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Power requirements of biogas upgrading by water scrubbing and biomethane compression: Comparative analysis of various plant configurations

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ABSTRACT

Biogas upgrading by water scrubbing followed by biomethane compression is an environmentally benign process. It may be achieved using various plant configurations characterised by various power requirements with associated effects on biomethane sustainability. Therefore, the current study has been undertaken to systematically investigate the power requirements of a range of water scrubbing options. Two groups of water scrubbing are analysed: (1) high pressure water scrubbing (HPWS) and (2) near-atmospheric pressure water scrubbing (NAPWS). A water scrubbing plant model is constructed, experimentally validated and simulated for seven upgrading plant configurations. Simulation results show that the power requirement of biogas upgrading in HPWS plants is mainly associated with biogas compression. In contrast, in NAPWS plants the main power is required for water pumping. In both plants the compression of the biomethane from atmosphereic pressure to 20 MPa also contributes remarkably. It is observed that the lowest specific power requirement can be obtained for a NAPWS plant without water regeneration (0.24 kW h/Nm^3 raw biogas) but this plant requires cheap water supply, e.g. outlet water from a sewage treatment plant or river. The second is HPWS without flash (0.29 kW h/Nm^3 raw biogas). All other HPWS with flash and NAPWS with water regeneration plants have specific power requirements between 0.30 and 0.33 kW h/Nm^3 raw biogas. Biogas compression without upgrading requires about 0.29 kW h/Nm^3 raw biogas. The thermodynamic efficiency of biogas upgrading is between 2.2% and 9.8% depending on the plant configuration while biomethane compression efficiency is higher, about 55%. This result implies that the upgrading process has a remarkable potential for improvement whereas compression is very close to its thermodynamic limit. The potential for minimising energy dissipation in the state-of-the-art HPWS upgrading plant with flash by applying a rotary hydraulic pumping device is evaluated at about 0.036 kW h/Nm^3 raw biogas meaning the specific power requirement reduction of 10%.

1. Introduction

Biogas is a renewable and sustainable fuel derived from digestible biomass that is suitable for natural gas substitution. However, biogas generated through anaerobic digestion is of low pressure, low specific gravity and large specific volume and is thus unsuitable for energy storage. The large share of CO_2 present in biogas lowers its calorific value, flame velocity and flammability limits compared to natural gas. Besides, the transportation of biomethane over longer distances is less costly than the transportation of CO_2 diluted biogas. These challenges may adversely affect biogas sustainability. Therefore, biogas upgrading to biomethane with subsequent use as a natural gas substitute attracts significant attention.

Biomethane, used directly as automotive fuel or being injected into the natural gas grid, has been identified as an important renewable fuel in Europe [1]. Current biomethanation technologies consume less than about 20% of biogas energy for upgrading and compression purposes. Thus biomethanation enables transforming more than about 80% of the energy content of raw biogas into the usable form of clean energy. In addition, biomethanation generates little or no low-grade heat and hence thermal losses are minimised. The biomethanation can therefore be competitive to raw biogas fed combined heat and power (CHP) systems. Namely, in CHP only about 35–40% of biogas energy is converted into useful

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Nomenclature

$\mathcal{A}$	interfacial area density of a column (1/m)
A_p	theoretical packing surface area (m^2/m^3)
CAPEX	capital expenditure
CHP	combined heat and power
C_p	specific heat (J/(kg K))
$\mathcal{D}$	column or pipe diameter (m)
$\mathbb{D}$	diffusive coefficient (m^2/s)
d	pipeline diameter (m)
d_p	packing characteristic dimension (m)
f	Colebrook-White friction coefficient (–)
F_p	packing factor of packing materials (m^2/m^3)
G	Gibbs free energy (J)
g	acceleration of gravity (m/s^2)
H	liquid head (m)
$\mathcal{H}$	column height (m)
H_i	Henry constant of species i ((Pa m^3)/mol)
HPWS	high pressure water scrubbing
K_L	global gas–liquid mass transfer coefficient (m/s)
$\mathcal{K}_1$	chemical equilibrium constant of reaction (7a) (m^3/mol)
$\mathcal{K}_2$	chemical equilibrium constant of reaction (7b) (m^3/mol)
$\mathcal{K}_w$	chemical equilibrium constant of reaction (7c) (mol^2/m^6)
L	pipeline length (m)
M	molar mass (kg/mol)
m	mass flow rate (kg/s)
n	number of compression stages (–)
N	mass transfer flux (mol/s)
NAPWS	near-atmospheric water scrubbing
OPEX	operating expenditure
p	pressure (Pa)
p^{std}	standard pressure = $1.013{\cdot}10^5$ Pa
PR	power requirement (W)
Δp	pressure drop of fluid (Pa)
RHPD	rotary hydraulic pumping device
q	volumetric flow rate, m^3/s or Nm^3/s or Nm^3/h 1 Nm^3 = 1 m^3 at $1.013{\cdot}10^5$ Pa, 273.15 K
$\mathcal{Q}$	mass flow rate (kg/s)
R	universal gas constant = 8.314 J/(K mol)
Re_L	Reynolds number (ρLuLdH)/μL or (ρLuL)/(awμL)
S	free interface area (m^2)
SPR	specific power requirement (W/Nm^3)
t	time (s)
T	temperature (K)
u	superficial velocity (m/s)
VLE	vapour-liquid equilibrium
W	work, J; specific work (J/Nm^3)
x	mass fraction (kg/kg)
y	molar fraction (mol/mol)
z	column height coordinate (m)
ε	pipe surface roughness (–)
εp	packing void fraction (m^3/m^3)
η	efficiency (–)
κ	ratio of specific heats = 1.32 (CH_4), 1.28 (CO_2)
μ	dynamic viscosity (kg/(m s))
ν	kinematic viscosity (m^2/s)
ξ	performance index, (–)
ρ	fluid density (kg/m^3)
σ	surface tension (N/m)
σ_C	critical surface tension of packing material (N/m)
τ	gas–liquid mass transfer rate density (kg/(m s))
Φ	enhancement factor for turbulent diffusion
ϕ_p	form factor (–)
Ω	column cross-section area (m^2)
[ ]	molar concentration of a species (mol/m^3)
$\frac{\Delta p}{\Delta z}$	linear pressure drop (Pa/m)

Subscripts and superscripts

ATM	atmospheric
B-A	blowing air
BASELOAD	baseload
BM	biomethanation
C	compressor
C-BG	compressed biogas
CBM	biomethanation with compression
CG	gas phase constant
CL	liquid phase constant
CLW	CO_2 loaded water
COOL	coolant
CPK	packing specific constant
D	dynamic
e	enriched biogas
FLS	flash tank
G	gas phase
INCREMENTAL	incremental
in	inlet
L	liquid phase
out	outlet
P-COOL	pumping cooling water
P-LW	pumping CO_2-loaded water
P-RW	pumping regenerated water
r	raw biogas
RW	regenerated water
S	static
SCR	scrubber
std	at standard $p = 1.013{\cdot}10^5$ Pa and T = 298.15 K
STR	stripper
DP	degassing pond
T	total
w	water

electricity. The remainder is obtained in-situ in the form of heat and, except for meeting the needs of digesters heating, most of the in-situ generated heat is often dissipated and wasted. Hence, the CHP systems enable to supply about 40% of raw biogas energy to power grids, i.e. less than half of that supplied by the biomethanation systems to gas grids or for transportation applications. In addition, biomethane can be stored, transported and used flexibly in order to meet fluctuating energy demands. Biomethane is thus a dispatchable sustainable biofuel which can complement the performance of renewable energy systems rich in naturally fluctuating wind and solar power sources. Major uses of biomethane include power-only production, CHP production (but in locations where both power and heat may be sold), vehicle fuel and cooking fuel. These uses require grid injection, fuel tank injection or bottling, i.e. all require compressed biomethane (typical pressure requirement is 20 MPa). In relation to gas compression, CO_2 separation brings benefits associated with reduced gas amount for compression having greater energy density and similar total energy content compared to raw biogas.

Power requirement of different biogas upgrading options is an essential parameter for assessing their technical performance and for achieving the sustainability of biogas. The power requirement