Investigation of a 5 kW micro-CHP PEM fuel cell based system integrated with membrane reactor under diverse EU natural gas quality

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Small scale power generation, focusing on the field of Proton Exchange Membrane fuel cell (PEMFC) based systems, are potentially characterized by high net electric efficiency and very low emissions targeting the application to distributed heat and power co-generation (CHP) in the urban areas. As drawback, these systems implies the adoption of fuel processor to produce pure hydrogen upstream the fuel cell. Natural gas (NG), with the most widespread network in industrialized countries, is the reference fuel for hydrogen production. So in the last years many studies have been focused on the integration of membrane reactor in micro-CHP system thanks to its unique feature of separating pure hydrogen. Since the heat and electric demand from a residential user can be lower than rated power output, this work deals with the system performances at partial loads assessing the impact of different European NG composition.

Micro-CHP system design and Natural Gas quality

Two lay-outs are investigated: the first adopts steam as sweep gas (SG) to reduce the hydrogen partial pressure at the permeate side, while in the latter the permeate side is kept below atmospheric pressure by a vacuum pump (VP). Both cases are evaluated because sweep gas configuration achieves a higher net electric efficiency, but the thermal integration and its control is complex due to the evaporation of two steam streams (reactant and sweep). The vacuum pump case is simpler because less heat exchangers are necessary and the membrane reactor requires less manifolds. The design parameters and the main assumptions of the reference case are summarized in Table 1. The values adopted for the system components result from studying benchmark technologies, typical O&M specifications, requirements for domestic heating, materials. A detailed parameter summary can be found in [1]. Figure 1 shows the example layout with sweep gas. The operating conditions were optimized to achieve a high electric efficiency while keeping a moderate membrane surface area. The temperature and feed pressure are set at 600°C and 8 bar, while the S/C ratio is equal to 2.5 and 3 for the sweep and vacuum case respectively.

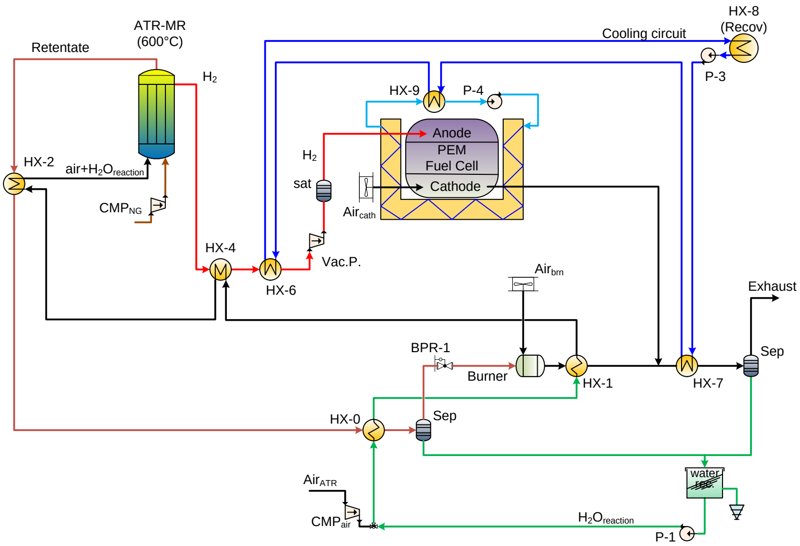

Figure 1. Layout of the micro-CHP system

Parameter	units	value
Natural Gas comp.	%mol	Table 2
Temperature	°C	600
Pressure reaction side	bar	8
Pressure permeate side SG	bar	1.3
S/C SG	-	2.5
Sweep to H_2 ratio	-	≈ 0.3
Pressure permeate side VP	bar	0.3
S/C VP	-	3.0
$\lambda_{ATR\text{-}MR}$ (air to ATR-MR)	-	≈ 0.23
Heat recovery supply/return temperature	°C	45/30
Single cell voltage	V	0.752
λ_{cath} (air to cathode)	-	2
Fuel utilization (Dead end)	-	0.99
$DC_{stack}/AC_{230V@50Hz}$ conversion efficiency	%	95

Table 1. Model assumptions and main parameters

Since the micro-CHP system can be placed all over the European countries, its design has to take into account the diverse quality of NG: in this work, four different cases were assumed as representative of the European situation. Their main properties are shown in Table 2. The UK composition features an average NG, Italian case is almost pure methane, while NL and ES have the minimum and maximum Wobbe index respectively. Moreover, the considered compositions vary in terms of inert concentration where inerts reduces the H2 fraction and consequently the permeation driving force across the membrane. The system performances with different natural gas compositions were determined at rated power. Results showed that the adoption of the most diluted natural gas (NL) is suggested in order to guarantee a high efficiency at any NG composition.

		NG type			
Species	**units**	**NL**	**UK**	**IT**	**ES**
CH_4	%mol	81.230	92.070	99.581	81.570
C_2H_6	%mol	2.850	3.405	0.056	13.380
C_3H_8	%mol	0.370	0.761	0.021	3.670
n-C_4H_{10}	%mol	0.080	0.177	0.002	0.400
i-C_4H_{10}	%mol	0.060	0.140	0.006	0.290
n-C_5H_{12}	%mol	0.020	0.048	0.000	0.000
i-C_5H_{12}	%mol	0.020	0.061	0.002	0.000
C_{6+}	%mol	0.080	0.090	0.007	0.000
CO_2	%mol	0.890	0.865	0.029	0.000
N_2	%mol	14.400	2.375	0.296	0.690
LHV	MJ/kg	38.0	46.7	49.7	48.6
H_2 potential	mol H_2/mol NG	3.52	4.07	3.99	4.66
x in C_xH_y	-	0.89	1.04	1.00	1.22
Wobbe index	MJ/Nm³	43.6	52.0	53.1	56.6

Table 1. Natural Gas reference cases

Micro-CHP performances at partial loads

Starting from the system design at rated power, micro-CHP behavior at partial load is evaluated considering the following assumptions. A polarization curve is implemented for the PEMFC where the current density is determined in order to respect the given surface area; Concerning the thermal integrations, heat exchangers work with constant UA, where U is the overall heat exchange coefficient and A the area of the heat exchanger and heat losses of the system components are conservatively kept constant to the value assumed at full load (in principle, this assumption coincides with having the same heat exchanger surface temperature, which is really close to the real case). Compressors and fans are assumed to be of reciprocating type, and regulated at variable speed while for the power conditioning system, efficiencies of the single components (converter and inverter) are affected in different way by the output load (relative to the design output). The efficiencies at partial load were taken from commercial system [2] and from literature [3]. Reactors operating parameters are varied to follow the power output from 100% to 40% (below 40% the micro-CHP is forced in stand-by mode) of designed power target which end up in controlling the hydrogen permeation. For the sweep case, the hydrogen permeation is controlled modifying the sweep flowrate, while for the vacuum case, the feed pressure is varied. Variation in the permeation driving force leads to different reaction duties requiring a control in the λ_{ATR-MR} (air to ATR-MR) parameter.

Results for the sweep gas and vacuum pump case are shown respectively in Figure 3 and Figure 4 for all the NG compositions.

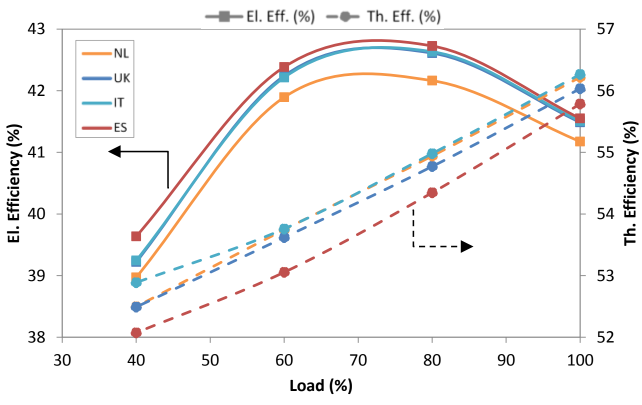

Figure 2. Sweep gas case: Off-design performances

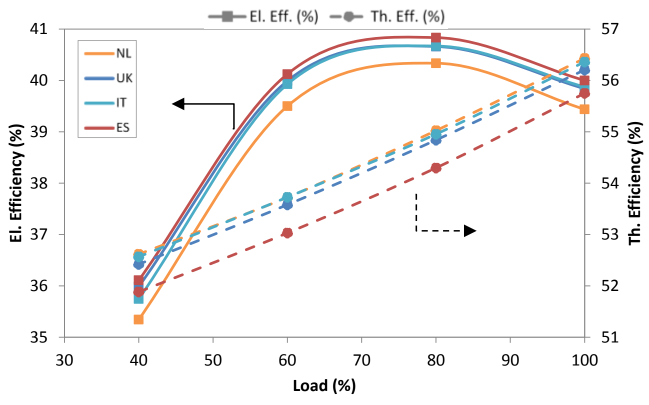

Figure 3. Vacuum pump case: Off-design performances

In general terms, the net electric efficiency increases for all the cases up to 70% of the rated load when it starts to drop. This is mainly consequence of the polarization curve of the PEM fuel cell, where the voltage (i.e. conversion efficiency) increases at lower current densities. The thermal efficiency reduces in the first part because of the higher electric efficiency, then because of the assumption of constant heat losses which becomes important. About the NG flowrate, it reduces of the same ratio of the load, while the sweep gas reduces only by 40% at 40% of the rated load. This is consequence of the 0.5 power law adopted in the hydrogen flux calculation across the membrane. The auxiliary consumption share on the gross power output increases at rated conditions (lower component efficiency), however its impact is limited. Indeed, the power consumption of some components (i.e compressors) is constant or even increases moving from 60% to 40% of the load mainly because of driver efficiency decay. Finally, differences between NG compositions in terms of efficiencies are almost negligible throughout the considered load range. The curves are shifted downward with respect to the sweep case by about 2% points while the trend is almost the same since the dominating effect is the fuel cell efficiency which coincides between the two cases. The efficiency drop after 60% load is more pronounced than the sweep case because of the higher impact of auxiliaries (i.e. hydrogen compressor), which further increases at partial load. Focusing on hydrogen compression work, it reduces only by 20% moving from 100% to 40% of the load. The thermal efficiency reduces at part-load, firstly, because of the electric efficiency increase and afterwards for the constant thermal losses assumed. Finally, it must be outlined that the electric efficiency at 40% of the load is 4%points lower than the one at rated conditions, while for the sweep case the decay was only 2%points.

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