Applied Energy xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Energy configuration and operation optimization of refinery fuel gas networks

Li Zhou [a], Zuwei Liao [a,*], Jingdai Wang [a], Binbo Jiang [a], Yongrong Yang [a], Wenli Du [b]

[a] State Key Laboratory of Chemical Engineering, Department of Chemical and Biological Engineering, Zhejiang University, Hangzhou, Zhejiang 310027, PR China
[b] Key Laboratory of Advanced Control and Optimization for Chemical Processes, Shanghai 200237, PR China

HIGHLIGHTS

- Complementary formulations are introduced to scheduling model of fuel gas system.
- Physical constraints of the pipes are covered by incorporating detailed pipe model.
- Dynamic multi-component feature of fuel gas system is considered in the model.
- Both the heat value and pressure of demand points are calculated by dynamic model.
- More practical and preferable result is obtained by applying the proposed method.

ARTICLE INFO

Article history:
Received 27 February 2014
Received in revised form 22 October 2014
Accepted 26 October 2014
Available online xxxx

Keywords:
Fuel gas system
Optimization
Scheduling
Mathematical modeling
MPEC

ABSTRACT

The production of regular clean fuels is faced with a problem of declining profit under more strict and costly environmental regulations. To satisfy the desire for higher profit and the firm requirements of environmental protection, it is imperative to improve the efficiency of energy systems within refineries. Over the past decade numerous attempts were made to enhance the energy system, addressing the steam power system and hydrogen system in particular. However, the fuel gas system, which serves as the dominant energy source of refineries, has drawn little attention in the research community. Industrial practices indicate that the energy efficiency of the fuel gas systems can be improved remarkably by optimizing the operation schedules. This paper presents a multi-period optimizing model for the scheduling of fuel gas system within refineries. Modeling of the pipeline system is considered important, which was usually ignored in the former studies. Flow reversal and flow transition in the pipe segments are taken into consideration. Pipelines with branching structure and loop structure can be easily modeled and solved with rational computation effort. Complementarity formulations are utilized in modeling of discrete decisions instead of the commonly used binary variables. Application of this method is illustrated with a case study.

1. Introduction

Energy has long been the focus of the research community [1–5]. Energy conservation and energy efficiency are recognized as major topics for the energy-security of US [4]. Additionally, it has also been pointed out that intimate connection exists between energy efficiency and the environmental impact [5]. In a word, it is of great importance to improve the energy efficiency of a system.

The oil refining industry is one of the most energy-intensive manufacturing industries. Energy is a major component of the refinery daily operating costs and is reported to be the second largest contributor to the total costs [6,7]. This energy is consumed by preheating of reactants, product separation or for onsite electricity generation. In refineries producing cleaner fuel, the energy consumption is even higher. Refineries are under pressure to produce cleaner fuels due to the trend in stricter environmental regulations on heavier crude oil processing. Various energy intensive units such as hydrogen production and hydro-treating units are under construction or being revamped to upgrade the quality of gasoline

Abbreviations: CDU, crude distillation unit; DS, desulfurization unit; FCC, fluid catalytic cracking; HP, high pressure gas; LP, low pressure gas; LPG, liquefied petroleum gas; MPEC, mathematical program with equilibrium constraints; PX, para-xylene.

* Corresponding author. Tel.: +86 571 87951227.
E-mail address: liaozw@zju.edu.cn (Z. Liao).

http://dx.doi.org/10.1016/j.apenergy.2014.10.078
0306-2619/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

Sets

A	pipeline segments
B	optional backup fuel sources
D	fuel gas consumers
K	components of the gas flow
N	junctions that connect pipes
S	fuel gas suppliers
T	operating periods
$ArctoNode\ (A,N)$	set mapping of pipeline arcs A to node N
$ArcfromNode\ (A,N)$	set mapping of pipeline arcs A out of node N
$Demand\ (D, N)$	set mapping of demand nodes D from nodes N in the network
$Supply\ (S, N)$	set mapping of supply nodes S to nodes N in the network
$Z = \{in, out\}$	inlet/outlet of pipe segment

Parameters

$Area_a$	cross-sectional area in arc a, m^2
C	speed of sound in the gas
ρ	gas density
Dia_a	diameter of pipe segment a, m
L_a	length of pipe segment a, m
ξ	penalty cost of fuel gas, yuan/N m^3
ζ_b	unit price of the backup fuel b
$F_{s,t}^{Capacity}$	producing capacity of the production unit s in period t (based on volume N m^3/h)
Mw_k	molecular weight of component k
$H_{d,t}^{Dem}$	energy demand of consumer b at t, MJ
HV'_b	heating value of backup fuel b based on volume, MJ/N m^3
HV_s	heating value of fuel gas s based on mass, MJ/kg
$y_{s,k,t}$	mass fraction of component k of source s at t
t_t	operating period t
Nt	the last operating period
Δt	time duration of each operating period
μ	gas viscosity, kg/(m s)
$Temp$	temperature, K
P^{Low}	lower bound of the safety pressure level
P^{Up}	upper bound of the safety pressure level
R	gas constant
φ_a	surface roughness of pipe in arc a

Variables

$\frac{dP}{dx}_{a,z,t}$	partial derivative of pressure with respect to position in arc a at endpoint z at t
$F_{s,t}$	fuel gas flowrate of source s at the corresponding source node in period t based on volume, N m^3/h
$F_{b,t}$	consumption of backup fuel b in operating period t
$F_{b,d,t}$	flowrate of backup fuel from source b to consumer d in operating period t
$F_{d,t}$	volume flow of consumer d, N m^3/h
M	mass flowrate, kg/s
$M_{a,in,t}$	inlet mass flowrate of pipe arc a at t, kg/s
$M_{a,out,t}$	outlet mass flowrate of pipe arc a at t, kg/s
$M_{s,t}$	mass flowrate of fuel gas from source s to the corresponding source node at t, kg/s
$M_{d,t}$	mass flowrate of fuel gas fed to consumer d at t, kg/s
$Mw_{a,t}$	molecular weight of the gas stream in arc a at t
$H_{d,t}$	energy provided to consumer d at t, MJ
$HV_{n,t}$	heating value of the gas flow at node n at t based on mass, MJ/kg
$HV_{a,t}$	heating value of the gas flow in pipe arc a at t based on mass, MJ/kg
$HV_{a,t}^{in}$	heating value of the inlet gas flow in pipe arc a at t based on mass, MJ/kg
$HV'_{d,t}$	heating value of the feeding gas flow of consumer d at t based on volume, MJ/N m^3
$HV_{d,t}$	heating value of the feeding gas flow of consumer d at t based on mass, MJ/kg
$\overline{P}_{a,t}$	average pressure in pipe a at t, kPa
P	pressure
$P_{a,in,t}$	pressure at the inlet of pipe a at t
$P_{a,out,t}$	pressure at the outlet of pipe a at t
$Re_{a,z,t}$	Reynolds number for gas in arc a at endpoint z at t
$f_{a,z,t}$	friction factor for gas in arc a at endpoint z at t
$f_{a,z,t}^{lam}$	laminar friction factor for gas in arc a at endpoint z at t
$f_{i,z,t}^{turb}$	turbulent friction factor for gas in arc a at endpoint z at t
$y_{a,k,t}$	mole fraction of component k of the flow in arc a at t
$y_{a,k,t}^{in}$	mole fraction of component k of the inlet flow of arc a at t
$y_{d,k,t}$	mole fraction of component k of the inlet of consumer d at t
$y_{n,k,t}$	mole fraction of component k of the gas flow at node n at t
$TInv_t$	total gas inventory of the pipeline system at t, kg
$Inv_{a,t}$	gas inventory of pipe segment a at t, kg
$TInv_{Nt}$	total gas inventory of the pipeline system at end of the scheduling time horizon, kg
$switch_{a,z,t}$	switching variable
$\lambda 1_{a,z,t}, \lambda 2_{a,z,t}$	auxiliary variables

and diesel products in order to meet the environmental requirement. As the energy consumption is increasing, the overall profit is shrinking. Consequently, refineries are facing challenges of satisfying both the profit demand and environment requirement. Energy conservation and energy efficiency are the keys to solve this challenge.

The energy system of the refineries consists of the following sub-systems: hydrogen, fuel gas and steam system [8,9]. The fuel gas sub-system is the greatest contributor to the total energy system. However, in compare to the well-studied hydrogen system [10–18] and steam system [19–23], only a few work has been focused on optimization of the fuel gas system. The researches cover systems design/revamping and decision making of the fuel gas system. Hasan et al. [24] developed a nonlinear program to tackle the synthesis of optimal fuel gas networks. It was reported that 40–50% of the total energy cost can be saved by applying the proposed method. Many realistic features were incorporated in their model such as auxiliary equipment, nonisobaric operation and nonisothermal mixing, but it was only valid for steady-state operation. Later, Jagannath et al. [25] adapted the model to handle dynamic operation system. In their extended model, a multi-period two stage programming model was reported. Network design including decisions regarding to the existence and sizes of equipments was determined in the first-stage, while the network operation details such as flows and operation duties were calculated in the second-stage. In case of the existing fuel gas systems the increase of efficiency should be first addressed through full utilization of the existing devices. Scheduling is one of the important methods to make competitive operation decisions. Zhang and Rong [26] developed a mixed integer linear programming model for fuel gas scheduling. In their model, the storing capability of the system and the consumption of fuel gas in cogeneration and production