Temperature Control of Autothermal Reformer System with Coefficient Diagram Method

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Abstract. The objective of this paper is to design the autothermal reformer (ATR) temperature control by using a coefficient diagram method (CDM). The adiabatic temperature is a main controlled variable of the ATR which is a combination of endothermic and exothermic reactions. The simulation results of control parameters were calculated to maintain the ATR reaction temperature by manipulating air feed flow rate. In this work, two strategies of ATR temperature controller system with and without the feed temperature control of a preheater unit are compared to investigate the appropriate controller system when the change of surrounding temperature is considered as a key disturbance. The results showed that by using the CDM, the stability and robustness for controlling the ATR temperature system were considered to offer the proper control parameters and the designed temperature control of ATR system gave a good performance to maintain the controlled variables and reject the disturbance. Moreover, the ATR control system design with the feed temperature controller can compensate the surrounding temperature better than that without the feed temperature control.

1. Introduction
An autothermal reformer (ATR) is one of hydrogen processing options for on-board hydrogen storage applying for the fuel cell to generate electricity. The moderate size of ATR, combining the exothermic reaction of partial oxidation (POX) with the endothermic reaction of steam reforming (SR) in a single process, is an advantage for the transportation application because of its high thermal efficiency and dynamics during transient operation as well as its lower system complexity [1]. The temperature control system design of ATR is important for controlling the reaction temperature to sustain the performance of hydrogen production. In our previous work, the modeling and simulation for ATR system was carried out to investigate the open loop response for designing the control system strategy [2] and an internal model control (IMC) method was performed to control the ATR temperature by manipulating the air flow rate [3-4]. Furthermore, there are many studies about the control design techniques for ATR process to produce hydrogen from gasoline [5-6], methanol [7-10], and other hydrocarbon fuels [11-13] whereas our researches have concentrated on the hydrogen production from ethanol [2-4]. By using several techniques of controller design, most of the studies were proposed to regulate the ATR reaction temperature and hydrogen yield by manipulating the air flow rate, water or fuel.

In this work, the controller design for ATR system is performed by using a coefficient diagram method (CDM) introduced by Manabe [14] when the change of surrounding temperature, which is a major effect for countries having cold weather, is also focused as the main disturbance. In order to
maintain the near adiabatic reaction temperature of the hydrogen production from ethanol, two strategies of controller design with and without the feed temperature control of the preheater unit are proposed and compared.

2. Mathematical Model and Control Strategy of Autothermal Reforming System
In the ATR system, hydrogen-rich gas can be produced from the reaction between ethanol fuel, water and air that they are mixed and fed together into a preheater before entering the ATR reactor. Two control loops of ATR process include a feed temperature control loop and an ATR temperature control loop as illustrated in figure 1. The details of nominal parameters and operating points of this ATR system were proposed in the previous work [2]. The feed loop controller employs the heating power fraction of preheater (X, [%]) as the manipulated variable (MV) and the feed temperature of fluid entering ATR (T_feed, [K]) as the controlled variable (CV). In the ATR loop controller, the air flow rate (N_Air, [mol/s]) is the MV for controlling the adiabatic temperature of ATR reactor (T_ATR, [K]) as the CV. Consequently, two transfer functions of the match of the CVs and the MVs for the ATR control system can be written as equation (1) and equation (2).

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T_{feed}(s) = \frac{1}{(2.0s + 1)}[320.5X(s) - 33.1N_Air(s)]
\]

\[
T_{ATR}(s) = \frac{1}{(41.4s + 1)}[137.3N_Air(s) + 0.8T_{feed}(s)]
\]

![Figure 1. Block diagram of two control loops for ATR process control [3].](image)

3. Control Design Using CDM
As a concept of coefficient diagram method (CDM) was described in a previous work [15], the control parameters of two control loops were designed by using CDM. In the ATR system control loop design, the desired settling time (t_s) of 50 sec is specified; therefore the equivalent time constant (τ) can be determined as 20 sec according to the standard Manabe form [14] given by τ = t_s / (2.5–3). In order to compare the effect of stability index on the controlled temperature response and control signal, the stability index were varied as 2.5, 5.0, 7.5, and 10.0 that the controller parameters of CDM-PI controller can be calculated as demonstrated in table 1.

In the feed temperature control loop design, table 2 presents the controller parameters of CDM-PI for different values of stability index of 2.5, 5.0, 7.5, and 10.0 when the desired settling time (t_s) is fixed at 2 sec; consequently, the equivalent time constant (τ) can be calculated as 0.8 sec.

4. Simulation Results
In this work, to regulate the ATR temperature that has an effect on an amount of hydrogen production, two strategies of the ATR temperature control system with and without the feed temperature control were designed and compared. According to the calculated control parameters using CDM at different values of stability index, the simulation results of the responses of ATR temperature and feed temperature were presented when an ambient temperature changed -25 K from a nominal condition is
a key disturbance to consider the suitable control system for applying in countries that have cold weather nearly the water freezing point.

**Table 1.** Controller parameters of CDM-PI for various values of stability index of ATR control loop.

| Stability index, \( \gamma_1 \) | \( K_p \) | \( K_i \) | \( \tau_i \) |
|-------------------------------|--------|--------|--------|
| 2.5                           | 0.0304 | 0.0019 | 16.1353|
| 5.0                           | 0.0681 | 0.0038 | 18.0677|
| 7.5                           | 0.1058 | 0.0057 | 18.7118|
| 10.0                          | 0.1435 | 0.0075 | 19.0338|

**Table 2.** Controller parameters of CDM-PI for various values of stability index of feed control loop.

| Stability index, \( \gamma_1 \) | \( K_p \) | \( K_i \) | \( \tau_i \) |
|-------------------------------|--------|--------|--------|
| 2.5                           | 0.0164 | 0.0244 | 0.6723 |
| 5.0                           | 0.0360 | 0.0489 | 0.7362 |
| 7.5                           | 0.0555 | 0.0733 | 0.7574 |
| 10.0                          | 0.0751 | 0.0977 | 0.7681 |

**Figure 2.** Response of ATR system without feed temperature control (a) Response of ATR temperature, (b) Control signal of air valve, (c) Response of feed temperature and (d) Control signal of heating power fraction of preheater.
In figure 2, the ATR temperature as the CV (figure 2 (a)) was controlled by changing the control signal as the MV (figure 2 (b)) for the ATR system without feed temperature control loop whereas the change of air flow rate affected the change of feed temperature (figure 2 (c)) with fixed control signal of a feed preheater (figure 2 (d)). When the stability index were varied between 2.5 and 10.0, the results showed that an increase of stability index decreases both of the deviation of ATR temperature from a set point of 912 K and the settling time but increases the control signal of air valve. In case of the ATR temperature control system with the feed temperature control loop, the control system designed by CDM showed a good performance that the ATR temperature is very well controlled in the range between 911.94 and 912.02 K in the whole range of varied stability index between 2.5 and 10 as shown in figure 3 (a) when the air flow rate was manipulated by control signal in the range between 44.9995 and 45.0015 % as shown in figure 3 (b). Additionally, the feed temperature was rapidly maintained (figure 3 (c)) by changing the control signal between 54.60 and 54.69 % (figure 3 (d)). As shown in figure 3, by varying the stability index between 2.5 and 10.0, the difference between the ATR temperature and its set point can be decreased by increasing the stability index and the increase of stability index also decreases the change of feed temperature from its set point. Moreover, the ATR and feed temperatures can speedily reach their set points as the stability index increase. It can be found that the designed ATR control system with the feed temperature control is robust to the fast change in ambient temperature which is considered as the key disturbance for this work. In addition, the deviation of ATR and feed temperatures of two control loops are smaller than that of ATR temperature control loop without the feed temperature control loop. Consequently, the proposed CDM method for the ATR control system achieved a good performance to reject the disturbance.

**Figure 3.** Response of ATR system with feed temperature control (a) Response of ATR temperature, (b) Control signal of air valve, (c) Response of feed temperature and (d) Control signal of heating power fraction of preheater.
5. Summary
In this work, a temperature control of ATR system for hydrogen production from ethanol was investigated by using CDM to regulate the adiabatic ATR temperature when two control loops of the ATR temperature control and the feed temperature control were proposed. In a feed control loop, the feed temperature is the CV and the heating power fraction is the MV. The ATR loop controller employs air feed rate as the MV and ATR temperature as the CV. For transportation application, because of the change of weather especially the countries having cold weather, a main change of ambient temperature was considered to be a major disturbance. It can be concluded that the ATR temperature control system designed by CDM achieves required performance. Moreover, the ATR control system design with the feed temperature controller can compensate the surrounding temperature better than that without the feed temperature control.

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