hours. Fig. 3 shows the CO2 evolution at T-GAS. It can be seen that the concentration of CO2 increases as the F-GAS increases due to increase in CO2 of the upstream. In order to increase the CO2 capture the MEA flow is increased as shown in Fig. 4. In response to the F-GAS change, the MEA flow is increased in order to maintain the required extraction of the CO2. This result shows the application of the EMPC optimization of the absorber-stripper for regulatory purpose. In order to ensure that the CO2 composition meets the specified requirement, constraints are applied to the CO2 concentration such that

$$\begin{aligned} \mathrm{CO2}_{TGAS} &= 0.1 \\ \mathrm{CO2}_{HWP} &= 0.8 \end{aligned} \tag{11}$$

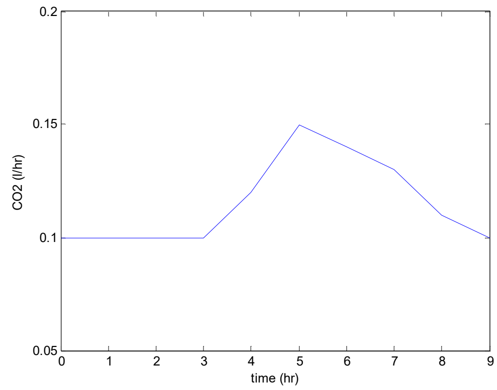

Fig. 3.Time evolution of the CO2 (T-GAS) for feed changes

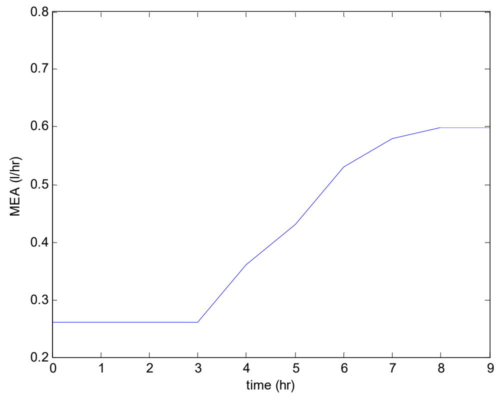

Fig. 4.The flow of MEA for feed changes

Fig. 5 shows the operating cost at different MEA flows and total duties when the feed changes. For this purpose, the MEA flow is constrained between 4 and 12 l/h and the total duty by the reboiler and condenser between 1.15 and 1.6 kW. The contour plot indicates the condition after the feed changes and it is used to show that the current operation is not at the optimum. The plant is initially operated at the operating point marked with filled circle (●). During the first 3 hours of operation, the feed remains constant and the process is able to maintain the operation at the desired CO2 concentration at both outlets. Subsequently when the disturbance occurs, the new optimum point is at the position marked by red square (■) in Fig. 5 and the non-filled squares (□) represent the transition path of the optimization with the numbers representing the time points. Apart from the process not meeting the desired outlet CO2 concentrations, the cost is not optimum if maintained at the initial position (blue Point (●) in Fig. 5).The new optimum operation is implemented after the disturbance occurs and the process is able to reach the new optimum point (red square (■) in Fig. 5).

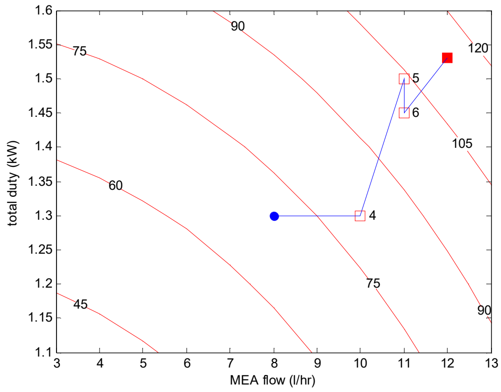

Fig. 5.Operating cost due to feed changes

4.3 Utility Price

Fig. 6 shows the changing cost of operation with time. It can be seen that as the disturbance occurs the cost increases. When the EMPC adjusts the cost, it returns to a lower level after 9 hours. It should be noted that this cost is higher than the original cost as it handles a larger CO2 content. As the EMPC takes into account of the evolution of the cost, it calculated new operating conditions that reflect these dynamic changes. Compared to the case of steady state changes, the operation is maintained at the current point as the steady state condition is not affected by the changes. If conventional steady state calculation is used the CO2 specification is not be meet. As a result of applying EMPC the changing cost due to the usage of the MEA for this new condition is optimized according the economic objective and thus EMPC results in a more cost effective method compare to conventional tracking design. It is noted that in a consistently dynamic operation, the benefits of EMPC can be greater due to dynamic optimization of the process economics.

In order to investigate the effect on operation due to the utility price changes, the simulation introduces a decrease in the utility price after 3 hours. It should be noted that in actual process, this changes can last over much large time duration and the short duration here is simply for illustration purpose. During the first 3 hours of operation, the utility prices remain constant and no other economic disturbance enters the plant. In this case the operation is maintained at the desired operation. For comparison purpose, the cost for the case when the operation is maintained after the introduction of utility price change is calculated. This is compared to the case when EMPC optimization is carried out. Fig. 7 shows the cost of operation when EMPC is performed and when the initial operation is maintained. It can be seen that in both cases, the costs are lowered. The case when EMPC is implemented the overall cost further lowered. This can be attributed to a more efficient usage of the utility through the adjustment of the recovery flow. This affirms the benefits of dynamically changing the operation with respect to the cost for greater savings. Fig. 8 shows the operating cost due to the changes in the utility price for different MEA flows and total duties. Similar to Fig. 5, the contour plot indicates the condition after the utility price change. The plant is initially operated at the operating point marked with filled circle (●). During the first 3 hours of operation, the utility prices remain constant and no other economic disturbance enters the plant. During this period, the process is able to maintain the operation at the desired CO2 concentration at both outlets. Subsequently when the disturbance occurs, the new optimum point is at the position marked by triangle (▲) in Fig. 8 with the hollow pyramid. The non-filled triangles (△) represent the transition path of the optimization with the numbers representing the corresponding time points. In this case after the utility prices change, the cost at the initial operating point is not optimum. Thus the EMPC has the incentive to drive the process towards the new optimum as this can result in a better return than if the process continues to operate at the previous operating condition. After the implementation of the EMPC the process is able to reach the new optimum point.

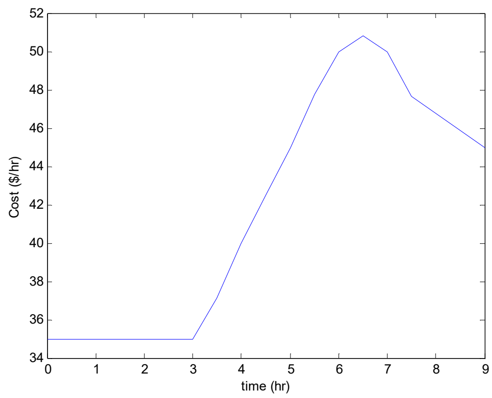

Fig. 6.The cost of operation due to feed changes

5. CONCLUSIONS

The EMPC of the CO2 capture is studied in this work. In order to adjust dynamically to the operation, EMPC adjusts the MEA flow and total duty accordingly. The case studies presented show that EMPC is able to drive the process to the most cost effective operation. Two disturbance effects have been investigated and due to the implementation of the EMPC to the CO2 capture process, the optimal operation in term of economic is achieved. Dynamic simulations show that EMPC can results in a lower cost for the CO2 recovery. The focus of this study is on the economic prices but the structure as well as the constraints on the controller scheme is not taken into account. The effect due to the controllers can be a topic of future research.

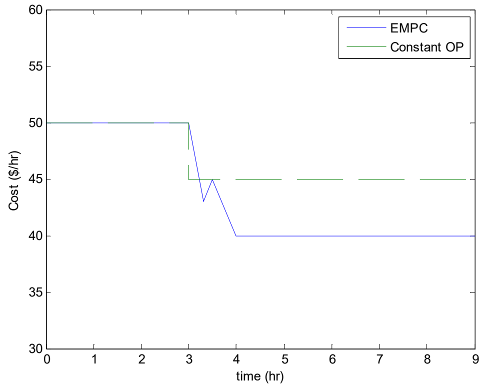

Fig. 7. Effect of utility price on cost

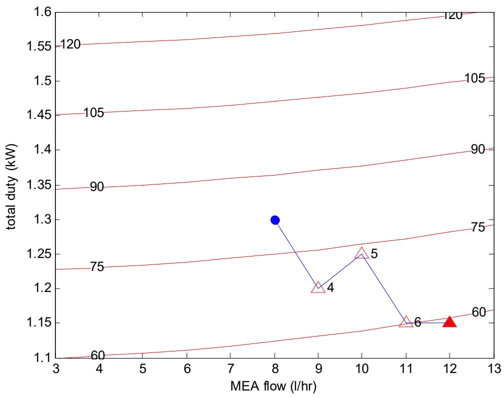

Fig. 8. Operating cost due to utility cost change

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