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IFAC PapersOnLine 50-2 (2017) 77–82

Application of Taiwo's Recycle Compensator to an Heat Integrated Ammonia Production Plant

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Abstract: Designing fixed-bed catalytic reactor to have heat integration is a common practice in the process industries. However, such design usually poses control challenges as a result of unusual dynamic behavior of the overall process, such as oscillations and instability. It is shown in this paper that the application of Taiwo's recycle compensator eliminates the undesirable dynamics and leads to a better performance. Thus facilitating the design of more effective control system for heat integrated processes.

Keywords: Recycle compensator, heat integration, catalytic reactor, recycle system, model uncertainties, ammonia process, feedback controller.

1. INTRODUCTION

Process designers are fond of designing fixed bed catalytic chemical reactors with heat integration. This is very much appealing under steady state design as it allows a great deal of energy to be conserved. However, dynamic controllability analysis reveals that such heat integration can result in positive feedback of heat and thereby allows the possible occurrence of multiple steady states, limit cycles, oscillatory response and even instability (Denn and Lavie, 1982; Kapoor *et al*., 1986; Tyreus and Luyben, 1993; Morud and Skogestad, 1994).

Morud and Skogestad (1998) reported an incident in an industrial fixed-bed reactor for the production of ammonia in Germany whereby after a sudden decrease in reactor pressure, the reactor became unstable and the temperature oscillated with large amplitudes (limit cycles). A mathematical model developed by the group replicated this phenomenon. They attributed this unusual behavior to the presence of an inverse response for the temperature through the reactor beds combined with the positive feedback of heat by the preheater.

Various approaches have been proposed in literatures for controlling fixed-bed reactors with heat integration (Foss *et al.*, 1980, Wallmann and Foss, 1979). In designing an effective control system for a heat integrated fixed-bed reactors two critical issues need to be addressed: the possibility for extinction and limit-cycle behaviour. Morud and Skogestad (1998) reported in their paper that the control of the inlet temperature of the first bed by the quench valve before the first-bed using simple PI controller suffice enough to stabilize the system. We present in this work however that the application of Taiwo recycle compensator (Taiwo, 1984) can help eliminate the undesirable dynamics and thus significantly improve the closed loop process performance. The idea about using the recycle compensator was first proposed in Taiwo (1984). Taiwo (1985) shed more light on its properties and applications. Its use for robust control system design for recycle plants was later published in Taiwo (1986). In Taiwo (1993, 1996) its extension to multivariable systems was proposed with satisfactory results. Very recently in Bamimore and Taiwo (2015), the recycle compensator was applied to open-loop unstable recycle process with good results. In Taiwo *et al.(*2015), it was found out that the recycle compensator confers robustness on recycle plants in the face of model uncertainties. Other researchers (Scali and Antonelli, 1995; Scali and Ferrari, 1997) have equally recognized the effectiveness of the recycle compensator. Scali and Ferarri (1999) reported its application to integrated plants with good performance. Tremblay *et al.* (2006) demonstrated in their work the robustness of recycle compensated system to model uncertainties and disturbances in the frequency domain. Lakshminarayanan and Takada (2001) reported its industrial applicability while Bamimore (2016) demonstrated its application to a laboratory three tank system with recycle. In section 2, we provide the general block diagram representation of recycle systems and present recycle compensator design procedure. In section 3, an ammonia production plant is used as an illustrative example while conclusions are drawn in section 4.

2. GENERAL REPRESENTATION OF RECYCLE SYSTEMS: RECYCLE COMPENSATOR DESIGN

The general block diagram representation of a process with recycle (Taiwo, 1986; Bamimore and Taiwo, 2014) including the feedback controller $G_c(s)$ and the recycle compensator $F(s)$ is shown in Figure 1 where y, u, d, u_c, u_F, and y_m are controlled, manipulated, disturbance, controller output, compensator output and measured variables respectively. G_1 refers to the forward path process transfer function, G_2 the process disturbance, G_3 the recycle path process transfer function, G_4 additional elements in the process path, and G_5 the process sensor dynamics. The effect of manipulated variable (u) and disturbance (d) on the measured output (y_m) for the open-loop global process G_{global} is given by

$$y_m(s) = G_5G_4(I - G_3)^{-1}G_1u(s) + G_5G_4(I - G_3)^{-1}G_2d(s) \quad (1)$$

The compensator F(s) that totally cancels the detrimental effect of recycle known as the perfect recycle compensator

10.1016/j.ifacol.2017.12.014

can be specified as found in (Taiwo, 1986; Bamimore and Taiwo, 2014).

$$F(s) = G_1^{-1}G_3G_4^{-1}G_5^{-1}(s) \quad (2)$$

On applying the recycle compensator $F(s)$ to the sub-system G_{global}, the open-loop compensated system $G_{compensated}$ becomes

$$y_m(s) = G_5G_4G'(I + FG_5G_4G')^{-1}u_c(s) + G_5G_4G'_d(I + FG_5G_4G')^{-1}G_2d(s) \quad (3)$$

where $G' = (I - G_3)^{-1}G_1$ and $G'_d = (I - G_3)^{-1}G_2$

If $F(s)$ is perfect and realizable, putting Eq. (2) into (3) reduces it to:

$$y_m(s) = G_5G_4G_1u(s) + G_5G_4G_2d(s) \quad (4)$$

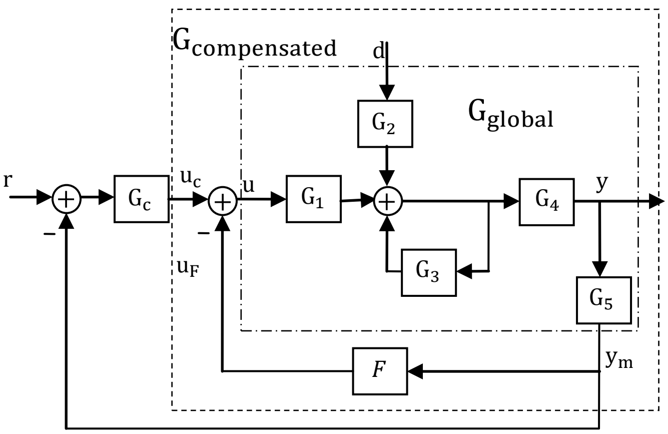

Figure 1. Block diagram of a system consisting of a plant with recycle, recycle compensator F and feedback controller G_c

3. HEAT INTEGRATED FIXED BED CATALYTIC REACTOR PROCESS

The heat integrated fixed bed catalytic reactor process was used as an illustrative example.

3.1 The dynamic model of heat integrated fixed-bed reactor

Morud and Skogestad (1998) presented a simplified model of heat integrated reactor process for the production of ammonia. It consists of three beds in series with fresh feed quenching between each bed and preheating of the feed with the effluent (Figure 2). The reaction is $N_2 + 3H_2 \underset{k_{-1}}{\overset{k_1}{\Leftrightarrow}} 2NH_3$ and the feed is stoichiometric.

Simple model of the reactor: Ammonia and temperature distribution across the bed of the reactor (Figure 2) are modelled using partial differential equations. The ammonia distribution across the whole length of the fixed bed reactor is given by:

$$w\frac{\partial c}{\partial z} = m_c r(T, c) \quad (5)$$

where

c=ammonia concentration (mass fraction), kg NH_3/kg gas

z=position in reactor

m_c=catalyst mass in the bed, kg

w=gas flow through the bed, kg/sec

$r(T, c)$=reaction rate, kg NH_3/kg cat, sec

The temperature distribution across the whole length of the fixed bed reactor is given by:

$$m_cC_{pc}\frac{\partial T}{\partial t} + wC_{pg}\frac{\partial T}{\partial z} = (-\Delta H_{rx})m_cr(T, c) + \Gamma m_cC_{pc}\frac{\partial^2 T}{\partial z^2} \quad (6)$$

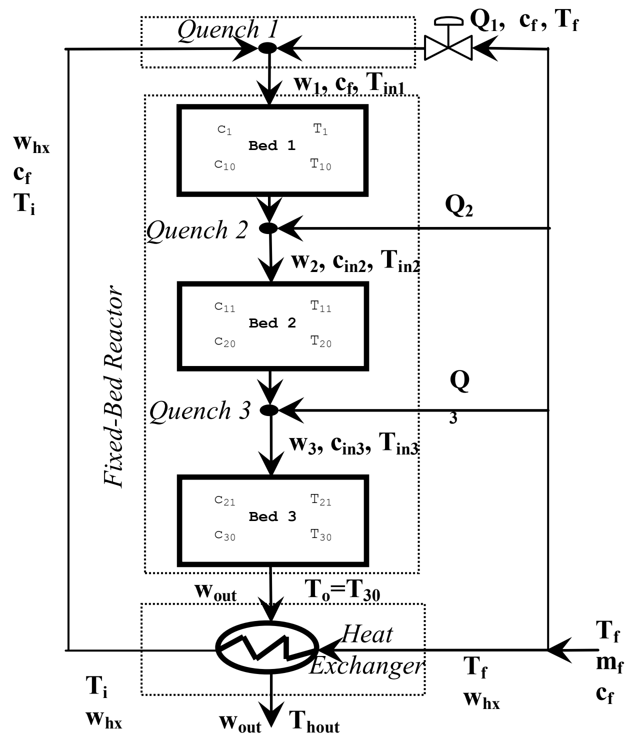

Figure 2: Fixed-bed Reactor representation for problem formulation

where

t=time, sec

T=catalyst particle temperature, K

ΔH_{rx}=heat of reaction, J/kg.NH_3

C_{pc}=heat capacity of catalyst, J/kg cat.K

C_{pg}=heat capacity of gas, J/kg. K

Γ=dispersion coefficient, L/sec

More detailed information about the process and model parameters can be found in Morud (1995).

Two assumptions have been made in this modelling: (i) the gas-phase holdup has been neglected because the gas density is low. (ii) the dispersion coefficient is a simplified way of taking into account the finite heat-transfer rate between the gas phase and the solid catalyst.

The solution approach to these models is to discretize using the finite difference method. By approximating the partial derivative $\frac{\partial c}{\partial z}$ by its finite difference approximation, we have

$$\frac{\partial c}{\partial z} = \frac{(c_j - c_{j-1})}{\Delta z} \quad (7)$$

where j stands for the grid point.