Chemical Engineering Science 170 (2017) 639–652

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Performance evaluation of biogas upgrading by pressurized water scrubbing via modelling and simulation

Christophe E. Wylock[a], Wojciech M. Budzianowski[b,c,*]

[a] Université Libre de Bruxelles, Transfers, Interfaces and Processes (TIPs), Av. F. Roosevelt 50, CP 165/67 - 1050 Brussels, Belgium
[b] Consulting Services, Poleska 11/37, 51-354 Wrocław, Poland
[c] Renewable Energy and Sustainable Development (RESD) Group, Poleska 11/37, 51-354 Wrocław, Poland

HIGHLIGHTS

- Modelling of a scrubber-flash-stripper HPWS system for biogas upgrading.
- A simulation procedure for optimized dimensioning of upgrading plant is proposed.
- The influence of the water recirculation parameters on the scaling is studied.
- Investigation of the operating and physico-chemical parameters on the performances.

ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form 12 November 2016
Accepted 9 January 2017
Available online 10 January 2017

Keywords:
Biogas
Biomethane
Water scrubbing
Scrubber-flash-stripper configuration
Process scaling

ABSTRACT

The water scrubbing of biogas is an efficient, cheap and environmental friendly process to remove CO_2 from biogas in order to upgrade it into biomethane. This work deals with the modelling and simulations of a scrubber-flash-stripper high pressure water scrubbing process, which is currently the most mature technology. The model and its associated simulation procedure can be used to estimate appropriate device sizes as well as to assess the performance of a given plant. Thanks to this tool, an optimized configuration is computed for a reference case. A sensitivity analysis is also realized in term of scrubbing efficiency and CH_4 slippage. The influence of parameters related to the water recycling as well as the operating parameters is investigated. Moreover, the sensitivity of the model with respect to the solubility and transfer coefficient parameters is analyzed, in order to gain insight on the parameter to focus in the framework of a model calibration by experimental results.

1. Introduction

Biogas is a renewable and sustainable fuel rich in methane (CH_4) generated through anaerobic digestion of organic matter. Digestible organic materials may come from various sources: dedicated crops, agricultural residues, household wastes, water treatment sludge's, etc. Biogas is a potential substitute to natural gas which attracts significant attention across countries importing fossil fuels. However, such raw biogas is of low pressure, low specific gravity and large specific volume. In addition, it contains a large part of carbon dioxide (CO_2), which lowers its calorific value, flame velocity and flammability limits compared to natural gas. Besides, the transport of CO_2 diluted biogas over long distance is more costly compared to e.g. natural gas pipeline transportation. This explains why the generated biogas is commonly burnt in-situ by combined heat and power (CHP) systems, which enables to convert 35–40% of biogas energy into usable electricity. A part of the cogenerated heat is used for meeting the digester needs but most is often dissipated and wasted because heat users are located far from biogas CHP plants. The dilution of flue gases by combusted CO_2 makes it more difficult to recover energy of flue gases which lowers thermal efficiency of biogas-fired CHP systems.

To overcome these issues, several processes have been created over recent years to upgrade biogas into biomethane. Upgrading basically relies on removing most of the CO_2 and potentially other trace compounds from the biogas (Sun et al., 2015; Abatzoglou and Boivin, 2009; Ryckebosch et al., 2011; Budzianowski, 2012). Such biomethane, which can be used directly as automotive fuel or being injected into the natural gas grid, is claimed as an important renewable fuel for Europe (Thrän et al., 2016).

The biogas upgrading processes are based on absorption, adsorption, cryogenic or membrane technology (Beil and Beyrich,

---

* Corresponding author at: Consulting Services, Poleska 11/37, 51-354 Wrocław, Poland.

E-mail address: wojciech.budzianowski@gmail.com (W.M. Budzianowski).

http://dx.doi.org/10.1016/j.ces.2017.01.012
0009-2509/

Nomenclature

Latin

$[\,]$	molar concentration, mol/m^3
$\mathcal{A}$	interfacial area density, m^{-1}
C_p	specific heat capacity, kJ/(kg K)
D	diameter, m
$\mathbb{D}$	diffusive coefficient, m^2/s
g	gravity acceleration, m/s^2
$\mathcal{H}$	Henry constant, (Pa m^3)/mol
H	height, m
k_G	transfer coefficient in the gas film, m/s
k_L	transfer coefficient in the liquid film, m/s
$\mathcal{K}$	chemical equilibrium constant
K_L	liquid-side global mass transfer coefficient, m/s
M	molar mass, kg/mol
p_G	gas total pressure, Pa
$p_{G,i}$	partial pressure of species i, Pa
$\mathcal{Q}$	mass flow rate, kg/s
u	superficial velocity, m/s
T	absolute temperature, K
x	mass fraction, kg/kg
y	molar fraction, mol/mol
z	vertical coordinate, m

Greek

ΔE	enthalpy variation, kJ/mol
η	removal efficiency, %
λ	gas loss, Nm^3/h
ρ	density, kg/m^3
ϑ	global mass transfer rate, kg/s
τ	mass transfer rate density, kg/(m s)
Ω	column cross-section area, m^2

Subscript and superscript

G	gas phase
L	liquid phase
in	inlet
out	outlet
CO_2	carbon dioxide
CH_4	methane
HCO_3^-	bicarbonate ion
CO_3^{2-}	carbonate ion
FLS	flash tank
RAW	raw biogas
SCR	scrubber
STR	stripper
w	pure water
r	reaction
abs	absorption

2013). In this work we investigate the gas-liquid absorption by water, called hereafter water scrubbing. Indeed, water is a cheap and environmental friendly solvent for removing CO_2. It makes use of the higher solubility of CO_2 (and other compounds like H_2S) than the solubility of CH_4 in water. The ratio of Henry constants between CO_2 and CH_4 is about 30 which makes water scrubbing of CO_2 from biogas relatively efficient.

The most mature technology is the scrubber-flash-stripper high pressure water scrubbing (SFS-HPWS), which is sketched in Fig. 1. The CO_2 capture from the biogas is performed in a scrubber, which commonly consists of a packed column. Due to the small CO_2 solubility in water, the absorption rate is enhanced by setting its operating pressure between 0.8 and 1.2 MPa, in order to increase CO_2 partial pressure in the biogas. This enables to reach high purity biomethane at the top of the scrubber. The dissolved CH_4 within the CO_2-rich water leaving the scrubber is also increased under elevated pressure operation. Therefore, the scrubbing solvent needs to be subsequently separated in a flash tank operating at a reduced pressure of about 0.11–0.2 MPa. The released gas, rich in CH_4 and CO_2 is then mixed with the raw biogas and reinjected into the scrubber. To regenerate the scrubbing water, the CO_2 has to be released. To achieve this solvent regeneration a second low pressure packed column is used as a stripper. In this case, CO_2 is desorbed from water at ambient temperature using air as stripping agent. This considerably reduces energy requirements for solvent regeneration compared to solvents with chemical compounds that strongly bind CO_2 and requires consequently higher stripping temperature.

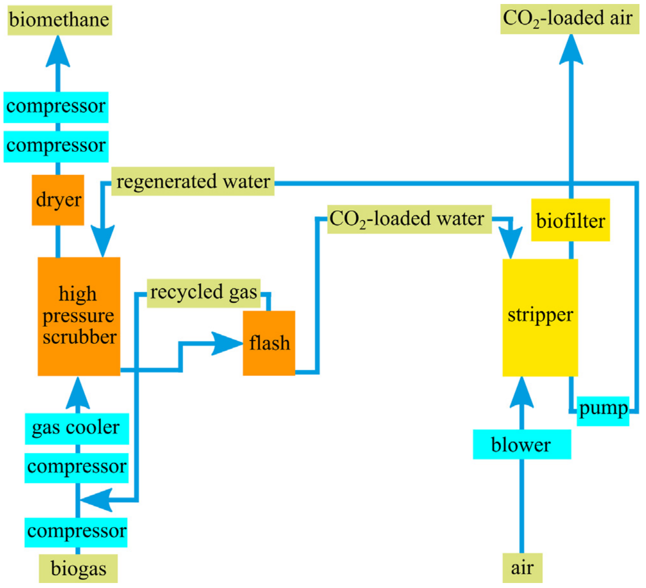

Fig. 1. Block-diagram of a scrubber-flash-stripper configuration of a pressurized water scrubbing process.

Several scrubber-flash-stripper HPWS plants already exist at the commercial scale. Some examples of such plants as well as their advantages and drawbacks are presented in Budzianowski et al. (2017). Despite, it seems that very few HPWS models are proposed in the literature. In addition, the available experimental data are generally sparse and often focused only on the scrubber analysis.

To scale appropriately the gas-liquid devices and the associated equipment's (pump, compressor, etc.) and to identify optimum operating conditions for the process, mathematical modelling and numerical simulation are particularly valuable to reach high-performance SFS-HPWS plant. The industrially validated models may be also useful in process control, including on-line monitoring of plant performance. This work deals with the mathematical modelling and the numerical analysis of the SFS-HPWS plant. The appropriate column dimensions are related to the characteristics of the biogas to upgrade (flow rate, concentration…), the targeted