



Steady-state multiplicity analysis of two-stage-riser catalytic pyrolysis processes

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ABSTRACT

New two-stage-riser fluidized catalytic pyrolysis (TSRFCP) for maximizing propylene yield technology is considered as an efficient route to moderate the propylene demand/supply gap and to lower the propylene price. The possibility of existence of complex nonlinear behavior associated with the TSRFCP process puts limitations on the supervision of this system. Based on the developed and validated model for the TSRFCP process, this paper focuses on the elucidation of multiple steady states and relevant (in) stability characteristic over a wide range of operating condition. First, graphic analysis of heat generation/removal curves demonstrates that the TSRFCP process has at least one steady state and a maximum of three output steady states under the considered operating conditions and uncertainties such as cooling water flow rates and Conradson carbon residue. Then, operating maps revealing topologies between important input and output variables can disclose detailed nonlinear behavior (input/output multiplicity). Moreover, depending on the choice of the input variable and the relevant operating/design condition, input multiplicity may exist. In short, these results can guide the succeeding control structure selection for realistic TSRFCP processes.

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1. Introduction

In terms of the expanding propylene supply/demand gap and enhancing propylene price, new fluidized catalytic techniques such as two-stage-riser fluidized catalytic pyrolysis (TSRFCP) are extremely required to improve propylene yield while achieving high yields of target products such as gasoline and diesel. In addition to innovations on catalysts and reactor structures, advanced control and monitoring systems for the TSRFCP process also have significant impacts in achieving high mass/energy conversion through the effective rejections of various internal/external disturbances (Stephanopoulos and Reklaitis, 2011). With regard to the design of a high-efficient control framework for a chemical process, comprehensive elucidations of steady state multiplicity and the corresponding (in) stability characteristic are necessary. This paper is therefore devoted to tackling the above issues associated with the TSRFCP process based on the developed and validated mathematical model (Liu, 2008; Wang et al., 2014).

Depicted in Fig. 1, multiplicity can be classified into two types including input multiplicity and output multiplicity. In case of input multiplicity, multiple input values are possible at a given output value. Output multiplicity is implied when multiple output values in the same input value. Input multiplicity is one complex phenomenon that poses limitations on achievable dynamic performance (Koppel, 1982). The existence of input multiplicity can severely compromise the robustness of control system due to the possibility of wrong control action causing by the sign change in the process gain. For processes with input multiplicity (such as points B1 and B2 in Fig. 1), a conventional controller with integral function can only keep one of these two steady states stable, and may turn into unstable for another. Nonlinear control strategy is hence recognized as the only feasible approach for effective supervision of those units which exhibit input multiplicity. Different steady state points with distinct economical revenues and (in) stabilities in the feasible operating region call for the identification of output multiplicities. In such case, under certain perturbations the process may wind down to the cold steady state or reach an unstable steady state. A traditional way for determining output multiplicity is to plot curves for removed and generated heat where intersections of two curves denote steady state points (Fogler, 1998). Since small perturbations in system parameters and operating conditions can radically alter qualitative properties such as input/output multiplicity, analyzing

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Notation*Abbreviation*

CCR	Conradson carbon residue
CSTR	continuous stirred tank reactor
FCC	fluidized catalytic cracking
HCO	heavy cycle oil
TSRFCP	two-stage-riser fluidized catalytic pyrolysis

Variables: TSRFCP processes

$A_{ris,1}$	area of the first riser, m ²
$A_{ris,2}$	area of the second riser, m ²
Cp_{cat}	specific heat of catalyst, kJ/(kg K)
Cp_g	specific heat of gas phase in regenerator, kJ/(kg K)
$Cp_{gasoline}$	specific heat of crude gasoline, kJ/(kg K)
Cp_{HCO}	specific heat of recycling oil, kJ/(kg K)
Cp_{oil}	specific heat of fresh feed stock, kJ/(kg K)
C_{rg0}	carbon content to the combustor, %
C_{rg1}	carbon content from the combustor, %
C_{rg2}	carbon content from dense bed, %
$C_{ris,1}$	coke deposited on catalyst from the first riser, %
$C_{ris,2}$	coke deposited on catalyst from the second riser, %
C_{sp}	coke content in the spent catalyst from the stripper, %
Cp_w	specific heat of water, kJ/(kg K)
$Cp_{v,1}$	specific heat of vapor phase in the first riser, kJ/(kg K)
$Cp_{v,2}$	specific heat of vapor phase in the second riser, kJ/(kg K)
E_C	activation energy for the carbon combustion, kJ/kmol
E_H	activation energy for the hydrogen combustion, kJ/kmol
$E_{i \rightarrow j}$	activation energy for the reaction from lump i toward lump j , kJ/kmol
F_g	flow rate of gas phase in regenerator, kmol/s
$F_{gasoline}$	flow rate of crude gasoline to the second riser, kg/s
F_{HCO}	flow rate of recycling oil to the second riser, kg/s
F_{oil}	flow rate of fresh feedstock to the first riser, kg/s
$F_{steam,1}$	steam flow rate to the first riser, kmol/s
$F_{steam,2}$	steam flow rate to the second riser, kmol/s
$G_{reg,1}$	regenerated catalyst flow rate to the first riser, kg/s
$G_{reg,2}$	regenerated catalyst flow rate to the second riser, kg/s
G_{rg1}	outlet circulated catalyst flow rate from the combustor, kg/s
G_{rg21}	circulated catalyst flow rate from dense bed to combustor, kg/s
G_{sp}	total spent catalyst flow rate to the regenerator, kg/s
$G_{sp,1}$	spent catalyst flow rate from the first riser, kg/s
$G_{sp,2}$	spent catalyst flow rate from the second riser, kg/s
H_{rg0}	hydrogen content to the combustor, %
H_{rg1}	hydrogen content from the combustor, %
$k_{0,C}$	pre-exponential factor for the carbon combustion
$k_{0,H}$	pre-exponential factor for the hydrogen combustion
$k_{0,i \rightarrow j}$	pre-exponential factor for the reaction from lump i toward lump j
$L_{ris,1}$	length of the first riser, m
$L_{ris,2}$	length of the second riser, m
Mf_{ha}	mass fraction of heavy aromatics in the feed stock, %
Mf_{ni}	mass fraction of basic nitrogen in the feed stock, %
$n_{i \rightarrow j}$	reaction order from lump i toward lump j
P_{rg1}	pressure in combustor, Pa
P_{rg2}	pressure in dense bed, Pa
R	ideal gas constant, 8.314 kJ/(kmol K)

$R_{C/O}$	catalyst-to-oil ratio
$r_{i \rightarrow j}$	reaction rate of lump i toward lump j , s ⁻¹
T_{rg1}	combustor outlet temperature, K
T_{rg2}	dense bed outlet temperature, K
T_{ris}	riser temperature, K
$T_{ris,1}$	first riser temperature, K
$T_{ris,2}$	second riser temperature, K
T_{steam}	steam temperature, K
$T_{Bo,oil}$	boiling temperature of fresh feed stock, K
$T_{oil,in}$	inlet temperature of fresh feed stock to the first riser, K
$T_{Bo,HCO}$	boiling temperature of recycling oil, K
$T_{HCO,in}$	inlet temperature of recycling oil, K
$T_{Bo,gasoline}$	boiling temperature of crude gasoline, K
$T_{gasoline,in}$	inlet temperature of crude gasoline, K
T_{rg0}	inlet temperature to the combustor, K
$T_{ris,1 Z=1}$	outlet temperature from the first riser, K
$T_{ris,2 Z=1}$	outlet temperature from the second riser, K
T_{sp}	temperature of the spent catalyst, K
W_{rg1}	catalyst inventory in combustor, kg
W_{rg2}	catalyst inventory in dense bed, kg
W_{st}	catalyst inventory in the stripper, kg
y_i	mass fraction of lump i , %
$y_{i,1}$	mass fraction of lump i in the first riser, %
$y_{i,2}$	mass fraction of lump i in the second riser, %
$Y_{K,1 Z=1}$	coke content outlet from the first riser, %
$Y_{K,2 Z=1}$	coke content outlet from the second riser, %
$Y_{O_2,rg0}$	inlet mass fraction of oxygen to combustor, %
$Y_{O_2,rg1}$	outlet mass fraction of oxygen from combustor, %
$Y_{O_2,rg2}$	outlet mass fraction of oxygen from dense bed, %
Z	dimensionless length of riser

Greek letters: TSRFCP processes

Φ_d	dimensionless catalyst relative activity
β_{ni}	adsorption coefficient of basic nitrogen
β_{ha}	adsorption coefficient of heavy aromatics
α_{coke}	deactivation coefficient
β_{coke}	deactivation coefficient
$\rho_{v,1}$	density of vapor phase in the first riser
$\rho_{v,2}$	density of vapor phase in the second riser
$\varepsilon_{ris,1}$	average void fraction in the first riser, %
$\varepsilon_{ris,2}$	average void fraction in the second riser, %
σ_{Al}	mass fraction of alkenes in gasoline, %
σ_{Ar}	mass fraction of aromatics in gasoline, %
$\Delta H_{r_{j \rightarrow i}}$	heat of pyrolysis reaction for lump j to lump i , kJ/kg
$\Delta H_{r_{i \rightarrow j}}$	heat of pyrolysis reaction for lump i to lump j , kJ/kg
$\Delta H_{vap,oil}$	heat of vaporization of fresh feedstock, kJ/kg
$\Delta H_{vap,HCO}$	heat of vaporization of recycling oil, kJ/kg
$\Delta H_{vap,gasoline}$	heat of vaporization of crude gasoline, kJ/kg
ΔH_C	heat of coke oxidation reaction, kJ/kg
ΔH_H	heat of hydrogen oxidation reaction, kJ/kg
λ_1	the ratio of CCR coke from the fresh feedstock to the first riser
γ_1	amount of un-stripped hydrocarbon of feedstock to the first riser
λ_2	the ratio of CCR coke from the feedstock to the second riser
γ_2	amount of un-stripped hydrocarbon of feedstock to the second riser
ρ_{cat}	density of catalyst, kg/m ³
ρ_g	density of gas phase in regenerator, kg/m ³
ε_{rg1}	average void fraction in combustor
ε_{rg2}	average void fraction in dense bed
η	hydrogen-to-carbon mass ratio, H/C
ξ	heat transfer coefficient, kJ/(m ² K)

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