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# Internal Model Control Design for Autothermal Reforming System

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**Abstract.** This paper focuses on the control system design for a process of autothermal reforming (ATR) of ethanol. The targeted application is within an on-board fuel processor of ATR operating at the adiabatic reaction temperature for hydrogen production. An internal model control (IMC) method is designed for controlling the adiabatic reaction temperature of ATR reactor by manipulating the input air flow rate. Two strategies of controller design with and without the feed temperature control of the preheater unit are proposed in order to determine the suitable controller system as the surrounding temperature is a major disturbance for cold weather. Theoretical analysis demonstrates that IMC strategy can achieve desired performance. Two loops of control system of the ATR process combined with the feed temperature control can compensate the surrounding temperature better than without the feed temperature control.

## Introduction

Hydrogen has been generally recognized as a clean and high efficiency energy carrier for future transportation fuel used in a fuel cell to produce electricity. One of the several challenges to the improvement of a fuel cell system for transportation applications is a fuel cell delivery system. This alternative is disappointed by the low storage capacity of hydrogen as well as the lack of a hydrogen distribution infrastructure while on-board hydrogen storage is requested. The choice is to install an on-board hydrogen production unit to convert high energy density hydrocarbon fuel. Unfortunately, this unit will increase substantially to the volume, weight and complexity of the overall system and the response time of the overall system will be degraded by that of the fuel processor [1]. Among many choices of fuels, ethanol is considered to be a renewable source easily produced from biomass fermentation and a promising candidate for on-board hydrogen generation using the fuel processor. Autothermal reforming (ATR), combining partial oxidation (POX) with steam reforming (SR) in a single process, is applied to be the most feasible alternative in the transportation application due to its high thermal efficiency and dynamics during transient operation as well as its lower system complexity [2]. In general, ATR reactions are assumed to be thermally self-sustaining that do not produce and consume external thermal energy [3]. The controller is one of the parts of fuel processor system to control the desired reactor temperature for maintaining the adiabatic reaction temperature for ATR process.

So far, many efforts have been achieved on control design for ATR by gasoline [1, 4], methanol [5-6], and other hydrocarbon fuels [7-8]. Most of the researches were proposed to regulate the reactor temperature and hydrogen yield when the inlet flow rate of air, water or fuel was considered to be manipulated variable by using various techniques of controller design. Even though there are many works concerning the controller design for ATR of various types of fuels, the research relating to the control strategy for ATR of ethanol is limited. In addition, no work focuses on the disturbance due to the change in the surrounding temperature which is a major effect for countries having cold weather.

In this paper, we concentrate on the control of reactor temperature to maintain the near adiabatic reaction temperature of the hydrogen production via ATR of ethanol. Internal model control (IMC) is applied for the controller design aimed at regulating ATR temperature. As the surrounding temperature is considered as a main disturbance for ATR system, two strategies of controller design with and without the feed temperature control of the preheater unit are compared.

## Mathematical Models and Control Strategy of Autothermal Reforming System

In the modeling and simulation, the assumptions, mathematic models, nominal parameters and operating points of the unsteady-state energy balance around the preheater and ATR reactor are proposed in [9]. As discussed in previous work [9] that two control loops were considered to maintain the adiabatic temperature of ATR reformer, in the first loop of controller design, the controlled variable is the feed temperature of fluid entering ATR reactor ($T_{feed}$, [K]) and the manipulated variable is considered as the heating power fraction of preheater ($X$, [%]); additionally, in the second loop, the air flow rate ($\dot{N}_{Air}$, [mol/s]) is probably optioned as the manipulated variable for regulating the adiabatic temperature of ATR reactor ($T_{ATR}$, [K]). Consequently, transfer functions of the match of controlled variables and manipulated variables for the ATR control system can be written as

$$T_{feed}(s)=\frac{1}{(2.0s+1)}[320.5X(s)-33.1\dot{N}_{Air}(s)] \tag{1}$$

$$T_{ATR}(s)=\frac{1}{(41.4s+1)}[137.3\dot{N}_{Air}(s)+0.8T_{feed}(s)] \tag{2}$$

Fig. 1 shows the control strategy for compensating the change of surrounding temperature causing the change of $T_{feed}$ before entering the ATR system. Therefore, two loops of feedback control of ATR system with the $T_{feed}$ control loop are proposed to regulate $T_{ATR}$.

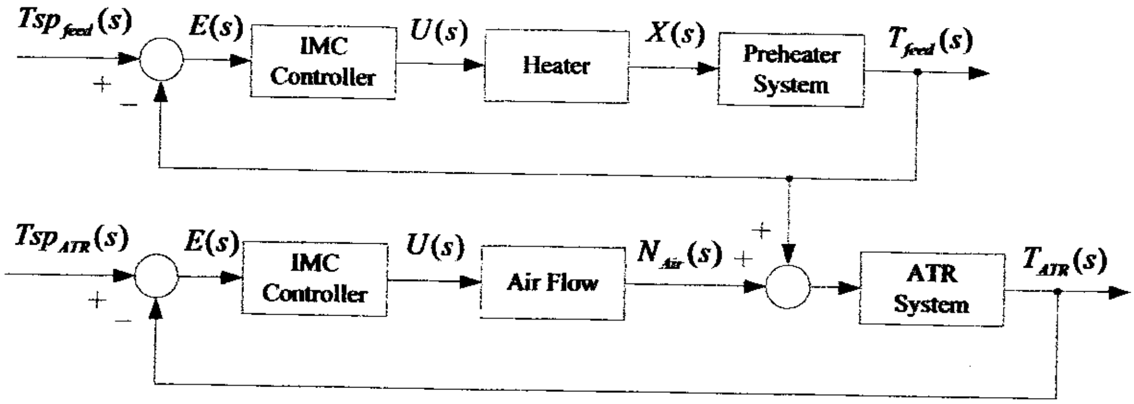

Fig. 1. Block diagram of two control loops for ATR control system.

## Internal Model Control Structure

The IMC method is based on an assumed process model and leads to analytical terms for the controller settings. In IMC basic structure illustrated in Fig. 2 with the process and the system model denoted by $G_p(s)$ and $\tilde{G}_p(s)$, respectively, the main idea is to include the model of the system into the controller. The IMC structure considers the model $\tilde{G}_p(s)$ as part of the control loop but not as part of the control design [10]. A process model $\tilde{G}_p(s)$ and the controller output $U(s)$ are used to calculate the model response, $\tilde{Y}(s)$. The model response is subtracted from the actual response $Y(s)$, and the difference, $Y(s)-\tilde{Y}(s)$, is used as the input signal to the IMC controller, $G_C^*(s)$. In general, $Y(s)\neq\tilde{Y}(s)$ due to modeling errors ($G_p(s)\neq\tilde{G}_p(s)$) and unknown disturbances ($D(s)\neq 0$) that are not accounted for in the model [11].

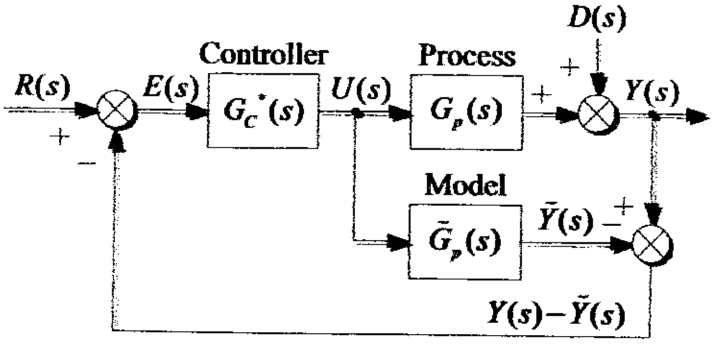

Fig. 2. IMC basic structure [11].

In the IMC design procedure, the process model is factored as shown in Eq. (3) where $\tilde{G}_{p-}(s)$ is minimum phase system and $\tilde{G}_{p+}(s)$ contains any time delays or right-half plane zeros (non-minimum phase system) required to have a steady-state gain equal to one to ensure that the two factors in Eq. (3) are unique.

$$\tilde{G}_p(s) = \tilde{G}_{p-}(s)\tilde{G}_{p+}(s) \tag{3}$$

The controller is specified as described in Eq. (4) where $G_f(s)$ is a low-pass filter with a steady-state gain of one and usually has the form as shown in Eq. (5) where $\tau_f$ is the filter parameter and $r$ is the order of the filter.

$$G_C^*(s) = \tilde{G}_{p-}(s)^{-1}G_f(s) \tag{4}$$

$$G_f(s) = \frac{1}{(\tau_f s+1)^r} \tag{5}$$

When the classical feedback control is considered, the equivalent controller, $G_C(s)$ can be written as

$$G_C(s) = \frac{\tilde{G}_{p-}(s)G_f(s)}{1-\tilde{G}_{p+}(s)G_f(s)} \tag{6}$$

With a proper choice of $G_f(s)$, the controller $G_C(s)$ must include the integral action and appear in the following form

$$G_C(s) = \frac{1}{s}Q(s) \tag{7}$$

By performing the Maclaurin series expansion for $Q(s)$, the controller $G_C(s)$ can be expressed as

$$G_C(s) = \frac{1}{s}\left[Q(0) + Q'(0)s + \frac{Q''(0)}{2!}s^2 + \ldots\right] \tag{8}$$

## Simulation Results

According to the IMC design procedure in previous part, the parameters of IMC controller for this case are equivalent to PI controller as presented in Table 1. In this IMC – PI controller design, the filter time constant ( $\tau_f$ ) was defined as ten times faster than time constant of open loop system. By using IMC – PI controller, the simulation indicated that this controller achieved good performance to regulate $T_{ATR}$.

Table 1 Parameters for IMC – PI controller

| Parameters | ATR system control loop | Preheater system control loop |
|---|---|---|
| $K_C$ | 0.0728 | 0.0312 |
| $\tau_i$ | 41.4 | 2.0 |
| $\tau_f$ | 4.14 | 0.2 |
| $K_i$ | 0.0018 | 0.0156 |

As mentioned earlier, Fig. 3 compares two strategies of controller design with and without the feed temperature ($T_{feed}$) control in the preheater unit due to the drop of surrounding temperature from nominal condition of 298 K to 273 K in order to determine an appropriate controller system for applying in countries that have cold weather nearly the water freezing point. As the surrounding temperature is a major disturbance of ATR system, it was found that two loops of the ATR control loop combined with the preheater control loop can compensate the disturbance better than without the feed temperature control.

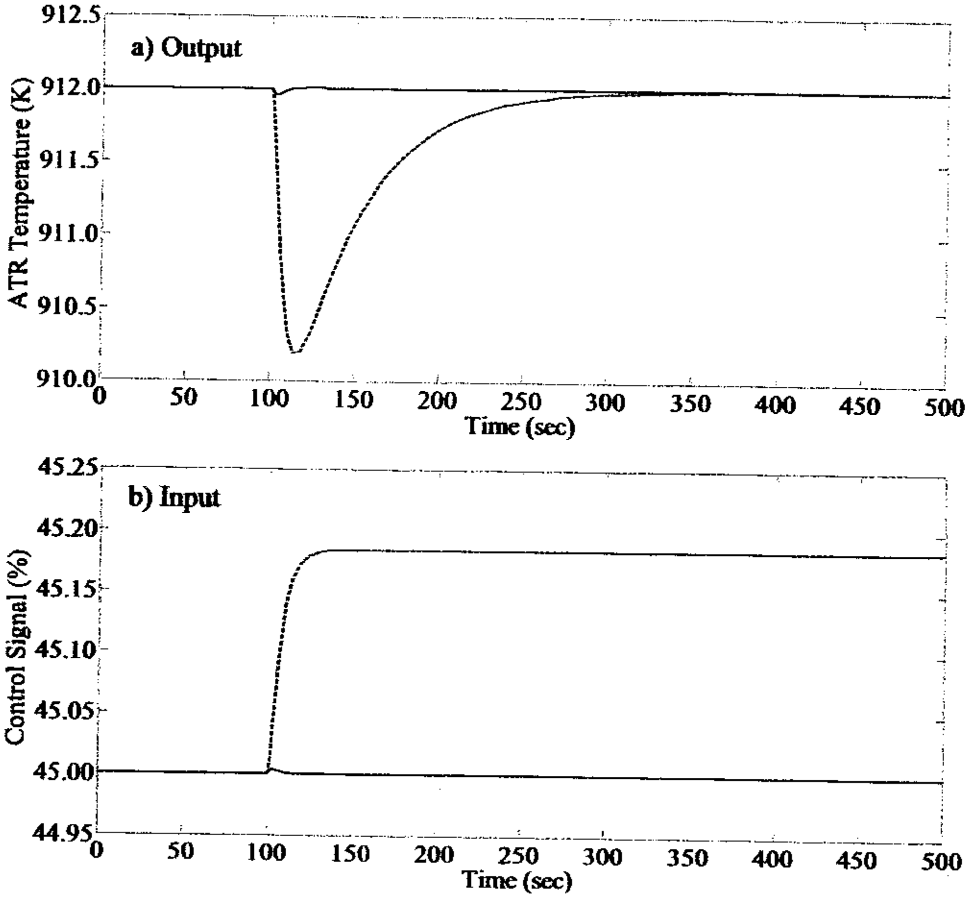

Fig. 3. Output and input response to a step change of surrounding temperature of – 25 K with the $T_{feed}$ control (solid line) and without the $T_{feed}$ control (dashed line).

## Conclusion

In this paper, an internal model control (IMC) design for autothermal reforming (ATR) of ethanol for hydrogen production was proposed for regulating the adiabatic reaction temperature of ATR reactor. The improvement of a fuel cell delivery system for transportation applications is one of the many challenges and the ATR processor is most feasible option for on-board hydrogen storage because of its moderate size. For transportation use, due to the different weather of each country especially the countries having cold weather, a dominant change of surrounding temperature was considered to be major disturbance. Therefore, the control strategy of two loops for the preheater and ATR systems was designed. In a preheater system control loop, the feed temperature of fluid entering to the ATR system was the controlled variable and the heating power fraction was designed as the manipulated variable. In an ATR system control loop, controlled and manipulated variables were the ATR adiabatic temperature and the inlet air flow rate, respectively. The IMC controller can be equivalent to IMC – PI controller by analytical method to simplify adjusting parameters of IMC. The simulation results showed that the IMC controller achieved desired performance. As the surrounding temperature was the major disturbance, two loops of the preheater and ATR control systems gave better performance for regulating the ATR temperature than the ATR control system without the feed temperature control.

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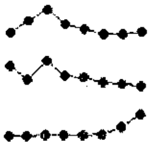

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