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Optimal production of power in a combined cycle from manure based biogas

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ABSTRACT

In this work, the production of power using a combined cycle gas turbine/steam turbine, which operates with biogas as fuel, is evaluated. The process begins with the production of biogas from pig and/or cattle slurry manure(s) using anaerobic digestion. Afterwards, the gas is cleaned up to remove humidity, hydrogen sulfide, carbon dioxide and ammonia. The cleaned gas (biomethane) is then used in a Brayton cycle (gas turbine) to produce energy. The flue gas that exits the Brayton cycle is typically at high temperature and it is further utilized to produce steam that generates power in a regenerative Rankine cycle (steam turbine). Two alternative steam production schemes are evaluated: either splitting the flue gas to have high temperature gas for the reheating step of the steam or sequential heating up. The model is formulated as a Mixer Integer Nonlinear Programming (MINLP) solved in GAMS® for the optimal production of power. For a typical production capacity of manure in farms, 2.6 MW are produced. The investment for the plant turns out to be 26 M€ and the production cost of the electricity is 0.35 €/kW h before including the credit from the conditioned digestate, that could be sold as fertilizer. The electricity cost goes down to 0.15 €/kW h considering a reasonable credit from the digestate, whose composition depends on the feedstock processed in the facility.

1. Introduction

Most countries have a powerful agricultural system to provide for food. As a result, large volumes of residues are generated. In particular, cattle and pigs farms generate vast amounts of residues (manures). Apart from the difficulty of dealing with such quantities of waste, the composition is also dangerous. Anaerobic Digestion (AD) provides the technology not only to dispose it but also to generate further value. The production of biogas through AD offers significant advantages over other forms of bioenergy production. It has been deemed as one of the most energy-efficient and environmentally beneficial technology for bioenergy production [1]. Furthermore, biogas generation can drastically reduce greenhouse gases compared to fossil fuels by utilization of locally available resources. Compared to other fossil fuels, methane produces fewer atmospheric pollutants and generates less carbon dioxide per unit energy; as methane is comparatively a clean fuel, the trend is towards its increased use for appliances, vehicles, industrial applications and power generation [2]. Finally, the digestate represents an improved soil conditioner which can substitute mineral fertilizer [3].

Typically in the literature, we can find experimental studies evaluating biogas generation and the effect of the operating conditions and feedstocks on the composition of the biogas as well as its use to produce heat and power [4–6]. Modelling studies are also available [7–11]. We can find the use of gas turbines, combined cycles or engines to produce energy from biogas [7,8]. Recently, Kang et al. [7] evaluated the economics of a combined heat and power cycle (CHP) using biogas as energy source. They simulated the plant using commercial software, GateCycle. Their results showed that, for a 5 MW gas turbine, the payback period was five years with promising electricity production costs. In another work, the same authors compared the production of energy using a gas turbine system with a combined cycle based on a 5 MW gas turbine [9] finding better results when using the combined cycle: 31% shorted payback time and 55% higher NPV. Other studies directly burn the biogas in an engine evaluating the power produced as a function of the air to biogas ratio and the biogas composition [8]. Modular simulators such as HYSYS have also been used to evaluate hybrid natural gas-biogas systems [10]. Apart from steady state simulations, dynamic studies are also available. They aim to help monitor the process and to provide further insight on its inertia [11]. Furthermore, Amiri et al. [12] presented the

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Nomenclature

a' — CH_4, CO_2, NH_3, H_2S, O_2 and/or N_2
a — H_2O, CH_4, CO_2, NH_3, H_2S, O_2 and/or N_2
$A(i)$ — Antoine *A* coefficient for vapor pressure of component *i*
$B(i)$ — Antoine *B* coefficient for vapor pressure of component *i*
$C(i)$ — Antoine *C* coefficient for vapor pressure of component *i*
Cp_{salt} — specific heat capacity of flue gas
d — C, N_{org}, N_{am}, P, K, H_2O and/or Rest
e — CH_4, NH_3 and/or H_2S
k — PS or CS
j — NH_3 and/or H_2O
h — {CH_4, CO_2, O_2, N_2}, {O_2, N_2} or {CO_2, O_2, N_2}
CS — cattle slurry
PS — pig slurry
C–N — carbon to nitrogen molar ratio
N_{am} — nitrogen contained in ammonia
N_{org} — nitrogen contained in organic matter
Rest — rest of the elements contained in the biomass
$EC_j(T)$ — equilibrium constant of component *j* at temperature *T*
$F_{(unit,unit1)}$ — mass flow from stream from unit to unit1 (kg/s)
$fc_{(J,unit,unit1)}$ — mass flow of component *J* from unit to unit1 (kg/s)
$H_{b(unit,unit1)}$ — enthalpy of the stream at the state *b* from the stream from unit to unit1 (kJ/kg)
$H_{steam(isoentropy)}$ — enthalpy of the stream at the if the expansion is isentropic (kJ/kg)
l_{j-i} — molar fraction of component *j* in the liquid phase of equilibrium system *i*
K_{index} — potassium index of fertilizer
MW — molar mass
$n_{(unit,unit1)}$ — total mol flow from stream from unit to unit1 (kmol/s)
N_{index} — nitrogen index of fertilizer
$P_{in/compressor}$ — inlet pressure to compressor (bar)
$P_{out/compressor}$ — outlet pressure of compressor (bar)
$P_j^*(T)$ — saturation pressure of pure component *j* at temperature *T* (bar)
P_v — vapor pressure (bar)
P_{index} — phosphorous index of fertilizer
p_{turbi} — inlet pressure to body *i* in the turbine (bar)
$Q_{(unit)}$ — heat exchanged in unit (kW)
$R_{C-N/k}$ — carbon to nitrogen ratio in *k*
$R_{C-N/fertilizer}$ — carbon to nitrogen ratio in fertilizer
$R_{V/F-i}$ — rate of evaporation in equilibrium system *i*
$s_{b(unit,unit1)}$ — entropy the stream at the state b for the stream from unit to uni1 kJ/kg K
$T_{turbimin}$ — saturating temperature at exit of body *i* (°C)
$T_{(unit,unit1)}$ — temperature of the stream from unit to unit1 (°C)
$T_{bubblei}$ — bubble point temperature of equilibrium system *i* (°C)
T_{mi} — average temperature in equilibrium system *i* (°C)
$T_{in/compressor}$ — inlet temperature to compressor (°C)
$T_{out/compressor}$ — outlet temperature of compressor (°C)
v_{j-i} — molar fraction of component *j* in the vapor phase of equilibrium system *i*
$V_{biogas,k}$ — biogas volume produced per unit of volatile solids (VS) ($m^3_{biogas}/kg_{VS/k}$) associated to *k*
$w_{DM/k}$ — dry mass fraction of *k* ($kg_{DM/k}$/kg)
$w'_{VS/k}$ — dry mass fraction of volatile solids out of the dry mass of *k* ($kg_{VS/k}/kg_{DM/k}$)
$w'_{C/k}$ — dry mass fraction of C in *k* ($kg_{C/k}/kg_{DM/k}$)
$w'_{Nam/k}$ — dry mass fraction of N_{am} in *k* ($kg_{Nam/k}/kg_{DM/k}$)
$w'_{Norg/k}$ — dry mass fraction of N_{org} in *k* ($kg_{Norg/k}/kg_{DM/k}$)
$w'_{P/k}$ — dry mass fraction of P in *k* ($kg_{P/k}/kg_{DM/k}$)
$w'_{K/k}$ — dry mass fraction of K in *k* ($kg_{K/k}/kg_{DM/k}$)
$w'_{Rest/k}$ — dry mass fraction of the rest of the elements contained in *k* ($kg_{K/k}/kg_{MS/k}$)
$W_{(unit)}$ — power produced or consumed in unit (kW)
$x_{a/biogas}$ — mass fraction of component *a* in the biogas
y_{biogas} — specific saturated moisture of biogas
$Y_{a'/biogas\text{-}dry}$ — molar fraction of component *a* in the dry biogas
$\Delta H_{reaction}|_{(Bioreactor)}$ — heat of the anaerobic digestion's reaction (kW)
$\Delta H_{comb}(k)$ — heat of combustion of component *k* (kW)
$\Delta H_{comb}(e)$ — heat of combustion of component *e* (kW)
ΔH_{comb}(Digestate-dry) — heat of combustion of dry digestate (kW)
$\Delta H_f(h)|_{T(unit,unit1)}$ — heat of formation of component *h* at temperature $T_{(unit,unit1)}$ (kW)
z — polytropic coefficient
Z — objective function

Symbols and constants

η_c — compressor's efficiency
η_s — isentropic efficiency = 0.9
P_{atm} — atmospheric pressure = 1 bar
T_{atm} — atmospheric temperature=25 °C
R — ideal gas constant = 8.314 J/mol K
Cp_{H_2O} — specific heat capacity of water = 4.18 kJ/kg °C

Equipments and others

Src1 — source of cattle slurry
Src2 — source of pig slurry
Snk*i* — sink *i* of stream
Bioreactor — digester
Compress*i* — gas compressor *i*
Turb*i* — gas expander *i*
GasTur — gas turbine
HX*i* — heat exchanger *i*
Spl*i* — splitter *i*
Mix*i* — mixer *i*
Sep*i* — separator *i*
MS*i* — molecular sieve *i*

use of a linear programming model for the minimization of the cost in the production of biogas. The model is simple, considering yields instead of the detail operation of the turbines and not paying attention to biogas composition, but it provides an interesting tool for examining the effect of heat and electricity prices on the profitability of the plant. Other optimization studies show a thermodynamics based approach for general cogeneration plants without paying attention to the source of energy [13].

In this work we optimize the production of energy from residues based biogas using a mathematical optimization formulation. The integrated facility uses the exhaust gases from the gas turbine to produce steam that eventually generates power in a steam turbine. This formulation allows simultaneous evaluation of the biogas composition for the optimal operating conditions of the facility together with the selection between different topologies for the efficient use of the flue gas in steam generation. The facility focuses on power production, but different steam qualities can also be produced if we decide to operate in a more classical CHP mode. We organize the paper as follows: in Section 2 we provide a brief description of the process; in Section 3, the different units are described and the modelling assumptions are presented; in Section 4, the results of the optimal operation of the facility are shown together with an economic evaluation; and finally, in Section 5, we draw some conclusions.