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Through Exergy Approach to More Efficient Processes*

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Abstract

This paper compares three different types of a turbine-converter-expander combination with respect to the exergetic efficiency. Converter stands for a combustion chamber, a Solid Oxide Fuel Cell and a reactor in which a chemical process is carried out. The exergy losses for the first examples are 22%. The exergy losses for the other two examples can be reduced by 50 and 10 to 80%, respectively. The calculations were done by means of an in-house developed process simulator. It is concluded that the integration of utilities in chemical processes can realize a substantial reduction of both energy and exergy loss.

Key words: gas turbine, exergetic efficiency, process integration, fuel cell, chemical reactor

1. Introduction

With modern process simulators it is possible to calculate the exergy of flows and the exergy losses in unit operations and processes. KEMA uses for that purpose its own developed process simulator SPENCE®. KEMA did the modelling for many and very different kinds of energy conversion processes. The processes, for example electricity production, can be improved if the efficiency of the process is increased. Analyzing the results of the calculations, it can be shown that at the same time the exergy losses are lower. So focusing on the possibilities of decreasing the exergy losses of the process gives options for increasing the efficiency.

In modern power generation plants gas turbines are mostly used. With the repowering of conventional power plants with gas turbines, it was possible to increase the efficiency of power plants over 10% (Ploumen and Veenema, 1996). The different options for repowering with gas turbines are described in (Ploumen and Veenema, 1996; Ploumen et al., 1998).

The most popular kind of power station is the combined cycle, where the first cycle is an open gas turbine cycle and the second cycle a steam/water cycle taking up the heat in the heat recovery steam generator. In the combined cycle the exergy losses are much lower than those in a conventional power plant where the steam cycle picks up the heat in the boiler with much higher temperature differences.

A general overview of combined and integrated cycles is given in Korobitsyn (1998).

In the following part some examples will be shown. In the first place, a gas turbine will be considered, where the combustion chamber is located between a compressor and an expander (see *Figure 1*). This kind of equipment is used in almost all the larger new power plants. In the second example, the combustor is replaced by a fuel cell. In the third example, a chemical reactor replaces the combustor.

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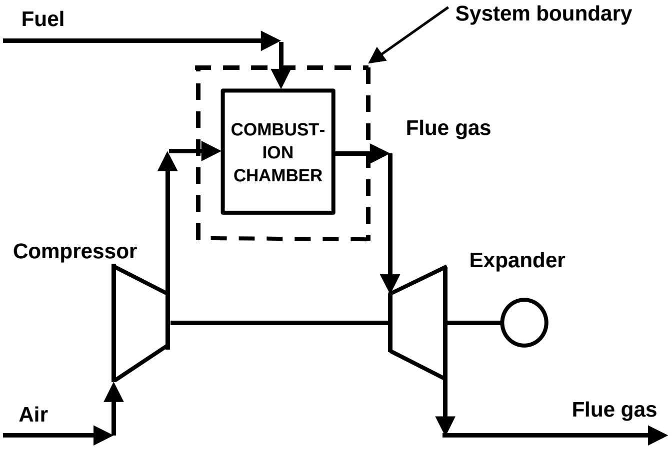

Figure 1. System boundary of the combustion chamber of the gas turbine

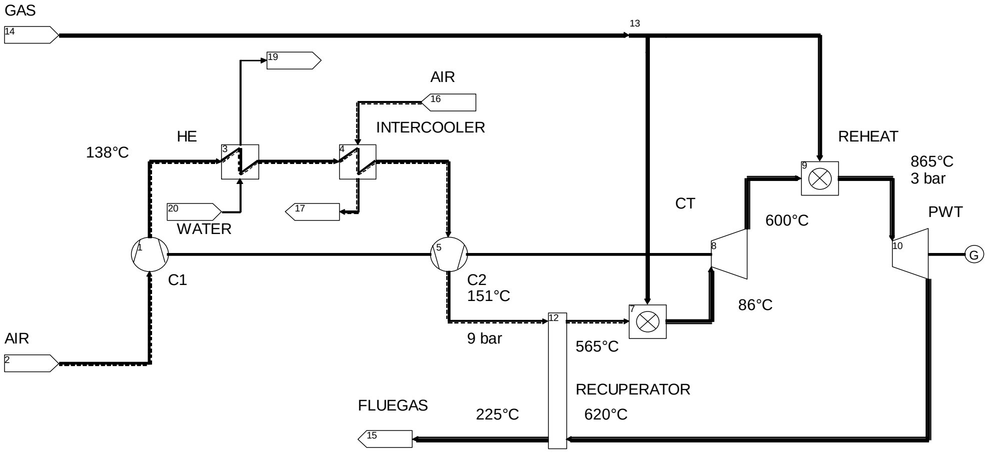

Figure 2. Process scheme of heron gas turbine

TABLE I. EXERGY LOSS IN A COMBUSTION CHAMBER OF A GAS TURBINE

Combustion Chamber Gas Turbine				
	Air	Fuel	Flue Gas	E-Prod.
m (kg/s)	598	16	614	
p (kPa)	1500	1800	1462	
t (°C)	394	25	1200	
ex (kJ/kg)	368	39631	1103	
Ex (MW)	220	650	678	0
Exergy balance				
Ex_{in} (MW)	870			
Ex_{out} (MW)	678			
Ex_{loss} (MW)	192			
$1 - \varepsilon$ (%)	22			

2. Results and Discussions

The exergy losses in the following examples are defined in terms of effectiveness (second law efficiency):

$$1-\varepsilon = 1-\mathrm{Ex}_{\mathrm{out}} / \mathrm{Ex}_{\mathrm{in}} \qquad (1)$$

It can be called relative efficiency.

All calculation were performed using the following conditions:

- All gases are treated as non-ideal
- The combustion process is complete
- Only internal irreversibilities are accounted for. The environmental pressure and temperature are 100 kPa and 288 K, respectively.
- The molar compositions of the components, such as Ar, O_2, N_2, H_2O and CO_2, in air are 0.0092, 0.2072, 0.7724, 0.0109, 0003.

2.1 Gas turbine

Though the energy conversion in the gas turbine takes place at a rather high temperature, the internal exergy losses in the combustion chamber are still high. The system boundary is given in *Figure 1*. For a gas turbine Frame 9F, as applied in the combined cycle units of Eems (1750 MW_e, Eemshaven, the Netherlands), the exergy losses were determined. The results are given in TABLE I. The exergy losses in the combustion chamber are 22%. Older gas turbines with a lower firing temperature will show losses of 30% to 35%.

The reduction of these losses can be achieved by increasing the firing temperature. However, there are strict temperature limitations given by the material used and the production of NOx. With increasing firing temperature the NOx-production will increase. These issues have to be handled by the designer and the manufacturers of gas turbines, for example through improved cooling techniques. However, there are other possibilities to achieve much lower exergy losses. The solution is given with the application of fuel cells that take the place of the combustion chamber.

2.2 Gas turbine integrated with a fuel cell

Replacing the combustion chamber by a fuel cell improves the efficiency of energy conversion considerably.

The gas turbine has to operate under pressure and higher temperatures. For this purpose only the Molten Carbonate Fuel Cell (MCFC) and the Solid Oxide Fuel Cell (SOFC) are possible candidates. The solid oxide fuel cell for the first 100 kWe unit started to operate in Westervoort, the Netherlands, in December 1997 (Gerwen et al., 1999). A gas turbine with medium pressure ratio is the HERON-turbine. The maximum pressure is approximately 9 bar. Process calculations have been carried out for the HERON-turbine and also for the alternative concept where the burners were replaced by two SOFC fuel cells. However, two burners were installed for start-up procedures. The process scheme of the HERON-turbine is given in *Figure 2*. The system boundary is around the fuel cell.

The results of the exergy loss calculations for the two fuel cells are given in TABLE II (cell 1, high pressure) and TABLE III (cell 2, low pressure), respectively. The exergy losses for cell 1 and cell 2 are 11% and 13%, respectively. From these tables it can be concluded that the exergy losses are reduced even more than 10%. This is also obvious since the concept of the gas turbine with two SOFC integrated can achieve an electrical net efficiency of approximately 70%, which is 10% higher than the efficiency of the best combined cycle. However, large-scale application of this technology affords a substantial production cost reduction of the fuel cell. Other possibilities to reduce the exergy losses are discussed in the next example.

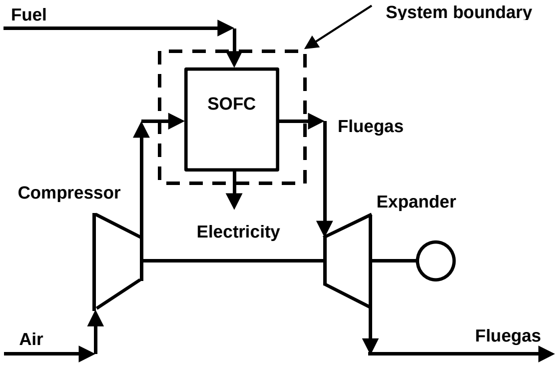

Figure 3. Integration of fuel cell in gas turbine

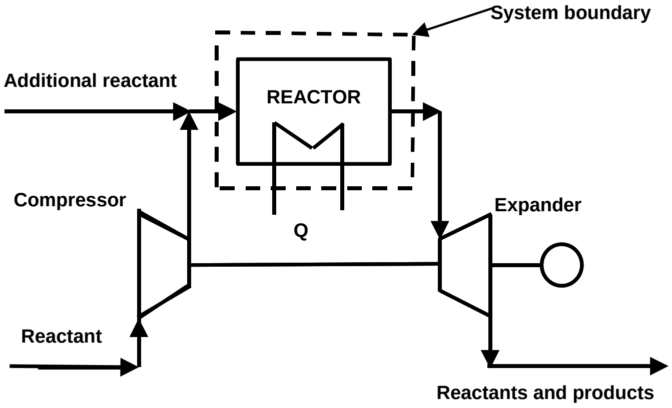

Figure 4. Integration of reactor in a gas turbine

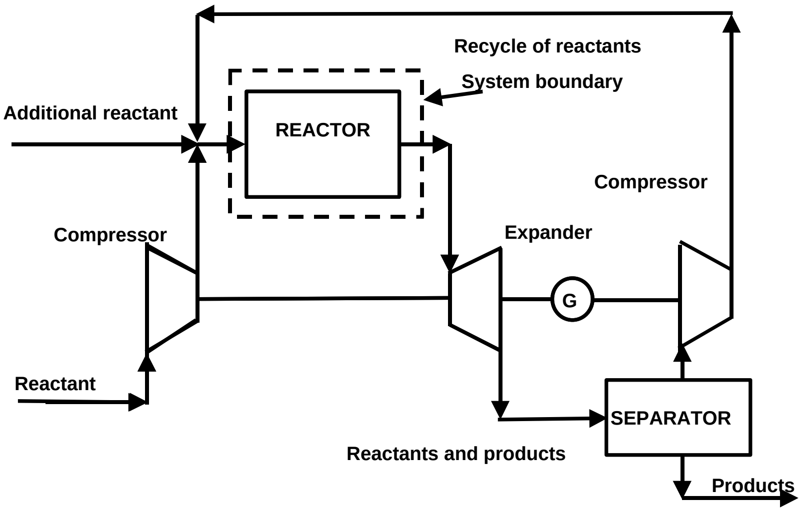

Figure 5. Process of reactor with separation and recycle loop

TABLE II EXERGY LOSS OF THE FIRST FUEL CELL (HIGH PRESSURE) INTEGRATED IN THE GAS TURBINE

Fuel Cell 1 (High Pressure) in GT				
	Air	Fuel	Flue Gas	E-Prod.
m (kg/s)	5.15	0.09	5.24	
p (kPa)	859	1255	824	
t (°C)	575	575	850	
ex (kJ/kg)	444	40475	692	
Ex (MW)	2288	3643	3626	1660
Exergy balance				
Ex_{in} (MW)	5931			
Ex_{out} (MW)	5286			
Ex_{loss} (MW)	645			
1 - ε (%)	11			

TABLE III. EXERGY LOSSES OF THE SECOND FUEL CELL (LOW PRESSURE) INTEGRATED IN THE GAS TURBINE

Fuel Cell 2 (Low Pressure) in GT				
	Air	Fuel	Flue Gas	E-Prod.
m (kg/s)	5.24	0.08	5.32	
p (kPa)	305	309	293	
t (°C)	639	575	850	
ex (kJ/kg)	429	40344	633	
Ex (MW)	2246	3227	3368	1410
Exergy balance				
Ex_{in} (MW)	5474			
Ex_{out} (MW)	4778			
Ex_{loss} (MW)	696			
1 - ε (%)	13			

TABLE IV. EXERGY LOSSES IN THE CHEMICAL REACTOR INTEGRATED IN THE GAS TURBINE

Chemical Reactor				
	Reactor in	Reactor out	Heat duty	E-Prod
m (kg/s)	1174	1174		
h (kJ/kg)	38798	36132		
p (kPa)	1000	1000		
t (°C)	175	800		
ex (kJ/kg)	35517	32408		
Ex (MW)	41713	38062	3131	0
Exergy balance				
Ex_{in} (MW)	41713			
Ex_{out} (MW)	40034			
Ex_{loss} (MW)	1679			
1 - ε (%)	4			
Carnot factor heat duty	0.63			

2.3 Gas turbine integrated with a chemical reactor

This system is compared for the synthesis of ammonia, ethene and methanol.

A simple scheme of the integration of a chemical reactor including the system boundaries is shown in *Figure 4* (Janssen et al., 1997). The reactant is fed after compression with a second reactant (for example, oxygen) to a chemical reactor (see *Figure 5*). The product and the not converted reactants expand through the expander producing electricity. With a separator the product has to be separated from the mixture and the remaining reactants have to be recycled with a recycle compressor to the inlet of the reactor. For a successful integration of a chemical reactor in a gas turbine, some preliminary conditions have to be fulfilled. The first one is that the reaction in the reactor has to be exothermic. Thus heat will be produced in the reactor and the temperature of the product gas will also increase. The heat of the product will be used to generate electricity during the expansion process. A second condition is that the product yield is sufficient, at least 15% or even 20% at elevated pressures. Otherwise the recycle loop will use too much energy for recompression.

The reactor types for the different processes will not be discussed in this paper.

Ethene

The synthesis of ethene by catalytic oxidative coupling of methane is a relative new process that has not yet been realized in the industry because of the low conversion of about 25% (Ito and Lunsford, 1985). The process consists of two feed streams, air and methane, which are combined just before entering the adiabatic reactor. The process is best carried out at pressures below 1 bar, but is also possible at 10 bars. For the calculation, a conversion rate of 25% was considered. With the process conditions considered in the analysis, the exergy analysis is carried out with the given system boundaries. The results are given in TABLE IV. In this concept the relative internal exergy losses due to the use of the chemical reactor are reduced to approximately 4%.

Ammonia

Ammonia is one of the major bulk chemicals in the world. The production takes place at a pressure of 200 bars and a temperature of 300°C. The reaction usually takes place over a catalyst in a double or multiple bed quench reactor. This is done because the product stream has to be cooled since the reaction is highly exothermic and the equilibrium lies unfavorably at higher temperatures. Conversions are typically low (20% - 30%), so after separation of NH_3 by condensation in a flash drum, the remaining gas is recycled. Using the discussed concept as an alternative, a direct conversion of the energy was considered in the production of ammonia. From detailed analysis the result was that the recycle stream should be 91% of the total feed. Due to the high process pressure, a huge amount of compression work is necessary and therefore the process is not suitable for direct conversion of the reaction heat into electricity.

Methanol

The oldest process for the industrial production of methanol is the dry distillation of wood. Methanol is currently produced on an industrial scale exclusively by catalytic conversion of synthesis gas. This process can be subdivided into three steps: production of synthesis gas, synthesis of methanol and processing of crude methanol. The synthesis of methanol is an exothermic reaction and takes place at pressures of approximately 50-100 bars and 200-300°C. The proposed concept of direct conversion is used to analyze as an alternative for the conventional process of methanol production with heat recovery for a steam cycle. In this process the recycle stream is also large, namely 90% of the total feed to the reactor. Using the complete expansion will cause less separation and will cause a considerable amount of recycle of the product. The process is not suitable for direct conversion of the reaction heat into electricity.

Integration of the direct energy conversion in chemical processes

In this paper only the chemical reactor is considered. The syntheses discussed are not selective. The not converted part of the feed has to be separated from the product and recycled to the feed. Besides, the temperature in the reactor should be limited so the extracted heat has to be used in the steam/water cycle. Looking at the exhaust stream of the reactor, there are two possibilities for using the energy in this stream. First, cooling the stream to produce steam and then the expansion through an expander, or first the expansion and after that the cooling to produce steam.

The conditions for an optimal separation also have to be investigated. Caused by the high recycle loop, the exergy losses of the reactor can better be considered as a loss of the effective flow. Part of the stream that has no contribution to the reactions in the chemical reactor should not be considered. In that case the exergy losses of the considered example increase to approximately 20%.

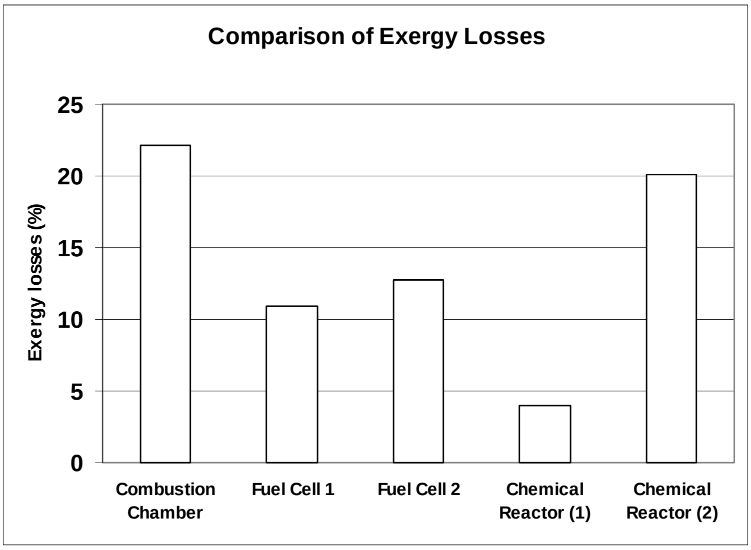

Figure 6. Comparison of relative exergy losses of the considered energy conversion processes

2.4 Comparison of the different processes of energy conversion

In *Figure 6* the relative exergy losses of the different options of energy conversion are compared with the given boundary conditions. In a modern gas turbine the exergy losses in the combustion chamber are approximately 22%. The exergy losses in the fuel cell (SOFC) are 50% lower. The lowest exergy losses can be achieved with a chemical reactor between a compressor and an expander based on the definition of Eq. (1). However, in this case a large amount of feed goes through the reactor without participating on the process (chemical conversion) and much compression work is needed for the recycle loop. If the exergy definition is based on the reactants that react in the reactor, then the losses are approximately 20%.

3. Conclusions

As has been shown with exergy analysis, it is possible to point to the main exergy losses in the process. Thus it is concluded that the exergy losses in the combustion chamber of a modern gas turbine are approximately 22%. With the integration of a fuel cell in the gas turbine, where a SOFC is used instead of the combustion chamber, the exergy losses can be reduced by 10%. With the integration of a chemical reactor, placed between the compressor and the expander, an even higher reduction of the exergy losses is possible. However, the exergy losses strongly depend on the definition of the exergy losses. To evaluate the benefits of the concept of integrating chemical reactors in the gas turbine, the complete process has to be considered, including the optimization of the energy generation.

With the help of modern process simulators, the process engineer has a tool for analyzing new ideas and concepts and for calculating the exergy losses. However, the simulators will not provide the engineer with the new ideas to find new optimal solutions.

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