Control Engineering Practice 25 (2014) 112–122

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Fuzzy logic control of a reverse flow reactor for catalytic oxidation of ventilation air methane

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ARTICLE INFO

Article history:
Received 11 July 2013
Accepted 25 December 2013
Available online 28 January 2014

Keywords:
Fuzzy logic controller
Reverse flow reactor
Catalytic oxidation
Ventilation air methane
Simulation
Reaction engineering

ABSTRACT

Fuzzy logic controllers of type-1 and type-2 were implemented to deal with the high nonlinearities and uncertainties in operation of a reverse flow reactor (RFR) for catalytic oxidation of ventilation air methane (VAM). The results indicated that the fuzzy logic controller is distinctly superior to the traditional logic-based controller and works well under the conditions with high nonlinearities and uncertainties. Owing to the robustness of RFR and particular control aim of regulating bed temperature within a relatively broad range, a fuzzy logic controller of type-1 is sufficient to cope with the uncertainty brought by the extensive variation of VAM concentration.

1. Introduction

Catalytic flow reversal reactor (CFRR) is a fixed bed reactor in which the feed flow direction is periodically switched between the two reactor ends and thus heat can be trapped in the center of the reactor for an exothermic reaction (Salomons, Hayes, Poirier, & Sapoundjiev, 2004). Owing to the forced unsteady-state operation condition and the heat trap effect, such a kind of reactor has found applications in many areas such as the catalytic oxidation of ventilation air methane (VAM) (Gosiewski & Pawlaczyk, 2013; Li et al., 2013a; Wang et al., 2013; Zhang et al., 2013), selective oxidation of ammonia (Budhi, Jaree, Hoebink, & Schouten, 2004), styrene synthesis (Kolios & Eigenberger, 1999), syngas production (Dillerop, van den Berg, & van der Ham, 2010), methane steam reforming (Simeone, Salemme, & Menna, 2012), etc. The mechanism, modeling and applications of a reverse flow reactor (RFR) have been reviewed in detail by Kolios, Frauhammer, and Eigenberger (2000) and Matros and Bunimovich (1996). Although a CFRR has numerous advantages such as auto-thermal operation, few harmful emissions, and improved performance from unsteady-state operation, etc., its application in industry was often restricted because of the complexity in the reactor control (Balaji, Fuxman, Lakshminarayanan, Forbes, & Hayes, 2007; Devals et al., 2009). The difficulties for controlling a RFR or CFRR result from the hybrid nature of both continuous and discrete behaviors and the nonlinearity of the reaction system, which are caused by the periodical flow reversal operation and the transport-reaction phenomena of severe nonlinearities, respectively (Balaji et al., 2007; Dufour & Touré, 2004).

Great progresses have been made recently on the control of a RFR. A model predictive control (MPC) strategy was adopted to avoid reaction extinction by feeding electrical power under very lean feed conditions (Dufour, Couenne, & Toure, 2003); to prevent catalyst from overheating, a second manipulated variable was introduced through bypassing a ratio of cold gas into the central zone (Dufour & Touré, 2004). To eliminate the periodic error, a repetitive model predictive control (RMPC) was proposed by repeatedly updating the state variables of the model (Balaji et al., 2007). Later, a characteristics-based MPC was used and the selection of prediction horizon was emphasized (Fuxman, Forbes, & Hayes, 2007). A terminal constraint MPC was used to achieve efficient heat extraction and smooth operation (Devals et al., 2009). Meanwhile, a linear quadratic regulator (LQR) controller based on a countercurrent pseudo-homogeneous model was proposed (Edouard, Dufour, & Hammouri, 2005). A LQR using an infinite-dimensional Hilbert space was formulated to keep the distribution of the temperature along the reactor at a stationary state (Fuxman, Aksikas, Forbes, & Hayes, 2008). Through comparing the performance of LQR with that of MPC, it was found that the LQR gave a better operation because of the direct use of the state estimation (Edouard, Hammouri, & Zhou, 2005). Furthermore, logic-based controller (LC) has also been proved effective in the

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http://dx.doi.org/10.1016/j.conengprac.2013.12.016

Nomenclature

a_v	surface area per unit volume (m^{-1})
A	type-1 fuzzy set
$\tilde{A}$	type-2 fuzzy set
C_{CH_4}	methane concentration (mol m^{-3})
C_P	heat capacity (J kg^{-1} K^{-1})
D_{eff}	effective dispersion coefficient (m^2 s^{-1})
D_R	diameter of reactor (m)
h	heat transfer coefficient (W m^{-2} K^{-1})
ΔH	enthalpy of reaction of methane (J mol^{-1})
J_x	primary membership
k_m	mass transfer coefficient (m s^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
L	reactor length (m)
R	rules
$-R_{CH_4}$	rate of methane disappearance (mol m^{-3} s^{-1})
t	time (s)
T	temperature (K)
u	superficial gas velocity (m s^{-1}) or primary membership
U_k	overall heat transfer coefficient (W m^{-2} K^{-1})
x	axial coordinate (m) or input variable
X	universe of discourse (x domain)
X_{CH_4}	average methane concentration (mol m^{-3})
y	output variable
Y	universe of discourse (y domain)

Greek letters

α	air dilution term
β	methane injection term
ε	porosity
μ_A	type-1 membership function
$\mu_{\tilde{A}}$	type-2 membership function
η	effective factor
ρ	density (kg m^{-3})
τ	tortuosity factor

Superscripts and subscripts

0	time $t=0$
end	time $t=t_{end}$, the total time of simulation
eff	effectiveness
f	fluid properties
in	inlet properties
out	outlet properties
s	solid properties
feed	feed properties

Abbreviations

CFRR	catalytic flow reversal reactor
FLC	fuzzy logic controller
FLS	fuzzy logic system
FOU	footprint of uncertainty
FS	fuzzy set
IT2-FLC	interval type-2 fuzzy logic controller
LC	logic-based controller
LMF	lower membership function
MF	membership function
RFR	reverse flow reactor
trap	trapezoidal-shaped membership function
tri	triangular-shaped membership function
T1-FLC	type-1 fuzzy logic controller
T1-FS	type-1 fuzzy logic set
T2-FLC	type-2 fuzzy logic controller
T2-FS	type-2 fuzzy logic set
UMF	upper membership function
VAM	ventilation air methane

CFRR control. By comparing the maximum bed temperature with the prescribed conditions, different manipulated variables like reversing the flow direction, cooling the bed or heating the bed were conditionally chosen to regulate the CFRR operation (Balaji & Lakshminarayanan, 2005; Barresi & Vanni, 2002; Fissore & Barresi, 2008; Hevia, Ordóñez, Díez, Fissore, & Barresi, 2005; Li et al., 2013a, 2013b, 2013c; Mancusi, Russo, Brasiello, Crescitelli, & di Bernardo, 2007; Marín, Ho, Ordóñez, & Díez, 2010).

All of the above-mentioned methods have made certain success in the operation of RFR or CFRR; however, it was also noted that their effective implementation can be inhibited by a lot of drawbacks like the computational intensity (Devals et al., 2009). Although the logic-based controller is easy to construct and implement, it may be improper for direct use in the control of RFR, as the switching time is limited by the performance of the control valves (Li et al., 2013a); the RFR performance can be further improved by a parameter tunable controller. Fuzzy logic controllers (FLCs) constructed by type-1 fuzzy sets (T1-FS) provide an effective way to control systems of high nonlinearities (Zadeh, 1965). Since the pioneering work of Mamdani (Mamdani & Assilian, 1975), this kind of controller has been successfully implemented in many areas such as industrial process control (Park & Cho, 2005), robot (Lin & Lewis, 2003; Takeuchi, Nagai, and Enomoto 1988; Thongchai, Suksakulchai, Wilkes, & Sarkar, 2000), traffic signal control (Wei, Zhang, Mbede, Zhang, & Song, 2001), reactor control (Sheikhzadeh, Trifkovic, & Rohani, 2008; Wakabayashi, Embiruçu, Fontes, & Kalid, 2009; Wu & Pai, 2009) and so on. However, the type-1 fuzzy logic systems (T1-FLSs) were limited in handling systems with great uncertainties (Castillo & Melin, 2012). Type-2 fuzzy sets (T2-FS), with the fuzzy characteristic of membership functions themselves, were then introduced (Zadeh, 1975); by using the T2-FS, the uncertainty in a system was reduced, as it can effectively handle the linguistic uncertainties by modeling vagueness or information unreliability (Wagenknecht & Hartmann, 1988). Recently, the theories of type-2 fuzzy logic systems (T2-FLSs) have been attracting great attentions (Castillo, Aguilar, Cázarez, & Cárdenas, 2008; Karnik, Mendel, & Qilian, 1999; Mendel & John, 2002). Concerning the computational cost, almost all applications in practice use a special kind of T2-FS, i.e. the interval type-2 fuzzy sets (IT2-FS) with their second membership of uniform value (Mendel, 2007); for instance, the interval type-2 fuzzy logic controller (IT2-FLC) has been successfully used in the control of reactor for several reaction processes (Cosenza & Galluzzo, 2012; Galluzzo & Cosenza, 2009, 2011; Galluzzo, Cosenza, & Matharu, 2008; Rihani, Bensmaili, & Legrand, 2009).

In this work, the fuzzy logic control of a RFR was considered. Catalytic combustion of ventilation air methane (VAM) was chosen as a study case, since 70% of anthropogenic methane emissions from coal mining come from VAM, which causes serious environmental problems and waste of valuable energy resources (Karakurt, Aydin, & Aydiner, 2011; Su, Beath, Guo, & Mallett, 2005; Li et al., 2013a, 2013c). The performances of type-1 fuzzy