

Project title: GaSTech

Project ID: 271511

Funding scheme: ERA-Net Cofund ACT (<http://www.act-ccs.eu/calls/>)

Topic: Research and innovation actions for CO₂ Capture and Storage (CCS)

Starting date of project: 1st of August, 2017

Duration: 36 months

WP N°	Del. N°	Title	Contributors	Lead beneficiary	Nature	Dissemination level	Delivery date from Annex I	Actual delivery date dd/mm/yyyy
3	3.2	Mass & energy balance and unit sizing of GSR/GSWS process	Shareq Mohd Nazir (NTNU), Schalk Cloete (SINTEF)	NTNU	R	PU	31/08/2019	31/10/2019

Summary

This report presents the mass and energy balances for two GSR-based plants, focused on power and hydrogen production, respectively. These details are used as input to economic assessments of these promising clean energy conversion processes. The combined cycle gas fired power plant integrated with GSR and CO₂ capture is defined as GSR-CC. The hydrogen generation process integrated with GSR and CO₂ capture is defined as GSR-H2. GSR-CC has been designed for optimum performance and allowing for flexibility with respect to the product, electricity and hydrogen, that enables easy integration of variable renewable energy. The GSR-H2 process has been designed for optimum performance to negate the efficiency penalty with respect to the conventional steam-methane reforming process without CO₂ capture. In addition, unit sizing of the reactors and other important process units for the economic assessment is presented.

Process description

This report focusses only on the GSR technology because GSWS was shown to be infeasible from an experimental point of view. The two different GSR configurations; GSR-CC and GSR-H2, are presented in more detail below.

Gas Switching Reforming Combined Cycle Power Plant (GSR-CC) [1]

The process flow diagram of the GSR-CC process for power production is shown in Figure 1 with stream data presented in Table 1. Natural gas and steam (steam to carbon ratio of 2) are reformed in the GSR unit in the presence of a Ni catalyst during the GSR reforming step. The resulting syngas is cooled to 395 °C and sent to the water gas shift (WGS) reactor, where CO and H₂O in the syngas are converted to CO₂ and H₂O. The shifted syngas from the WGS reactor is further cooled to 65 °C before entering the pressure-swing adsorption (PSA) unit to recover 86% of 99.99% pure H₂. The H₂ stream is compressed, mixed with water and pre-heated in Hex 4 by recovering the remaining heat in the shifted syngas to prepare a mixture of H₂ and saturated steam (H₂ fuel) at 260 °C. The off-gas from the PSA is compressed (compressor with 90% polytropic efficiency) to 18.4 bar and heated up to 1000 °C before being sent to the GSR reduction step. The off-gas is combusted during this reduction step to reduce the oxygen carrier, which subsequently acts as a catalyst during the reforming step. The resulting gases from the GSR reduction step are cooled to condense the H₂O present, resulting in a CO₂ stream that is compressed to 110 bar and sent for storage. The oxygen carrier is oxidised with air during the GSR oxidation step, resulting in a hot N₂ stream. Air for the oxidation step is extracted at the compressor discharge of the gas turbine (GT) system of the combined cycle power plant. The N₂ stream is sent to the GT since it can be used as a diluent in H₂ combustion. The pre-heating of the NG and steam mixture is done to 890 °C in heat exchanger Hex 1 by recovering heat from the syngas from the GSR, whereas the PSA off-gas is pre-heated in Hex 3 by recovering heat from the gas stream resulting from the GSR reduction step.

The power plant consists of two GTs and two heat recovery steam generators (HRSGs) connected to a single steam turbine (ST) system. The steam cycle is a three-pressure level (166/32.7/3.4 bar) with reheat for the medium pressure steam. Atmospheric air is compressed to 18.4 bar and is combusted with H₂ fuel along with N₂ stream from the GSR acting as a diluent. The combustion gases are expanded in a turbine to produce power. The exhaust gases from the turbine are cooled and the heat is recovered to produce steam for power generation. The GSR-CC is integrated so that all the steam required for reforming is produced by heat recovery from the process streams like the syngas and PSA off-gas stream. NG and water are heated to produce a mixture of NG and saturated steam at 18 bar in Hex 5 by recovering the remaining heat in the gas resulting from the reduction step of the GSR. The remainder of the steam for reforming is produced by recovering heat from the shifted syngas in Hex 2. The GSR-CC power plant combusts 46.35 TPH of H₂ fuel when run under base load conditions. However, the GSR-CC plant was especially designed with minimal integrate between the H₂ production section and the power plant so that the plant can easily switch to producing H₂ during off-design conditions and when the electricity demand is low.

catalyst to form syngas. The pre-heating of NG and the NG-steam mixture in Hex 1, 2 and 3 respectively is done by recovering heat from the hot syngas exiting the GSR reforming step. Similar to the reference plant, the syngas is treated in the WGS reactor to produce a stream containing mostly H₂ and CO₂, after which 99.999% pure H₂ is recovered in the PSA and compressed to 150 bar and 30 °C for export. The PSA off-gas is compressed, pre-heated and sent to the GSR reduction step. The reduction step outlet stream contains mostly CO₂ and H₂O, from which the H₂O is condensed, and the CO₂ stream is compressed for transport and storage. The reduced oxygen carrier is oxidized with compressed air during the oxidation step, leaving a hot stream containing mostly N₂. The N₂-stream is cooled and then expanded in a turbine before being vented.

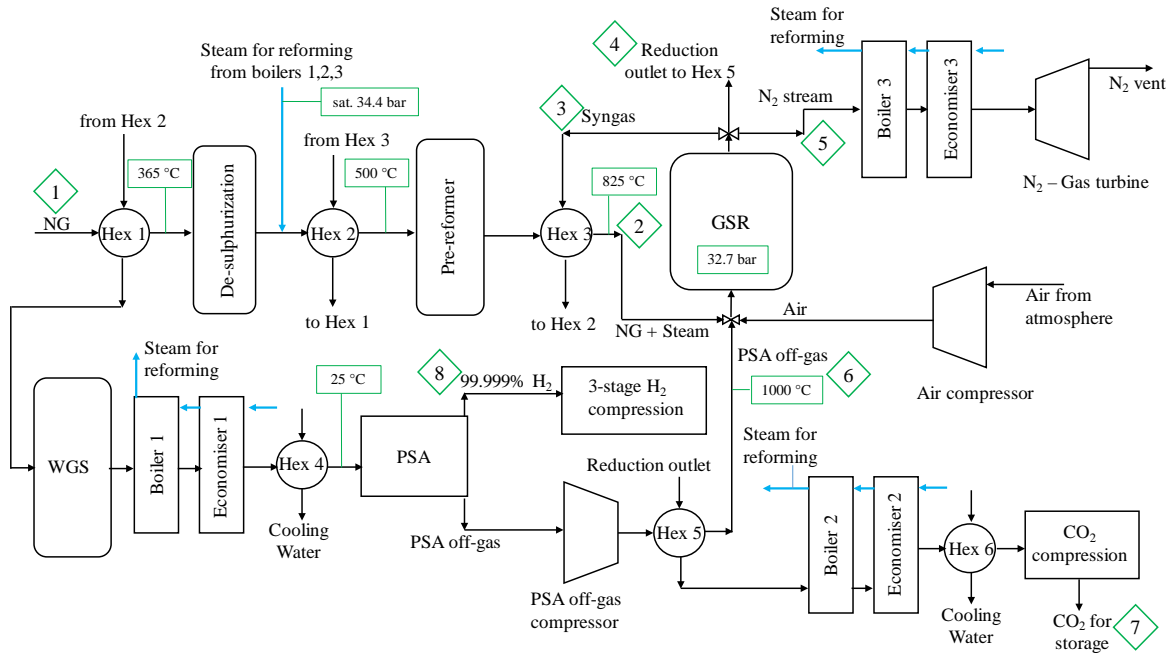


Figure 2: Schematic of the GSR-H2 plant [2]

Table 2: Stream data for GSR-H2 process in Figure 2

Stream	P (bar)	T (°C)	Flow (TPH)	H ₂ O mol %	CO ₂ mol%	CH ₄ mol %	CO mol%	H ₂ mol %	N ₂ mol%	O ₂ mol %	Ar mol%	C+ mol%
1	70	15	10	-	2	89	-	-	0.9	-	-	8.1
2	32.7	825	40.7	67.7	2.7	22.8	0.0	6.6	0.2	-	-	-
3	32.2	939	42.2	32.2	5.1	2.1	11.2	48.4	1	-	-	-
4	32.2	1080	33.9	3.6	57.4	-	0.2	0.1	5.6	-	0.1	-
5	32.2	990	35.0	4.3	1.5	-	-	-	93.1	-	1.1	-
6	32.7	1000	24.8	0.4	52	8.0	9.9	26.1	3.6	-	-	-
7	113.2	25	27.1	0.2	9.2	-	0.3	0.3	8.9	-	0.1	-
8	27.9	25	3.3	-	-	-	-	100	-	-	-	-

Unit sizing for economic assessment

The installation cost of most of the process units in these two GSR plants can be estimated from cost functions based on the inlet stream feed rates (e.g. WGS reactors and PSA unit) or power rating (compressors, turbines and heat recovery steam generators). Heat exchangers were sized based on the heat transfer and log mean temperature difference data provided by the process simulations, assuming appropriate heat transfer coefficients.

The GSR reactors were sized by assuming a fluidization velocity of 0.5 m/s, which is typical for bubbling fluidized bed reactors. This determined the total reactor cross sectional area required. To determine the height and diameter of individual reactors, a typical aspect ratio of 2 was assumed and the lowest cost reactor size was determined using the reactor cost correlation as explained in Szima, Nazir [3]. Using this method, the lowest-cost reactor dimensions were found to be 2.2 m in diameter and 4.4 m in height. A cluster of several such reactors is required for operating a large-scale GSR plant.

Conclusions

This report presents the mass and energy balances for two promising GSR-based plants: one flexible power and hydrogen configuration and another dedicated hydrogen plant. This data provides all the details required for the subsequent unit sizing and economic assessment.

References

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- [2] Nazir SM, Cloete JH, Cloete S, Amini S. Efficient hydrogen production with CO₂ capture using gas switching reforming. *Energy*. 2019;185:372-85.
- [3] Szima S, Nazir SM, Cloete S, Amini S, Fogarasi S, Cormos A-M, et al. Gas switching reforming for flexible power and hydrogen production to balance variable renewables. *Renewable and Sustainable Energy Reviews*. 2019;110:207-19.