EXERGO-ECONOMIC ANALYSIS OF AN HCCI-ENGINE POLYGENERATION SYSTEM

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Abstract
Fuel rich combustion processes in engines can also be used for the production of base chemicals like syngas together with work and heat. In this work, such an HCCI engine polygeneration system, which was previously modeled in python/cantera, with respect to kinetics and thermodynamics, is now investigated by conducting an exergo-economic analysis including a global sensitivity analysis. It was found that the systems product costs depend strongly on certain device costs, interest rate, operating hours and lifetime, although the exhaust gas recirculation rate primarily determines the product costs. The highest exergy destruction rate and therefore the highest costs caused through this, occur in the HCCI engine with about 46 % of the total exergy destruction. The analysis indicates that, for lowering the product costs, the investment costs of the hydrogen membrane and the shift reactor should be reduced or substituted for a different, cheaper hydrogen separation technology and the lifetime and operating hours of the system should be increased. It was found that the hydrogen costs per kg have a reasonable range of 2.6 to 10.4 €/kg.

Introduction
In order to reduce the emissions of carbon dioxide, the consumption of finite fossil fuel resources and to stabilize the grid that is increasingly affected by volatile renewable energy systems, a more flexible energy system is needed. If a facility, e.g. a chemical plant, has an additional need for chemicals a partial oxidation in gas engines could provide, the efficiency and flexibility would improve even more. In earlier studies therefore a polygeneration process concept with HCCI engines that produces heat, power and chemicals by partial oxidation has been studied to compare this concept to the conventional, separate production on a thermodynamic basis. It was found that the exergetic efficiency of an HCCI engine polygeneration process producing acetylene is more than 20% higher than a separate production [5]. Most often economic reasons are essential for building certain devices. Therefore, beside the thermodynamic and kinetic analysis of the polygeneration system this study has been conducted to do a exergo-economic research. The results help to determine in which part of the system it is important to improve the exergy effiency due to high costs that are generated by the exergy destruction and where it is less important in

order to reduce the costs of the final products. Due to the uncertainty in costs, that are needed for the analysis, the global sensitivity of the prices on the different estimated costs is applied.

Process concept

The investigated polygeneration energy system [5] mainly consists of an HCCI engine, a watergas-shift reactor, a hydrogen membrane reformer and several shell and tube heat exchangers and hydrogen compressors to produce hydrogen in addition to power, heating water and process steam. The systems process flow diagram is shown in figure 1.

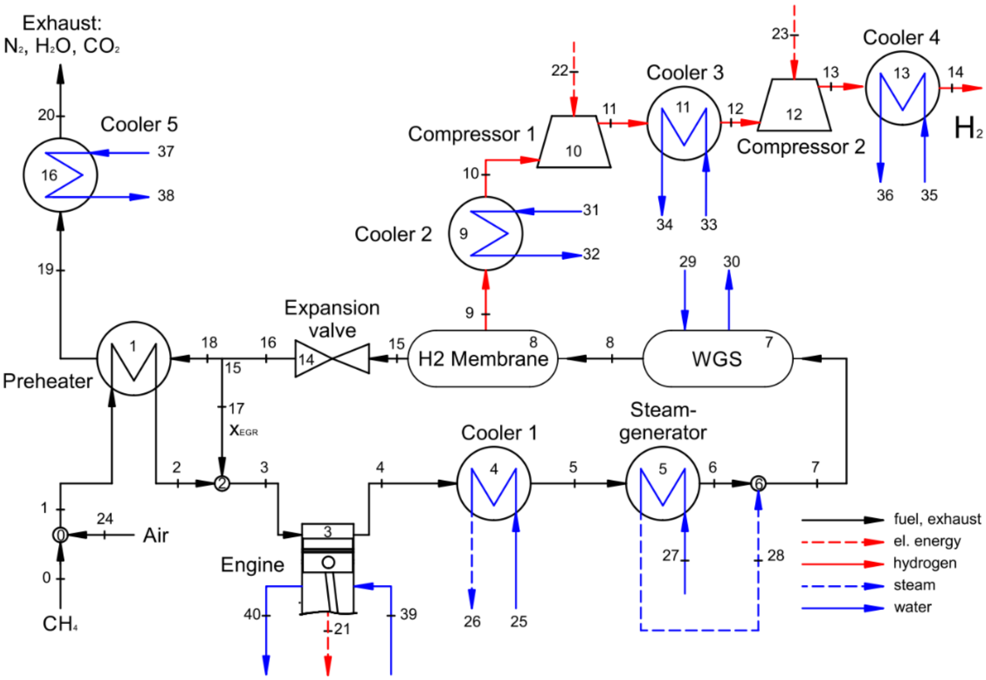

Figure 1. Process flow diagram of the polygeneration process.

To achieve ignition with neat, relatively inert methane as fuel, a preheater using the exergy from the exhaust gas to heat the air-fuel mixture and an exhaust gas recirculation (EGR) to increase the temperature und number of reactive radicals in the intake are used. For further information on the system and its components it is referred to previous work of Hegner et al. [5].

Exergo-economic analysis

The main principle of exergo-economic analyses is defining the costs of an energy flow i as the product of the specific exergy costs c_i and the exergy flow $\dot{E}_i$ according to (1). To calculate the specific exergy costs of the products, cost balances (2) for each component k are conducted that lead to a linear equation system [2].

$$\dot{C}_i = c_i * \dot{E}_i \tag{1}$$

$$\sum \dot{C}_{F,i} + \dot{Z}_k = \sum \dot{C}_{P,i} + \dot{C}_{L,k} \tag{2}$$

The total device costs per time unit $\dot{Z}_k$ are defined as the sum of the total investment costs and the total operating and maintenance costs per time unit. For these costs the time value of money and the salvage value of the devices are considered [1]. The device investment costs are established by using the purchased equipment costs method from Turton et al. for known device costs [8]. Subsequently the maximum device costs of all EGR ratios x_{EGR} are used for the calculations. The chosen financial parameters for the analysis are shown in table 1.

Table 1. Financial parameters

Description	Symbol	Value	Unit
Lifetime	T	15	a
Operating hours	τ	7920	h/a
Interest rate	i	0.1	-
Salvage value factor	Ω	0.05	-
Op. & maint. factor	Φ	0.03	-
Air exergy costs	c_{air}	7.2	€/MWh
Methane exergy costs	c_{CH4}	17.9	€/MWh
Water exergy costs	c_{water}	86.0	€/MWh
Electricity costs	c_{el}	42.0	€/MWh

For devices with n exiting flows $n-1$ auxiliary relations are required to solve the cost balances [2]. Based on the extraction method [6] the engines electrical energy costs are maximized and the water costs are kept constant to charge all costs to the exhaust gas. The cost balance equations (2) do not take exergy losses into account even though they are very important when correlating exergy flows with cost flows. Therefore, the costs of exergy destruction $\dot{C}_{D,k}$ are calculated corresponding to [2] with the assumption that the exergy destruction $\dot{E}_{D,k}$ is independent on the specific fuel costs $c_{F,k}$ (3).

$$\dot{C}_{D,k} = c_{F,k} * \dot{E}_{D,k} \tag{3}$$

To distinguish the increase of the specific product costs by the device costs from the exergy related exergy destruction and exergy loss costs, Bejan et al. [2] defines the exergo-economic factor f_k as the ratio of the non-exergy-related cost increase to the total cost increase (4). If the value is low, the cost increase is mainly caused by exergy-loss-related costs and thus the exergetic efficiency of the device should be improved even if it increases the device costs. On the contrary the device costs should be lowered if the factor has a high value at the expense of the exergetic efficiency.

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{F,k} * (\dot{E}_{D,k} + \dot{E}_{L,k})} \tag{4}$$

In addition to the constant financial parameters a global sensitivity analysis is conducted to determine the influence of changing device costs, fuel costs and financial parameters on the final product costs using the Sobol method [7]. The sensitivity of an input parameter describes the part of uncertainty of the results the input parameter is accountable for. If only one parameter is varied and therefore there is no interdependency with other parameters the result is called the first order sensitivity. In this work, the first order sensitivity and the total sensitivity is regarded. The latter is the sum of all sensitivities (of all orders) of the investigated input parameter and thus gives the information how significant the sensitivities of higher orders are.

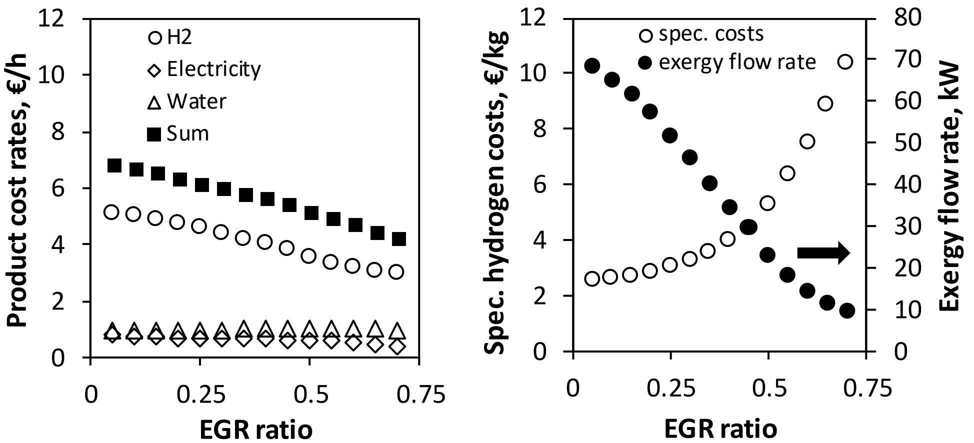

Figure 2. Product costs per hour (left figure) and hydrogen costs per kg (open symbols, left scale, right figure) and exergy flow rates (filled dots, right scale, right figure) as a function of EGR ratio.

Results and discussion

For the given constant financial parameters, figure 2 shows the product costs per hour of H_2, electricity and water. Since hydrogen was chosen as the main product, and thus charged with all costs of the exhaust gas flowing into the H_2 membrane and the device costs of the membrane itself, the hydrogen costs represent 68 – 75 % of the total product costs. Due to the decreasing exergy flows with increasing EGR ratios, the H_2 costs per kg rise strongly. The effect of the decreasing exergy flows on the product costs with maximum device costs is shown in figure 2. The hydrogen costs per kg rise gradually with EGR ratios at 0.5 and above, leading to four times higher hydrogen costs compared to the lowest EGR ratio (0.05). For this reason, high EGR ratios should be avoided or reduced to small periods per year which limits the flexibility of the polygeneration systems according to the financial parameters. Table 2 shows the results for the sensitivity analyses for EGR ratios of 0.05 and 0.7 where the first order sensitivity S_1 is larger than 0.03. It is found that only four parameters have non-negligible sensitivities: the interest rate, lifetime, operating hours and the device costs of the hydrogen membrane (it has the highest investment costs of all devices). Depending on the demand for the products, it can be desirable to increase the operating hours per year by running the system at higher EGR ratios for this additional period instead of shutting it down completely.

Table 2. Sensitivity analysis results for $S_1 > 0.03$

EGR ratio	0.05		0.7	
Sensitivity parameter	S_1	S_{T1}	S_1	S_{T1}
H_2 membrane costs $\dot{Z}_8$	0.1784	0.1831	0.1971	0.2025
Interest rate i	0.2011	0.2079	0.1986	0.2058
Lifetime T	0.2051	0.2134	0.2031	0.2117
Operating hours t	0.3800	0.3835	0.3760	0.3797

As it can be seen in table 3, the engine, the hydrogen membrane and the water gas-shift reactor cause the highest exergy destruction rates with about 12 % for the reactor and the membrane and 46 % for the engine.

Table 3. Most impact of exergo-economic factors for $x_{EGR} = 0.05$.

Device	$\dot{E}_{D,k}$	$y_{D,k}$	f_k	$\dot{C}_{D,k}$
	W	%	%	€/h
3) Engine	10883.6	46.46	85.8	0.211
7) Water gas-shift reactor	2883.6	12.31	79.3	0.087
8) H_2 membrane	2875.5	12.28	95.6	0.086
14) Expansion valve	1087.0	4.64	50.5	0.000

The hydrogen costs increase by the hydrogen membrane is mainly caused by its high investment costs and not by the exergy destruction as the exergo-economic factor f_k has a high value of 95.6 %. The engine and the reactor have a greater amount of exergy destruction costs with 85.8 % and 79.3 % being caused by the device costs.

In contrary the expansion valve has a relatively high exergy destruction, but because its investment costs are low there is no effect on the product costs.

Conclusion

An exergo-economic analysis of the polygeneration engine system helps to determine in which case an improvement of the exergetic efficiency is reasonable and in which case non-exergy-related parameters, e.g. investment costs, are limiting. To reduce the product costs – especially the H_2 costs – of the investigated HCCI polygeneration system the investment costs of the hydrogen membrane and the water gas-shift reactor should be reduced or substituted by a different, cheaper H_2 separation technology. The H_2 costs per kg for the given financial parameters have a reasonable range of 2.6 to 10.4 €/kg, compared to about 4.2 to 5.67 €/kg when using a separate water electrolysis [3] or hydrogen membrane reformer [4]. In further investigations these results shall be compared to an exergo-economic analysis of distinct processes: a CHP plant and a separate hydrogen production.

Acknowledgements

Financial support of this work by the Deutsche Forschungsgemeinschaft within the framework of the DFG research unit FOR 1993 'Multi-functional conversion of chemical species and energy' (AT24/13-2) is gratefully acknowledged.

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