

Application of exergy analysis for evaluation of CO₂ emission from operation of steam power unit

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Abstract Szargut proposed the algorithm for determination of the influence of irreversibility of components of thermal process on the emission of CO₂ [6]. In the presented paper, basing on Szargut's proposal, the example of analysis of influence of operational parameters of coal fired power plant on the local increase of CO₂ emission is presented. The influence of operational parameters on the local exergy losses appearing in components of investigated power plant are simulating making use of the semi-empirical model of power plant.

Keywords: Exergy; Exergy losses, CO₂ emission

Nomenclature

\dot{B}	–	exergy flow, kW
c	–	mass fraction of c element in fuel
\dot{m}	–	mass flow, kg/s
M	–	molar mass, kg/kmol
p	–	emission, kg CO ₂ /kW
Wd	–	lower heating value, kJ/kg
Wg	–	higher heating value, kJ/kg

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Greek symbols

- α – ratio of chemical exergy to chemical energy (LHV)
- β – ratio of chemical exergy to chemical energy (HHV)
- δ – losses

Subscripts

- F – fuel
- P – product
- int – internal
- ext – external
- B – exergy

1 Introduction

According to 3×20 package, it is planned to lower the greenhouse gases emission (including CO₂) by 20% in relation to emission level from 1990 year. Reduction of greenhouse gases can be achieved by improvement of thermal processes, energetic and exergetic efficiency or by CO₂ sequestration or oxy-combustion. The second mentioned group of measures is however power-consuming and should be only applied after running out of capability of thermal processes perfection improvement. It is known that the CO₂ emission from combustion processes is proportional to fuel consumption. Minimal fuel consumption would occur during ideal process characterized by lack of exergy losses (both internal and external). Minimal fuel energy consumption is always associated with unavoidable CO₂ emission. Each increase of internal or external exergy losses in considered component of energy system leads to increase of component's exergetic cost and in the end to increase of overall fuel consumption and CO₂ emission above earlier defined level of unavoidable emission. Having a mathematical model of process which allow to connect operational parameters with local exergy losses or local exergetic cost it is possible to investigate the influence of thermodynamic perfection of these components on overall emission in the considered system. Such analysis allow to detect places which are especially responsible for the local increase of CO₂ emission. In the present work methodology to investigate the influence of operational parameters on local exergetic cost has been presented.

2 Application of exergy analysis to determine the local increase of CO₂ emission

Due to the second law of thermodynamics real processes are nonreversible. This means that each real process is more or less responsible for degradation of energy resources [4,5,7,8]. Considering the process that is supplying with the stream of resources exergy \dot{B}_F (fuel) and within this process the flow \dot{B}_P (product) of useful of exergy is producing, the exergy balance [4,5] can be simply formulated as follows:

$$\dot{B}_F = \dot{B}_P + \delta\dot{B} ,$$

where $\delta\dot{B}$ means the sum of internal and external losses.

The higher the exergy losses $\delta\dot{B}$ the higher is the flow of fuel \dot{B}_F by keeping the constant production \dot{B}_P . The minimum consumption of flow of fuel \dot{B}_F could be obtained in the ideal reversible process [6]. It means that the following conditions are fulfilled;

$$\delta\dot{B} = \delta\dot{B}_{int} + \delta\dot{B}_{ext} = 0 \quad (1)$$

or

$$\dot{B}_F = \dot{B}_P , \quad (2)$$

where $\delta\dot{B}_{int}$ and $\delta\dot{B}_{ext}$ denote the internal and external exergy losses.

Fulfillment of the conditions (1) and (2) ensures the minimum flow of required exergetic fuel for the considered process [6]:

$$\dot{m}_F \min b_F = \dot{B}_P . \quad (3)$$

For such conditions the exergetic efficiency yields:

$$\eta_B = \frac{\dot{B}_P}{\dot{B}_F} = 1 , \quad (4)$$

as well as the local unit exergetic cost is:

$$k_B = \frac{\dot{B}_F}{\dot{B}_P} = \frac{1}{\eta_B} = 1 . \quad (5)$$

Szargut proposed that the emission corresponding to the hypothetical reversible process fulfilling the conditions (1) or (2) should be treated as

a minimum unavoidable emission [6]. Such emission can be expressed as follows:

$$p_{\text{CO}_2} = \frac{\dot{m}_{F \min}}{\dot{B}_P} c \frac{M_{\text{CO}_2}}{M_C}, \quad (6)$$

where:

- $\dot{m}_{F \min}$ – hypothetical minimum flow the exergy of fuel feeding the analyzed energy system,
- c – mass fraction of c element in fuel,
- M_{CO_2}, M_C – molar mass of CO_2 and C -element.

The chemical exergy of fuel b_F appearing in Eq.(3) can be expressed by means of LHV or HHV:

$$b_F = \alpha W_d = \beta W_g, \quad (7)$$

where:

- W_d – Lower heating value (LHV),
- W_g – Higher heating value (HHV),
- α, β – ratio of chemical exergy to chemical energy expressed as LHV or HHV [4,5].

Introducing (3) and (7) into (6) the unavoidable emission proposed by Szargut [6] can be expressed as follows [4]:

$$p_{\text{CO}_2} = \frac{c}{\alpha W_d} \frac{M_{\text{CO}_2}}{M_C}. \quad (8)$$

In real process the conditions (4) and (5) are not fulfilled. Each component of analyzed system is characterized by local exergy losses δB_i comprising both internal as well as external exergy losses. The local exergy losses lead to the increase of exergy flow of fuel appearing in the balance control volume of analyzed system. The relation between local exergy losses δB_i and the increase of flow of fuel $\Delta \dot{m}_i$ delivered to the system and resulting from irreversibilities of i -th component can be expressed as follows:

$$\frac{\delta \dot{B}_i}{\dot{B}_P} = \frac{\Delta \dot{m}_{F,i} b_F}{\dot{B}_P}, \quad (9)$$

assuming the constant production of the whole system.

Basing on the condition (9) the increase of emission of CO_2 resulting from irreversibility of i -th component of the system can be expressed:

$$\Delta p_{\text{CO}_2} = \frac{\Delta \dot{m}_{F,i}}{\dot{B}_P} \frac{c}{M_C} M_{\text{CO}_2} = \frac{\delta \dot{B}_i}{\dot{B}_P} \frac{1}{b_F} \frac{c}{M_C} M_{\text{CO}_2}, \quad (10)$$

$$\Delta p_{\text{CO}_2} = \frac{\delta \dot{B}_i}{\dot{B}_P} \frac{1}{\alpha W_d} \frac{c}{M_C} M_{\text{CO}_2} . \quad (11)$$

Introducing (8) into (11) yields:

$$\Delta p_{\text{CO}_2} = \frac{\delta \dot{B}_i}{\dot{B}_P} p_{\text{CO}_2} . \quad (12)$$

And the total system CO₂ emission can be evaluated as:

$$p_{\text{CO}_2, \text{tot}} = p_{\text{CO}_2} + \sum_{i=1}^n \Delta p_{\text{CO}_2, i} . \quad (13)$$

3 Model of the plant

For the simulative calculation of influence of operational parameters on exergetic cost the mathematical model of the plant has to be applied. A mathematical model can be achieved in two ways. Using the physical laws, an analytical model is formulated. Carrying out the measurements with the application of the identification methods, an empirical model is determined [3]. Development of the measuring techniques and a computer technology causes a wider application of the mathematical modelling of the processes basing on registered measurement data. The advantages of constructing models on the basis of the process identification methods prevail:

- the analytical models are impossible or extremely difficult and time-consuming to construct (for example modelling of the processes proceeding in the steam power stations),
- real-time optimisation of the process parameters.

The models obtained on the basis of the identification of the processes have some features which differ from the analytical models:

- their application is limited (can be applied in a specific range, extrapolation is the most often inadmissible),
- they do not explain physical meaning of the process,
- they are quite easy to elaborate and apply.

The mathematical models obtained as a result of the identification are used to:

- simulate and optimise the processes,
- regulate and control the objects,
- diagnose the process.

A conventional power unit is a complex energy system. Such a system comprises a boiler, turbine, condenser, regenerative heat exchangers and a cooling tower. A useful tool which identifies complex systems can be an integration of the analytical modelling techniques with the artificial intelligence techniques in a hybrid model [2]. An elaborated model of the power unit contains models of a boiler, steam-water cycle and a cooling tower. Figure 1. presents a diagram of the hybrid model of a power unit.

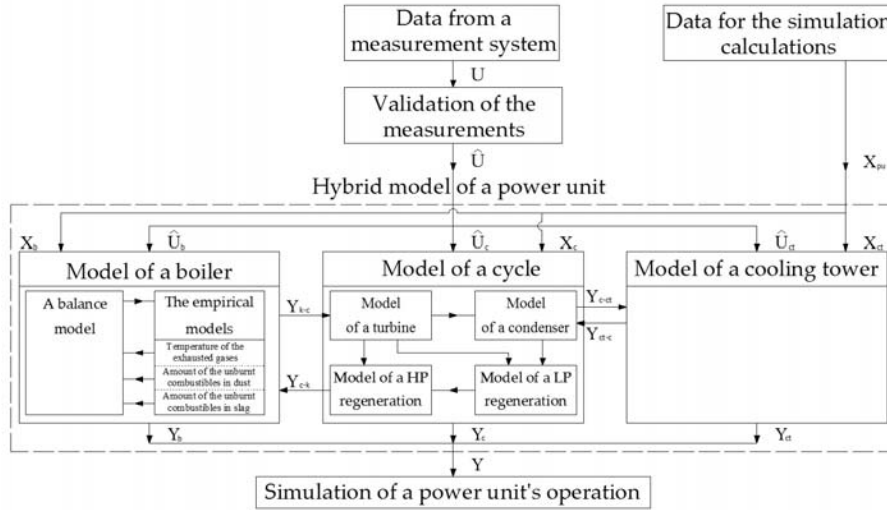


Figure 1. The diagram of the simulation model of the power unit.

The developed hybrid model of the boiler includes a balance model as well as the empirical models worked out by means of the regression and the neural network techniques. The balance model has been built basing on DIN-1942 standard [2]. The neural network model describes the dependence between the flue gas temperature and the main operating parameters of the boiler. The regression models describing a dependence of a mass fraction of unburnt carbon in slag and dust on the boiler operating parameters. These models were developed by using a step-wise regression method.

A model of a steam-water cycle comprises a model of a turbine, models of heat exchangers and a model of a condenser [1]. A model of a turbine con-

tains the mass and energy balances for each part of the turbine, the models of the steam expansion lines for each group of turbine's stages and the auxiliary empirical functions. There are methods which use a flow modelling or methods based on the steam flow capacity and efficiency of the process equations applied for the evaluation of the steam expansion line in a turbine. Combining these methods is also possible. However, the flow computations demand knowledge of a flow system geometry. Such computations are time-consuming and require the complex models. The computations on the basis of the steam flow capacity and efficiency of the process equations are simpler and less time-consuming but require the identification of empirical coefficients of the equations.

4 Results of calculations

The simulative calculations of the influence of operational parameters on exergy losses and emission of CO₂ have been carried out for the conditions of one of Polish power plants. Analyzed system is the 370 MW power unit with double steam reheat: 17.65 MPa/535 °C/535 °C. Investigated steam-water cycle includes the steam turbine, condenser (CON), high-temperature (HP1-4) and low-temperature regeneration system (LP1-4), feed water tank with deaerator (WT), auxiliary turbine and pumps (AUXT). The steam turbine consists of three sections: high-pressure part (HP), medium-pressure part (MP), low-pressure part (LP), with six bleeds (Fig. 2, streams no. 12, (18+21), 24, 27, 29, 31). The low-temperature regeneration system contains four regenerative exchangers ($i = 12-15$) which are fed with the steam form from the low- and medium-pressure part of the turbine. The high-temperature regeneration system comprises two parallel threads with two heat exchanger installed on the each. The heat exchangers HP3 ($i = 21$) and HP4 ($i = 22$) are fed with the steam from the outlet of the high-pressure part of the turbine, whereas the heat exchangers HP1 ($i = 19$) and HP2 ($i = 20$) are fed with the steam from the first bleed (12) of the medium-pressure part of the turbine. The schematic diagram of the system is presented in Fig. 2.

Table 1 presents the results of calculation of:

- exergy efficiency η_b ,
- local exergetic cost k ,
- exergy losses δb (internal and external),
- increase of CO₂ emission Δp_{CO_2} .

The results have been carried out for two states of investigated power unit:

- reference x_0 ,
- operational x_1 .

Table 1. Results of calculation of specific exergy losses and increase of CO₂ emissions.

Component i	η_b		k		Δb		Δp_{CO_2} [kg/GJ]	
	$x = x_0$	$x = x_1$	$x = x_0$	$x = x_1$	$x = x_0$	$x = x_1$	$x = x_0$	$x = x_1$
1 Boiler	0.4645	0.4646	2.1531	2.1522	0.5355	0.5354	119.1869	120.8183
2 Turbine HP	0.9293	0.9318	1.0761	1.0732	0.0083	0.0080	1.8544	1.8034
3 Turbine MP I st	0.9590	0.9586	1.0428	1.0431	0.0024	0.0025	0.5440	0.5581
4 Turbine MP II st	0.9586	0.9578	1.0432	1.0441	0.0021	0.0022	0.4723	0.4884
5 Turbine MP III st	0.9635	0.9647	1.0379	1.0365	0.0015	0.0014	0.3257	0.3198
6 Turbine LP I A st	0.9025	0.8701	1.1080	1.1492	0.0040	0.0052	0.8839	1.1821
7 Turbine LP I B st	0.9025	0.8701	1.1080	1.1492	0.0014	0.0018	0.3060	0.4050
8 Turbine LP II A st	0.9025	0.8701	1.1080	1.1492	0.0015	0.0021	0.3440	0.4649
9 Turbine LP II B st	0.9025	0.8701	1.1080	1.1492	0.0036	0.0048	0.8069	1.0869
10 Turbine LP III st	0.9025	0.8701	1.1080	1.1492	0.0034	0.0045	0.7498	1.0144
11 Condenser	0.0285	0.0286	35.1476	34.9803	0.0370	0.0378	8.2310	8.5309
12 Heat Exchanger LP1	0.9490	0.9483	1.0537	1.0545	0.0002	0.0002	0.0357	0.0369
13 Heat Exchanger LP2	0.8657	0.8656	1.1552	1.1552	0.0007	0.0007	0.1521	0.1547
14 Heat Exchanger LP3	0.8260	0.8253	1.2107	1.2117	0.0020	0.0020	0.4431	0.4531
15 Heat Exchanger LP4	0.8897	0.8910	1.1239	1.1223	0.0011	0.0010	0.2341	0.2364
16 Deaerator	0.9727	0.9583	1.0280	1.0435	0.0005	0.0008	0.1111	0.1765
17 Feed water turbo-pump	0.5574	0.5547	1.7939	1.8028	0.0058	0.0059	1.2850	1.3232
18 Turbopump's condenser	0.0221	0.0221	45.2872	45.2872	0.0027	0.0027	0.5954	0.6082
19 Heat Exchanger HP1	0.8929	0.8928	1.1199	1.1201	0.0008	0.0008	0.1755	0.1800
20 Heat Exchanger HP2	0.8896	0.8895	1.1240	1.1242	0.0008	0.0008	0.1755	0.1801
21 Heat Exchanger HP3	0.9296	0.9291	1.0758	1.0763	0.0009	0.0009	0.1903	0.1960
22 Heat Exchanger HP4	0.9298	0.9293	1.0756	1.0760	0.0009	0.0009	0.1982	0.2039
23 Generator	0.9780	0.9780	1.0225	1.0225	0.0084	0.0083	1.8753	1.8753
33 Feed water mixer	0.9995	0.9995	1.0005	1.0005	0.0000	0.0000	0.0099	0.0101
System	0.3746	0.3694	2.6696	2.7070	0.6254	0.6306	139.1860	142.3067
Unavoidable emission							83.3666	83.3666
Total emission							222.5526	225.6733

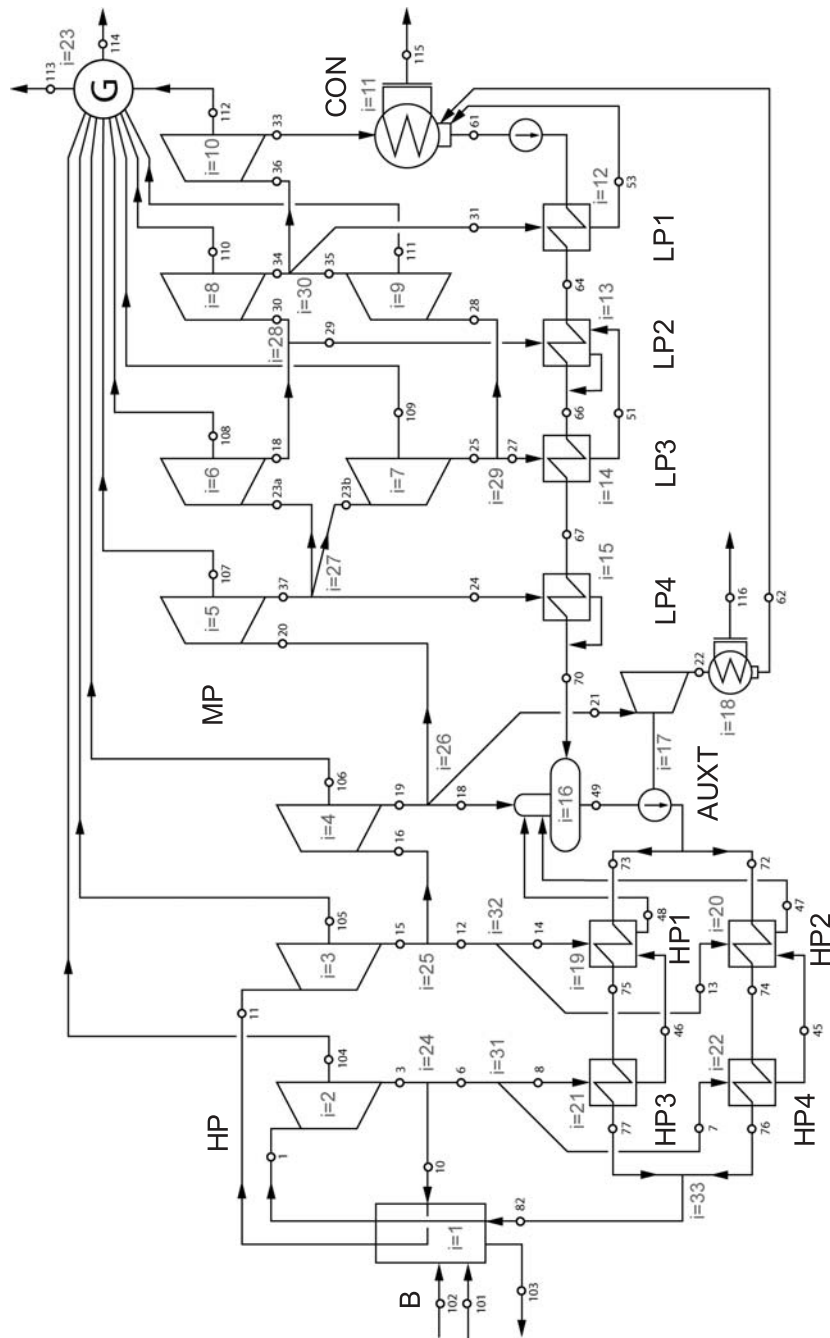


Figure 2. Schematic diagram of analyzed power plan.

The difference between states x_0 and x_1 is caused by the increase of the pressure in condenser by $\Delta p = 0.2$ kPa. The flows of exergy \dot{B}_j in each characteristic point presented in Fig. 2 have been evaluated using the simulator described in Section 2.

The obtained results show, first of all, that in the investigated system the boiler and condenser are characterized by the lowest exergy η_b and local exergetic cost k . The boiler is responsible for the greatest exergy destruction and for this reason is the main source of the increase of emission. The increase of emission Δp_{CO_2} caused by the boiler as well as that one caused by the all components are greater than the unavoidable emission. Among the components of steam-water cycle the highest increase of CO₂ emission is due to irreversibility of condenser followed by the one of turbines and heat exchangers.

5 Summary

The authors applied the Szargut's methodology of CO₂ emission evaluation basing on exergy losses. The methodology has been introduced into the simulative hybrid model of the condensating power unit. The developed by the authors algorithm let to investigate the influence of operational parameters of each single component of power unit on increase of emission of CO₂. Using the algorithm the authors carried out example calculation for one of modern Polish power plants. Results of simulation shown that boiler is responsible for the highest increase of CO₂ emission upon the level of unavoidable emission. It is worth to stress that the increase of CO₂ emission is greater than the unavoidable one. The application of simulative hybrid model of the power unit with inclusion of Szargut's method of exergetic evaluation of CO₂ emission ensure to investigate the influence of operational parameters on the total emission of CO₂. In the presented work the example calculation have been done for two states (reference and operational), in general the proposed methodology can be applied for any sate of power unit work. Moreover it can be applied for sensitivity analysis of CO₂ emission caused by the power unit parameters changes.

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