Systematic Evaluation of Efficiency Improvement Options for sCO_2 Brayton Cycles

Mathias Penkuhn[1*], George Tsatsaronis[2]

[1] Technische Universität Berlin, Institute for Energy Engineering
Berlin, Germany
mathias.penkuhn@tu-berlin.de

[2] Technische Universität Berlin, Institute for Energy Engineering
Berlin, Germany
georgios.tsatsaronis@tu-berlin.de

* Corresponding Author

ABSTRACT

Nonconventional working fluids have the potential to improve conventional, high-temperature thermal power generation processes and to enable the efficient exploitation of low-temperature heat resources. In particular, supercritical CO_2 (sCO_2) based power cycles have gained increased attention because of their potential to offer increased cycle efficiency, improved process economics, and operational flexibility. Various simple and more complex cycle layouts have been suggested and analyzed with the objective of improving cycle efficiency. However, with respect to potential further development and commercialization, the right balance between cycle efficiency, design complexity, and economics is required.

The present study analyzes possible pathways to improve the design of generic sCO_2 Brayton cycles for power generation based on a structured pattern known from conventional water-steam cycles. Starting from a simple cycle design, different options such as preheating by internal recuperation, intercooled compression, reheating, and split-recompression are investigated and their impacts on cycle efficiency and complexity are evaluated. The application of an exergy analysis for each design provides the possibility to identify the location and magnitude of thermodynamic inefficiencies for each design option. With the use of a complexity measure, the offset between efficiency improvement and the increase in system size and complexity can be quantified in the absence of economic data. The combined results thus provide a possibility to identify and evaluate promising options in system design for sCO_2 cycles.

1. INTRODUCTION

The increasing demand and significant future changes in the availability and use of primary energy resources (Birol et al., 2018) drives the development of new technologies for an efficient conversion and application of energy. In particular, the industrial and power generation sectors are facing a fast changing and highly competitive economic environment which is likely to promote innovation in technologies that enable the use of energy resources where an exploitation is currently economically not feasible. Regarding applications for power generation, high-efficiency, low-emission technologies are going to satisfy the demands that address the requirements that arise among different conflicting priorities like environmental regulations, economic competitiveness, and operational flexibility (Beér, 2007).

New and alternative technologies in power generation (Zhu, 2015) are likely to enter the market in areas where substantial economical and operational advantages are offered compared to well-established technologies like water-steam cycles and gas turbines. The application of non-conventional working fluids (Chen et al., 2010), comprising different inorganic and organic substances, provides the possibility to significantly improve the efficiency of thermal power generation technologies therefore addressing above-mentioned requirements.

In the field of non-conventional working fluids for application in power generation, the use of supercritical CO_2 (sCO_2) in direct and indirect cycles gained wide-spread attention in the last years (Brun et al., 2017). Based on the pioneering works in the late 1960s, the interest in sCO_2 recurred in the early 2000s (Crespi et al., 2017b). Significant research and development activity has identified potential applications of sCO_2 in direct and indirect power cycles using fossil, nuclear, and renewable resources and even for waste heat recovery. Studies show that compared to conventional working-fluids, sCO_2-based power cycles have the potential to achieve a higher efficiency and flexibility as well as lower capital cost and smaller plant footprint (Brun et al., 2017; Crespi et al., 2017b). However, despite substantial research activity and progress that has been made in the design of sCO_2 power cycles, several important questions, e.g., the economic feasibility, remain unanswered. With only limited data being publicly available (Ho et al., 2016; Carlson et al., 2017; Wright et al., 2016), it is currently not possible to determine which power cycle layouts are promising and which improvement options have to be developed in order to achieve high-efficiency power generation and economic feasibility regarding the potential of long-term commercialization.

In the context of a general conflict between thermodynamic and economic performance, the present study on indirect (closed-cycle) sCO_2 power cycles addresses the resulting trade-off by using a complexity measure to compare different layouts and improvement options on an overall level. Furthermore, exergy analyses are used to compare the different designs on the overall cycle and on the component level, whereas sensitivity analyses are employed to further explore the design space.

2. SYSTEM DESCRIPTION

Based on their properties, most working fluids share a basic power cycle layout (Haywood, 1991). Furthermore, improvement options for power cycles through, e.g., recuperation, reheating, intercooling, and split-recompression are well-known.

2.1 Cycle Design

Different sCO_2 power cycle configurations are found in literature, with the most common designs having been compiled by Crespi et al. (2017b). The most common features of a sCO_2 power cycle are a single train consisting of compressor, turbine, heat exchangers for heat supply and removal, and, notably, a recuperator because of the particular thermodynamic properties of CO_2 at high pressures and temperatures (Brun et al., 2017).

The different power cycle designs showing the basic cycle with internal recuperation (1) and the different improvement options are shown in Figure 1. Possible improvement options include designs that incorporate reheating (2), intercooling (3), and split-recompression (4) which is also simply known as recompression. Furthermore, it is possible to combine these different options for further improvement (5-8). The actual flowsheet designs are depicted by the superstructure in Figure 2 that shows all possible combinations based on Figure 1.

2.2 Cycle Parameters and Simulation

Within the literature a wide variety of different sCO_2 power cycle parameterizations have been proposed, simulated, and analyzed. It is therefore necessary, to use established best practice guidelines (Weiland and Thimsen, 2016; Crespi et al., 2017a) that represent proper assumptions providing the possibility to obtain results that can be used for benchmarking and comparing different designs.

The sCO_2 power cycle designs shown in Figure 2 are implemented in AspenPlus using the REFPROP library (Lemmon et al., 2013) for the calculation of thermodynamic properties. For the purpose of comparison, the environmental conditions are set to a temperature of 15 °C and 1.01325 bar which are also used for the calculation of the physical exergy of each process stream using a FORTRAN subroutine. The parameters that were used for the parameterization of a reference case study are given in Table 1. For the supply and removal of heat to and from cycles, generic heat sources and sinks are used.

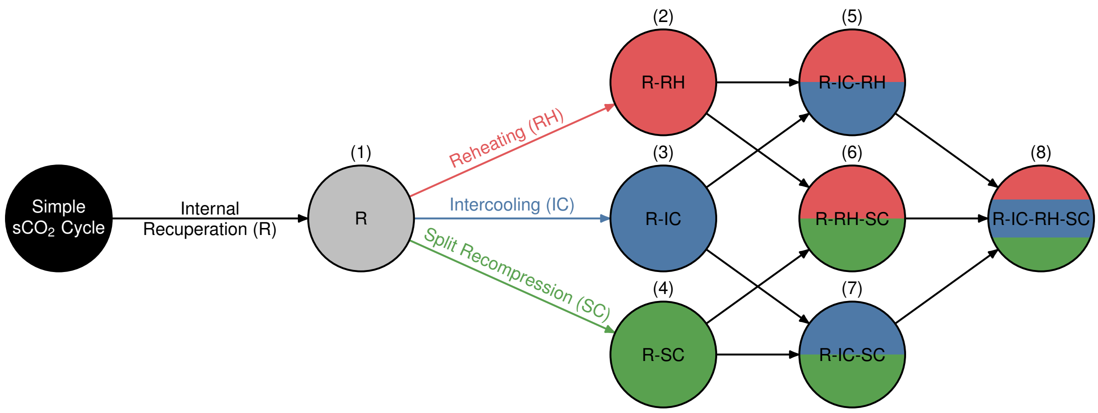


Figure 1: Structual improvement options for sCO_2 Brayton cycles

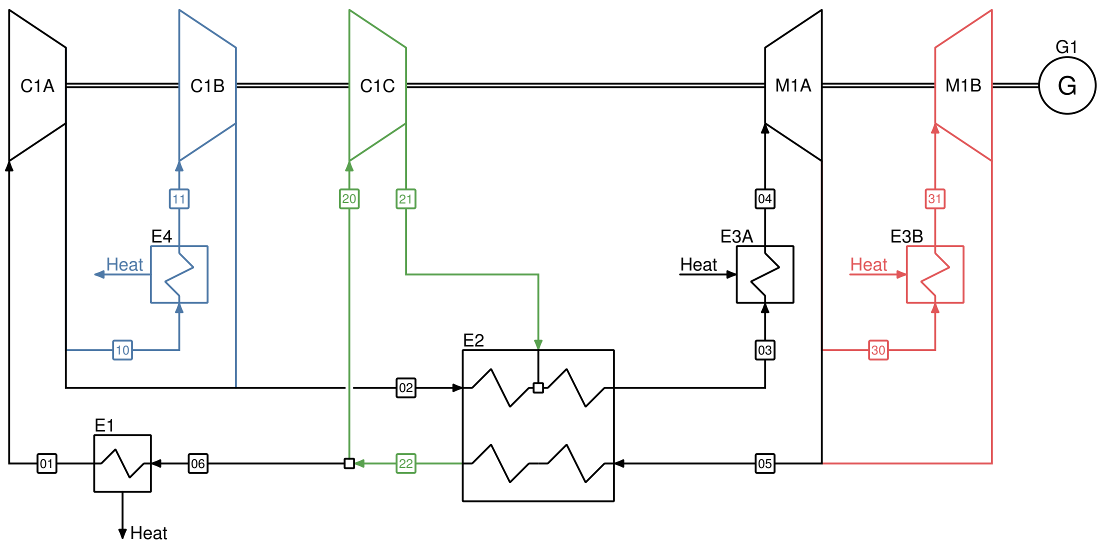


Figure 2: Flowsheet with superstructure showing the layout and connections of different improvement options for an sCO_2 power cycle

3. METHODOLOGY

In order to obtain comparable information on the different power cycle designs and their performance, a complexity measure function is introduced, and the thermodynamic efficiency is quantified using thermal (energetic) and exergetic efficiencies. Furthermore, a sensitivity study varying the most important cycle parameters is employed.

3.1 System Complexity Quantification

In order to quantify the complexity of a process system, Koolen (2002) suggests a simple complexity function C that is derived from the number of different influential items C_i combined with a weighting factor c_i describing the importance of different aspects.

$$C = \sum_{i}^{n} c_i C_i \tag{1}$$

Koolen (2002) further suggests to count the different process items, e.g., the number of components, material and energy streams, measurements, and control set points and loops.

In the present case, Equation (1) can be applied by taking into account only the number of the different cycle components and the connecting material and energy streams which are available from a flowsheet

Table 1: Simulation parameters and ranges used for the analysis and sensitivity study of the sCO_2 power cycles based on literature data for benchmarking given by Weiland and Thimsen (2016), and Crespi et al. (2017a)

Unit ID	Parameter	Value	Range
M1 A/B	Turbine Inlet Temperature	600 °C	600-700 °C
M1 A	Turbine Inlet Pressure	250 bar	200-300 bar
M1 A/B	Turbine Isentropic Efficiency	90 %	
M1 A/B	Turbine Mechanical Efficiency	99 %	
C1 A/B/C	Compressor Inlet Pressure	75 bar	70-80 bar
C1 A	Precompressor Inlet Pressure	50 bar	40-60 bar
C1 A/B/C	Compressor Isentropic Efficiency	85 %	
C1 A/B/C	Compressor Mechanical Efficiency	99 %	
G1	Electric Generator Efficiency	99 %	
E1, E4	Cooler Outlet Temperature	32 °C	32-40 °C
E1, E4	Cooler Pressure Drop	15 kPa	
E2	Maximum Recuperator Cold Side Outlet Temperature	400 °C	
E2	Maximum Recuperator Effectiveness	0.9	
E2	Recuperator Hot-Side Pressure Drop	280 kPa	
E2	Recuperator Cold-Side Pressure Drop	140 kPa	
E3 A/B	Primary Heat Exchanger Pressure Drop	200 kPa	
E3 A/B	Primary Heat Exchanger Minimum Temperature Difference	50 K	

characterizing the system structure. Based on the flowsheet in Figure 2, the complexity takes into account the number of different components, the material and energy streams, and the associated weighting factors.

$$C = c_{\text{Comp}}N_{\text{Comp}} + c_{\text{HE}}N_{\text{HE}} + c_{\text{Turb}}N_{\text{Turb}} + c_{\text{Gen}}N_{\text{Gen}} + c_{\text{S}}N_{\text{S}} \tag{2}$$

Furthermore, if all components and streams are accounted for by a weighting factor of 1, e.g., in case of a simple scoping analysis, the system complexity becomes the sum of all available components (C), and material and energy streams (S).

$$C = N_{\text{C}} + N_{\text{S}} \tag{3}$$

Such a complexity factor, in its different formulations, can be used to investigate and quantify the influence of changing the system structure of a process system if no cost data is available. Experience suggests that it is very likely that more complex systems are also more expensive in terms of investment cost.

3.2 Thermodynamic System Analysis

Based on the results of the AspenPlus simulations, the thermal (energetic) efficiency η (Haywood, 1991) can generally be used to characterize and compare different power cycles. It is defined as the ratio of net power delivered to heat supplied.

$$\eta = \frac{\dot{W}_{\text{net}}}{\dot{Q}_{\text{supply}}} \tag{4}$$

Taking into account that only a small subset of information is obtained by a conventional energy-based power cycle analysis, an exergy analysis (Tsatsaronis, 1999) provides more detailed information on the location and quantity of thermodynamic inefficiencies, and further gives the possibility to compare the performance of different cycles from an unbiased point of view.

With the process operating at steady-state, the exergy balance (Bejan et al., 1996) of each component is used to calculate its exergy destruction $\dot{E}_{\text{D},k}$. Furthermore, within each component, the conversion of energy and exergy can be assigned to terms representing exergy rates of fuel $\dot{E}_{\text{F},k}$ and product $\dot{E}_{\text{P},k}$ of which the difference is given as the exergy destruction $\dot{E}_{\text{D},k}$ (Tsatsaronis, 2007).

$$\dot{E}_{\text{D},k} = \dot{E}_{\text{F},k} - \dot{E}_{\text{P},k} \tag{5}$$

For the overall system, an additional term $\dot{E}_{\mathrm{L},k}$ is introduced to quantify exergy losses of the overall cycle to the environment.

$$\dot{E}_{\mathrm{D,cycle}} = \dot{E}_{\mathrm{F,cycle}} - \dot{E}_{\mathrm{P,cycle}} - \dot{E}_{\mathrm{L,cycle}} \tag{6}$$

Based on the respective exergy rates of fuel and product, the real thermodynamic efficiency of the overall cycle can be calculated by the exergetic efficiency ε which definition for each component is given in Bejan et al. (1996).

$$\varepsilon_k = \frac{\dot{E}_{\mathrm{P},k}}{\dot{E}_{\mathrm{F},k}} = 1 - \frac{\dot{E}_{\mathrm{D},k}}{\dot{E}_{\mathrm{F},k}} \quad \text{and} \quad \varepsilon_{\mathrm{cycle}} = \frac{\dot{E}_{\mathrm{P,cycle}}}{\dot{E}_{\mathrm{F,cycle}}} = 1 - \frac{\dot{E}_{\mathrm{D,cycle}} + \dot{E}_{\mathrm{L,cycle}}}{\dot{E}_{\mathrm{F,cycle}}} \tag{7}$$

3.3 Sensitivity Analysis

A sensitivity analysis provides additional information on the effect of the input parameters on the obtained results. In the present study, it is thus possible to identify potential limits on the efficiency of each sCO_2 power cycle design within plausible parameter ranges. For that reason, the main simulation parameters are varied according to the parameter ranges given in Table 1. A randomized latin hypercube sampling (Kleijnen, 2015) with a sampling size of 100 is used providing the potential to explore the power cycle design space, to identify possible interconnections among the different design parameters, and to account for the uncertainty in case of the weighting factors.

4. RESULTS

Based on the simulation of the different process models using the reference parameterization, a complete set of information is obtained for conducting the abovementioned analyses.

4.1 Analysis of the Reference Case Designs

The results of the analyses for the overall power cycle design are shown in Table 2. The complexity C of the different power cycle designs, simply using complexity weighting factors of 1 for a first scoping analysis, increases significantly from the simple recuperated cycle (1) to the most complex cycle (8). Based on Equation (3), it is about twice as complex as cycle (1). Furthermore, cycle (4) using split-recompression is more complex than the reheating or intercooling designs (2,3). The same holds for the combined cycle designs (5,6,7,8).

From the perspective of the thermal efficiency η of the different cycle designs, cycle Design (8) exhibits the highest thermal efficiency of 43.22 %. The second highest thermal efficiency is found for cycle Design (4) followed closely by Design (7). The least efficient design is the simple recuperated cycle (1) with a thermal efficiency of 35.67 %. A similar ranking is found in case of the exergetic efficiencies ε, however, some important information is obtained from the exergetic analyses. Even though the highest efficiency is still found for Design (8), the cycle Design (2) with reheating is found to be the least efficient which results from the requirement of additional high-temperature heat. Moreover, it is shown that the intercooling cycle designs (3,7,8) and split-recompression cycle designs (4,6,7,8), in general, show

Table 2: Results of the reference case simulations for the different cycle designs

Cycle-Design	N_{C} (–)	N_{S} (–)	C (–)	C/C_1 (–)	η (%)	$\varepsilon_{\mathrm{cycle}}$ (%)	$\dot{E}_{\mathrm{D,cycle}}/\dot{E}_{\mathrm{P,cycle}}$ (–)
(1)	6	12	18	1.00	56.00	35.67	0.7856
(2)	8	16	24	1.33	54.87	36.02	0.8225
(3)	8	16	24	1.33	58.80	36.87	0.7006
(4)	9	18	27	1.50	63.95	41.56	0.5637
(5)	10	20	30	1.67	58.72	38.02	0.7029
(6)	11	22	33	1.83	63.46	41.30	0.5758
(7)	11	22	33	1.83	64.15	41.53	0.5588
(8)	13	26	39	2.17	65.94	43.22	0.5165

Table 3: Exergy analysis results of the different cycle components for the reference case simulations

Component	E1	E2	E3	E4	C1	M1	G1
Cycle-Design	Exergy Destruction per Unit of Product Exergy $\dot{E}_{D,k}/\dot{E}_{P,cycle}$ (–)						
(1)	0.2652	0.3064	0.0834	0.0000	0.0452	0.0752	0.0101
(2)	0.2714	0.3548	0.0749	0.0000	0.0428	0.0686	0.0101
(3)	0.1545	0.2322	0.0899	0.0717	0.0579	0.0843	0.0101
(4)	0.1777	0.1701	0.0636	0.0000	0.0585	0.0836	0.0101
(5)	0.1565	0.2659	0.0760	0.0663	0.0535	0.0746	0.0101
(6)	0.1785	0.1818	0.0680	0.0000	0.0561	0.0812	0.0101
(7)	0.1107	0.1157	0.0650	0.0619	0.0885	0.1068	0.0101
(8)	0.0896	0.1375	0.0629	0.0615	0.0686	0.0864	0.0101
Cycle-Design	Exergetic Efficiency ε_k (%)						
(1)	–	80.09	95.33	–	87.49	94.80	99.00
(2)	–	80.89	95.89	–	87.49	95.17	99.00
(3)	–	77.98	94.71	–	87.11	94.54	99.00
(4)	–	90.48	95.93	–	88.64	94.80	99.00
(5)	–	78.90	95.54	–	87.12	95.02	99.00
(6)	–	89.86	95.68	–	88.48	94.85	99.00
(7)	–	91.54	95.83	–	89.43	94.54	99.00
(8)	–	90.01	95.85	–	88.59	94.91	99.00

favorable results as indicated by the ranking of exergetic efficiencies and comparing the exergy rate of destruction to exergy rate of product ratios. In contrast, the cycle designs incorporating the reheating improvement options show less favorable results.

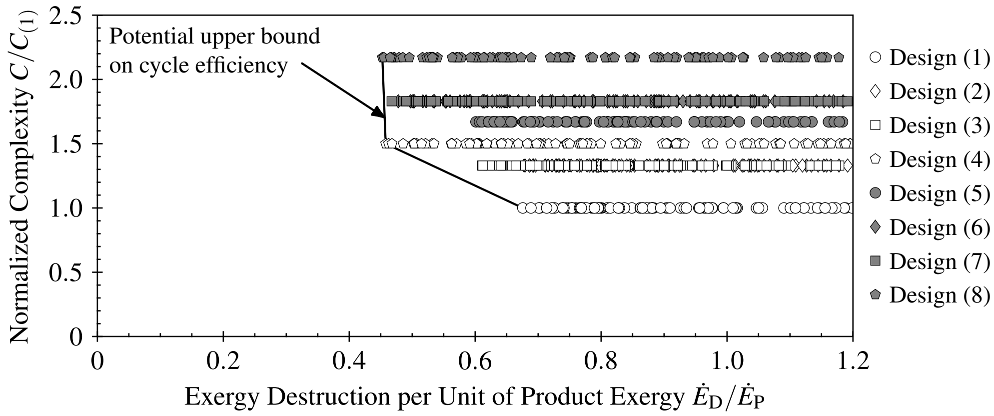
This is further emphasized by the results of the exergy analyses on the cycle component level given in Table 3. By grouping the different components according to their function, it can be seen that each improvement options reduces the specific exergy destruction in one component at the expense of increasing the specific exergy destruction in other components. As for the present results, the incorporation of an intercooled compression or split-recompression highly reduces the specific exergy destruction within the cooler E1 and the recuperator E2 which is also beneficial with respect to the more complex designs. Furthermore, intercooling and split-recompression also compensate for the disadvantages introduced by the reheating option.

Based on the results of the reference design cases, it is concluded that all improvement options improve indeed the cycle efficiency. Based on the results of the different cycle designs, it is shown that the split-compression and intercooling options can be regarded as the most beneficial ones. Because of the general high temperature, low pressure ratio, and high recuperation characteristics of an sCO_2 power cycle, the reheating option only provides a limited potential.

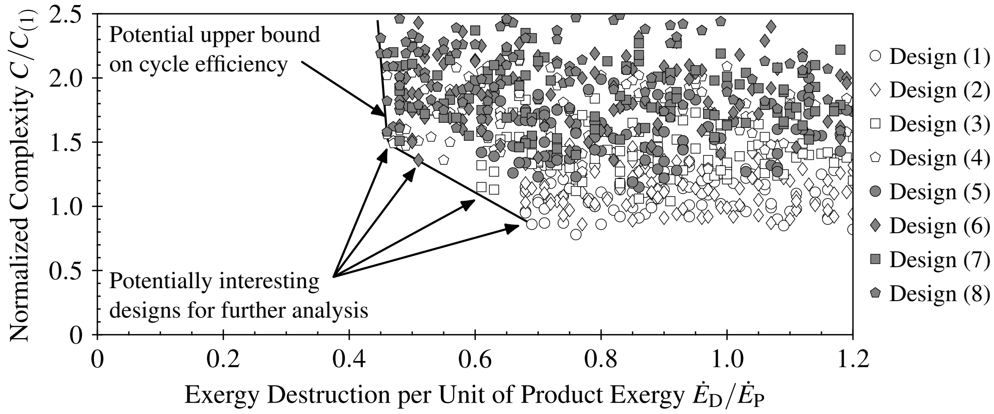
4.2 Sensitivity Analysis

The results of the randomized sensitivity analyses changing different cycle parameters simultaneously within the defined parameter ranges are shown in Figure 3. For the reference case study, with all weighting factors set to 1, it is found in Figure 3a that the cycle efficiency varies significantly within the given parameter ranges, exhibiting the highest efficiencies in case of the high pressure and high temperature parameterization. Furthermore, analyzing the sensitivity of the weighting factors, as shown in Figure 3b, it is found that the potential upper bound on cycle efficiency is only slightly depended on the weighting factors and some cycle designs form clusters of similar efficiency and complexity.

The most interesting result of the sensitivity analyses is the relationship between the cycle complexity and the maximum obtainable efficiency. The well-known Pareto frontier as found in thermoeconomic analyses depicting the conflicting objectives of favorable economics and high thermal efficiency.



(a) Sensitivity of cycle efficiency with all weighting factors set to 1.



(b) Sensitivity of normalized cycle complexity with varying weighting factors.

Figure 3: Sensitivity plots showing the dependence of cycle complexity and the exergy rate of destruction per exergy rate of product ratio.

5. CONCLUSIONS

The present study has analyzed the potential of using a complexity measure for evaluating the potential of different improvement options in case of closed-cycle sCO_2 power cycles. The results are promising with respect to the simplicity and robustness of the used complexity measure. It is concluded that the combination of a simple complexity function and an exergy analysis for the evaluation of process improvement options offers tangible results in cases where no reliable economic data for assessing the different options is available. Future work is going to concentrate on improving the level of detail of the complexity measure, e.g., by incorporating and quantifying design changes within different components as design parameters are modified.

NOMENCLATURE

C	Design complexity	(–)
$\dot{E}$	Exergy rate	(MW)
N	Quantity	(–)
$\dot{Q}$	Heat stream	(MW)
$\dot{W}$	Power	(MW)
c	Weight factor	(–)
ε	Exergetic Efficiency	(–)
η	Thermal Efficiency	(–)

Subscript

C	Components
D	Destruction
F	Fuel
L	Loss
P	Product
S	Material and energy streams

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