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Multi-level energy integration between units, plants and sites for natural gas industrial parks

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ABSTRACT

Natural gas industrial parks are composed of raw natural gas refining plants, urea plants and power plants. The processes of natural gas refining and utilization in industrial parks are energy-intensive and involve complicated mass and energy networks. This study concentrates on heat and material stream integration for sustainable energy utilization in natural gas industrial parks. Energy integration of industrial parks is reviewed and a mixed integer non-linear programming framework is presented to minimize the total annual cost for the retrofitting of energy integration across plants in natural gas industrial parks. The mathematical framework combines the optimization models of energy-intensive processes, power plant operation and a new heat exchanger network design using some key variables. Total site analysis is proposed for a natural gas industrial park to obtain energy-intensive processes with energy saving potential and determine the process streams for energy integration across plants. The mathematical framework is then applied to the natural gas industrial park and can be solved using the deterministic global optimization solver in a reasonable solution time. The results demonstrate that the static investment payback period is less than two months and the total hot utility decreases by 30.5% through the energy retrofit of the entire natural gas industrial park.

1. Introduction

Natural gas is a significant source of energy and chemical feed because of its cleaner properties. Raw natural gas industrial parks have been constructed and expanded to increase the production and utilization of natural gas [1]. For example China, in facing the challenges of environmental protection and greenhouse gas reduction, is forced to increase natural gas production from 4% to 10% in the ratio of primary energy before 2020 [2]. The processes of natural gas refining and utilization are energy consuming and are complicated in mass and energy networks. Hence, optimization and integration of natural gas industrial parks is desirable to increase the profitability and efficiency of sustainable resources and energy utilization [3]. Significant emphasis has been placed on system-level studies investigating the purification of natural gas, the conversion of methane (and other light hydrocarbons) into more valuable products and the supply chain framework for natural gas-based technologies [4]. This study focuses on energy integration for all natural gas industrial parks that involve natural gas refining and utilization processes. The energy-intensive CO_2 treatment processes, utility systems, heat exchange across plants in such industrial parks are all analyzed using total site analysis (TSA) and integrated to formulate a mathematical programming model. The objective is to optimize total annual cost (TAC) and reduce the energy requirement. Energy savings are an important aspect for the sustainability of energy. This work can promote the sustainability of energy through the optimization retrofit for natural gas industrial parks.

The methodologies that were conducted on energy integration can be generally classified into three categories: pinch analysis, mathematical programming and meta-heuristic optimization methods [5]. There is considerable number of papers that have contributed to the area of energy integration. The methodologies about process and energy integration were thoroughly reviewed by El-Halwagi [6], Morar and Agachi [7], and Liew et al. [8]. The methodologies have been studied over several decades and are sequentially applied to heat exchanger networks (HENs), processes, plants, total sites, and now to industrial parks and even larger scale facilities. Process and energy integration

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Nomenclature

Sets/indices

B/*b*	set of boilers indexed by *b*
C/*c*	set of components indexed by *c*
D/*d*	set of steam turbines indexed by *t*
I/*i*	set of hot streams indexed by *i*
J/*j*	set of cold streams indexed by *j*
K/*k*	set of intervals indexed by *k*
P/*p*	set of process plants indexed by *p*

Superscript

°	environmental state
ab	absorption in CO_2 treatment process
bd	blowdown of boiler
cd	condenser of regenerator
cs	cold stream
cu	cold utility
dg	dry gas
dm	dry gas directly going to mixer
dt	dry gas entering CO_2 treatment process
ds	desorption tower in CO_2 treatment process
en	end status of process streams
gm	purified gas to mixer
gp	gas to power or boilers
gu	purified gas to urea
hps	high pressure steam
hpsv	phase change of high pressure steam
hs	hot stream
hu	hot utility
hx	heat exchanger
in	inlet
lcv	lower calorific value
lps	low pressure steam
max	maximum
min	minimum
oh	steam overheating in boiler
out	outlet
pg	purified gas
pl	pipeline
po	power output
re	reboiler of desorption tower in CO_2 treatment process
rm	CO_2 removed from CO_2 treatment process
sc	condensate stream at the top of desorption tower
shps	saturated high pressure steam
shpo	overheated high pressure steam
sk	flue gas from boiler
st	start status of process streams
sv	solvent in CO_2 treatment process
wl	wall loss of boiler
wp	water preheating in boiler
wt	water
wv	water vaporizing in boiler
xh	hot side of heat exchanger
xc	cold side of heat exchanger

Greek symbols

α, β, γ	stoichiometric ratio of hydrocarbon burning [dimensionless]
δ,ϵ	parameters of heat exchanger cost [dimensionless]
ε, θ	parameters of steam turbine model [dimensionless]
ζ	steam consumed by condensing turbines before optimization [10^6 mol/h]
λ	price [power: $/(MW h); cold utility: $/GJ]
μ	absorption ability of solvent [mol CO_2/mol solvent]
ν	power production of existing natural gas industrial park [MW]
ξ	parameters of pipeline cost [dimensionless]
ρ	cold duty of condensing turbine [GJ/(10^6 mol steam)]
τ	heat loss ratio from boiler wall [dimensionless]
φ	big data [dimensionless]
χ	solvent weight percent in solution [dimensionless]
ψ	condenser duty of regenerator before optimization [GJ/h]
ω	air excess ratio of boiler [dimensionless]
ϑ	moisture ratio of turbines [dimensionless]

Letters

ΔH	enthalpy change
ΔT	heat transfer temperature difference [°C]
A	operating hours per year [hour/year]
Cp	specific heat capacity [GJ/10^6 mol/°C]
CP	heat capacity flow rate [GJ/°C]
E	power [MW]
F	flowrate [10^6 mol/h]
G	specific isentropic enthalpy change of steam [GJ/10^6 mol]
L	length of pipeline [m]
M	molar fraction [dimensionless]
O	mole weight [kg/kmol]
Q	heat [GJ/h]
R	reflux ratio of desorption tower [dimensionless]
S	utility cost or income [$/h]
T	temperature [°C]
U	heat transfer coefficient [kW/°C/m^2]
V	useful life [year]
W	area of heat exchanger [m^2]
Y	0, 1 variable, denoting new pipeline or heat exchanger [dimensionless]
Z	0, 1 variable, denoting the operation of equipment [dimensionless]

have significantly promoted energy savings and sustainable development for energy-intensive processes and industries. They have supplied powerful support to the optimization, energy saving and emission reduction for processes and industries. Pinch analysis-based graphic techniques and mathematical modelling are the main tools for process and energy integration. These two tools are very useful and are being thoroughly studied. Pinch analysis-based graphic techniques have been significantly developed for complex systems including energy, water, emission and other supply and demand relationships. Mathematical modelling is being focused on how to build simple and accurate models and how to quickly obtain a global optimum solution. The recent work on energy integration between plants, energy integration with processes and utility systems, and energy integration for industrial parks are reviewed in this study.

Energy integration between plants has been widely investigated over recent years, including the graphical techniques based on pinch technology [9], mathematical programming models [10], and heuristic strategies [11,12]. Energy integration between plants can be realized using process streams [13,14], intermediate streams [15,16], and hot direct discharges/feeds between plants [17,18]. Using process streams and hot direct discharges/feeds between plants can reduce heat transfer temperature differences while decreasing the flexibility of operation.

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