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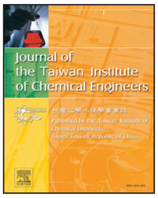

Temperature control of polypropylene thermal cracking reactor by input/output linearization with two-degree-of-freedom structure

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A B S T R A C T

This work presents a model-based controller with a two-degree-of-freedom (2DOF) control structure for handling bed temperature of polypropylene cracking in a fluidized bed reactor. The control system is formulated based on a developed dynamic mathematical model of the reactor. The developed control system consists of an input/output (I/O) linearizing controller for tracking the desired output, a high-gain controller for disturbance rejection and an observer with linearizable error dynamics for compensated state variables from the measured outputs. The control performances of the method are evaluated through simulation under process uncertainties and model mismatch by comparing with a 1DOF input/output controller and a proportional-integral controller. The results show that the proposed controller based on 2DOF scheme can improve the control performances both process uncertainties and model mismatch.

Abbreviations

BFBR	Bubbling fluidized bed reactor
LPG	Liquefied petroleum gas
PP	Polypropylene

1. Introduction

Plastics play an important role in modern human life due to their light weight, durability and ability to be molded into various shapes. An increase in plastic consumption leads to concern as regards plastic wastes disposal as well. Waste treatments such as landfill and incineration have to face many issues such as a lack of landfill spaces, dioxins and furans from incineration, and contamination of soil and water around the landfill area. One of the waste treatment techniques that has received much attention is a conversion of waste plastics into light hydrocarbons by thermal cracking. The plastic wastes are pyrolyzed at high temperature – in a rage 400–800 °C depending on plastic types and desired products – in an oxygen-free atmosphere. A bubbling fluidized bed reactor (BFBR) has been extensively studied for plastic pyrolysis because it offers excellent heat and mass transfer, uniform temperature and short residence time [1–4]. The quality and quantity of products from plastic cracking depend on several factors, especially the reaction temperature. However, maintaining the BFBR at the desired temperature is quite difficult due to many factors involved, for example, complex reaction of plastic cracking, high energy consumption of an endothermic reaction, tardy response of the bed temperature, parametric uncertainties, and unmeasured disturbances, causing difficulty to predict the reactor dynamics. Therefore, an effective control system to maintain the reaction temperature at a given setpoint is necessary to achieve desired product yield.

There are some techniques for handling the BFBR temperature published in the literature, but the control of the reactor for a plastic cracking application has not yet been much studied. Kendi and Doyle [5] applied two feedback control schemes, approximate input/state linearization and approximate input/output (I/O) linearization, to handle the bed temperature of the BFBR for maleic anhydride production. With the same process model in Kendi and Doyle's work [5], Femat *et al.* [6] proposed the I/O feedback with a dynamic compensator for an uncertainty of heat transfer coefficient. The mentioned methods were formulated based on the I/O linearization with one degree-of-freedom (1DOF) control structure. When large uncertainties or process/model mismatch occur in real operation, the controllers may be insufficient to provide robustness due to the limitation of the structure. A two degree-of-freedom (2DOF) control structure is an interesting technique that can handle such limitation. It improves robustness by using two controllers working independently – one provides for tracking setpoint and the other for rejecting disturbances [7–11]. The 2DOF control structure has been basically developed in a linear system [7–8, 12]. However, the application of the

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Nomenclature

A_w	Heat transfer area, m^2
$c_{p,g}$, $c_{p,s}$, $c_{p,w}$	Heat capacity of the mixed gas, sand bed and reactor wall, J/(kg K)
$c_{p,pp}$	Heat capacity of PP pellets, J/(kg K)
$c_{pN,in}$	Heat capacity of the nitrogen feed, J/(kg K)
$c_{pN,out}$	Heat capacity of the exit nitrogen, J/(kg K)
E_i	Activation energy of the *i*-th reaction, J/mol
F_{in}	Flow rate of nitrogen feed, m^3/s
H_{comb}	Heat of combustion of LPG, J/kg
h	Heat transfer coefficient, J/(m^2 s K)
K	Tuning gain of disturbance rejection controller, m^3/(s K)
K_c	Proportional gain, m^3/(s K)
k_{0i}	Frequency factor of the *i*th reaction, s^{-1}
k_i	Rate constant of the *i*th reaction, s^{-1}
L	Observer gain
Mw_A, Mw_B, Mw_C	Average molar mass of PP vapor phase, gas and light products, kg/mol
Mw_N	Molar mass of nitrogen, kg/mol
m_s	Mass of sand bed, kg
m_w	Mass of reactor wall, kg
$\dot{m}_{PP}$	Mass of PP feed rate, kg/s
P	Reactor pressure, Pa
P_{in}	Inlet pressure, Pa
Q	Energy for PP decomposition to a vapor, J/kg
R	Gas constant, (m^3 Pa)/(mol K)
r_i	Reaction rate of the *i*th reaction, kg/ (m^3 s)
T	Bed temperature of the reactor, K
T_{in}	Temperature of the nitrogen feed, K
T_{pp}	PP feed temperature, K
T_w	Wall temperature, K
u	Vector of manipulated inputs
u_r	Vector of rejection manipulated inputs
u_t	Vector of tracking manipulated inputs
V	Reaction volume, m^3
w_i	Mass per reaction volume of the *i*th component, kg/m^3
x	Vector of state variables
$\hat{x}$	Vector of estimated variables
y	Vector of output variables
$\hat{y}$	Vector of estimated outputs
y_{sp}	Vector of output setpoints
z	Vector of compensated state errors
β	Tuning gain of the setpoint-tracking controller, s
θ	Combustion efficiency
ρ_g	Density of mixed gas product, kg/m^3
ρ_{in}	Density of feed nitrogen, kg/m^3
ρ_{LPG}	Density of LPG, kg/m^3
τ_i	Integral time, s
ΔH_r	Overall heat of reaction of PP thermal cracking, J/kg

2DOF controller in a nonlinear system has not been much presented. Wright and Kravaris developed a model-state I/O feedback control algorithm with 2DOF structure to maintain the process with unmeasured disturbances in continuous-time [9] and discrete-time [10] systems. Sukkarnkha and Panjapornpon [11] presented the 2DOF control method in which an I/O linearizing controller with a disturbance-free state estimator is applied for a tracking setpoint, while a high-gain controller eliminates offsets from parametric uncertainties.

In this work, a nonlinear model-based control system with a two-degree-of-freedom (2DOF) structure is proposed to handle a bed temperature in a BFBR, for which polypropylene thermal cracking is considered as a case study. For the proposed method, an I/O linearizing controller is applied to provide a setpoint-tracking ability while a high-gain controller offers a fast compensation for effects of uncertainties. A nonlinear observer with linearizable error dynamics is integrated into the control scheme to improve the quality of state estimation for the I/O controller. The advantage of the proposed method is the capability of providing robustness for handling the BFBR that quickly compensates for the process uncertainty and unmeasured disturbances despite the presence of large process/model mismatch due to complex reactions and parametric uncertainties. To illustrate the control performances, the proposed method is compared with 1DOF I/O linearizing control schemes and with a PI controller and all are discussed under the setpoint tracking with three cases of uncertainties.

2. Mathematical model of the BFBR for PP cracking

2.1. Kinetics of PP thermal cracking

Thermal cracking of Polypropylene (PP) occurs in a temperature range from 400–600 °C, at which large molecules of PP are broken down into several smaller fragments by random chain scission and chain transfer reactions [13–14]. The heavier molecule fragments may undergo further decomposition to lighter fragments. Due to the complexity of the cracking reactions and various generated products, it is hard to detect intermediate hydrocarbon species during PP decomposition in the reactor. The development of detailed kinetics that can describe all PP pyrolysis behavior may be not suitable for the practical purposes of reactor design and process optimization which have the limit of obtained information; for example, the pyrolysis products of the BFBR are typically collected at outside the reactor in a form of gas products (C_1–C_4) and light products (C_5–C_{44}).

Accordingly, a competing reaction model is utilized in the development of the kinetics for PP thermal cracking in the BFBR. The competing reaction model is a technique in which the primary and secondary reactions are lumped over a range of operating temperature by means of parallel reactions. It has been used for many studies of the pyrolysis reaction [3–4, 15–16]. Reanthong [4] studied the kinetic model of PP thermal cracking in a pilot-scale BFBR by means of two competing (parallel) first-order reactions of the PP vapor (A) converting to gas products (B) and light products (C).

$$\begin{aligned} &A \xrightarrow{k_1} B \\ &A \xrightarrow{k_2} C \end{aligned} \tag{1}$$

where k_1 and k_2 are apparent first-order rate constants of the lumped reactions. The experimental results showed that, in the range of temperature 460–520 °C, the PP pyrolysis favors to the gas product route with an increase in the reaction temperature. This is possibly due to the secondary decompositions of pyrolysis vapors in the reactor that may give elevated yields of gas products at higher temperature.

In this work, the kinetic constant data of Reanthong [4] are used for developing the empirical rate equations of the reactions with Arrhenius relation, and the reaction rates of A, B and $C$are assumed to follow a first-order model described by Eq. (2):

$$\begin{aligned} r_A &= (-k_{01}e^{\frac{-E_1}{RT}}w_A - k_{02}e^{\frac{-E_2}{RT}}w_A) \\ r_B &= k_{01}e^{\frac{-E_1}{RT}}w_A \\ r_C &= k_{02}e^{\frac{-E_2}{RT}}w_A \end{aligned} \tag{2}$$

where w_A is the mass concentration of the component A in the reactor, k_{0i} and E_i are frequency factor and activation energy of the reaction *i*, respectively. The frequency factor and activation energy parameters were estimated by carrying out a least-squares fitting of the kinetic

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