

## THE USE OF COAL IN A THEORETICAL GAS TURBINE

### SUMMARY

*In the paper has been presented the application of the on thermodynamic analyzes and ratings oriented modeling method of power systems. Simple combustion reaction with equilibrium on the products side was taken into account. Furthermore the modeling method of simple chemical reactions has been introduced, which is based on the so-called reaction intensity coefficient, analogous to the heat exchange process intensity in a membrane apparatus. The presented discussion is an introductory investigation of the modeling of systems for the so-called clean solid fuels combustion systems, where additionally gasifying and absorption of carbon mono- and carbon dioxide are to be analyzed.*

**Keywords:** thermodynamic analysis, modeling, exergy, gas turbine

### ZASTOSOWANIE WĘGLA W TEORETYCZNEJ TURBINIE GAZOWEJ

*W artykule przedstawiono zastosowanie metody zorientowanego na analizy i oceny termodynamiczne modelowania systemów energetycznych na układ spalania węgla. Przyjęto reakcję z równowagą po stronie produktów. Ponadto przeanalizowany został sposób modelowania prostych reakcji chemicznych za pomocą wielkości, nazwanej intensywnością reakcji, analogicznie do intensywności procesu wymiany ciepła w aparacie przeponowym. Przeprowadzone rozważania są wstępem do modelowania układów tzw. czystego spalania paliw stałych, gdzie dodatkowo uwzględnia się zgazowanie oraz absorpcję tlenu i dwutlenku węgla.*

**Słowa kluczowe:** analiza termodynamiczna, modelowanie, egzergia, turbina gazowa

### 1. INTRODUCTION

Although the model of a coal fed gas turbine is not a very practical problem of an existing power utility, but it can be used in thermodynamic analyzes if it is only created in a proper way. It should be mentioned, however, that there were successful projects of turbines, in which the granulated coal has been applied as a primary fuel. The example is the Nazi-German fighter LP-13a, was designed by Alexander Lippisch, one of the world's pioneers of aviation. The most interesting part of the plane was a SÄNGER turbine propulsion that has been planned also for the Czech (in that time Protektorat Böhmen und Mähren) fighter project P.14 Škoda-Kauba. Another fuel for the engines mentioned was the coal powder suspension in crude oil that was also invented by Alexander Lippisch (e.g. [1]).

Leaving now out of discussion practical tests, the coal as a fuel can be thermodynamically analyzed in the manner that some another chosen simple fuels can be compared one with another. They are e.g. methane, hydrogen and carbon monoxide, [2] and [3]. The importance of analyzes of that kind is, the so-called clean combustion technologies has been already invented and there will be needed an appropriate thermodynamic analysis and rating methodology. The principle of this clean combustion consists in an initial coal gasifying, CO-shift (conversion) and CO<sub>2</sub>-wash out (usually absorption/desorption) and finally the combustion in a hydrogen gas turbine. Direct use of coal in a gas turbine scheme will be important for the later comparing of simple fuels and their mixes.

In the following discussion a very special attention will be paid to the modeling of chemical reactions in general, especially that of combustion and gasifying ones, because of the first rank importance of the problem. The method should agree with earlier proposals, e.g. [2–3].

### 2. THE SCHEME OF A COAL GAS TURBINE

The system of the coal fed gas turbine includes the air compression, combustion chamber, regenerative air preheating and the flue gases expansion in a turbine (Fig. 1). Every single process, which occurs in an appropriate constituent device or apparatus of a whole system, will be determined by a dimensionless parameter. Such an approach leads to the univocal meaning of every constituent process and allows then the use of the practical apparatus or device, e.g. the appropriate air compressor, combustion chamber or heat exchanger unit.

Pressure changing processes, just like air compression or expansion of flue gases in a hydrogen turbine will be determined by their polytropic efficiencies. This dimensionless parameter allows then calculating a polytropic exponent, and thus the heats and useful works exchanged with the surroundings. In the case of adiabatic compression or expansion the so-called pseudo-polytrope will be defined. The polytropic exponent is not only valid for reversible processes according to Zeuner. In general it can describe (determine) also the irreversible ones [4].

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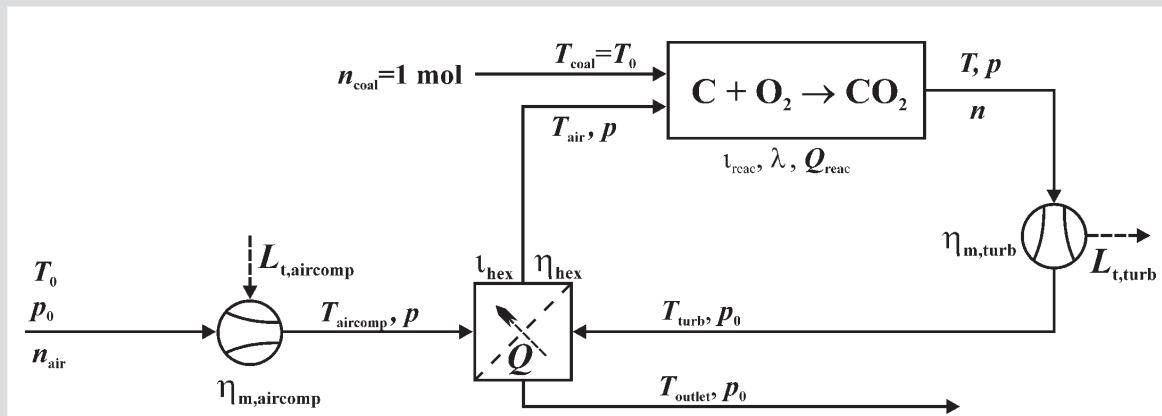


Fig. 1. The investigated system of the coal fed gas turbine

The heat exchange process in a regenerative air preheater can be univocally determined by two dimensionless parameters. The first of them is the thermal efficiency of the appropriate process that will be equal one, if no heat losses to the environment occur (the so-called adiabatic heat exchange), and equal zero, if there are only losses, and no heat will be transferred from the hot stream to the cold stream in a process. To achieve simplicity, which is a very important feature of the proposed methodology, the thermal efficiency will be usually set to one. The second dimensionless parameter is the process intensity, the numerical value of which varies from zero to one. Its meaning is, how much heat has been exchanged “in reality” in relation to the heat, that would be exchanged in the case of an equilibrium process. The last condition requires that the heat exchange area of the apparatus should be infinite.

Hence

$$l_{\text{hex}} = \frac{Q}{Q^*} = \frac{Q}{Q_{\infty}} \quad (1)$$

Finally, the combustion process will be determined by the reaction intensity parameter, which can be calculated as a quotient

$$l_{\text{reac}} = \frac{\xi}{\xi^*} \quad (2)$$

whereby  $\xi$  is an extent of a chemical reaction (according to [6], or *reactions coordinate* according to [7]; in Polish: *liczba postępu reakcji* [5]). The superscript asterisk means the state of equilibrium. Numerical values of  $\xi$  vary from zero (no reaction) to  $\xi = \xi^*$  (equilibrium). Józef Szarawara, who also defined such a parameter ([5], page 405) calls it the thermodynamic (theoretical) yield (Polish: *termodynamiczna teoretyczna wydajność reakcji*) and marks it symbolically by the Greek letter  $\eta$ . The extent of a chemical reaction in a differential form is defined by

$$d\xi = \frac{dn_A}{|v_A|} = \frac{dn_B}{|v_B|} = \frac{dn_C}{|v_C|} = \dots$$

and it can be written down in an integral form as

$$\xi = \frac{\Delta n_A}{|v_A|} = \frac{\Delta n_B}{|v_B|} = \frac{\Delta n_C}{|v_C|} = \dots$$

or

$$\begin{aligned} n_{\text{substrate}} &= n_{\text{substrate,start}} - |v_{\text{substrate}}| \cdot \xi = \\ &= n_{\text{substrate,0}} - |v_{\text{substrate}}| \cdot \xi \end{aligned} \quad (3)$$

for parent substances (substrates), and

$$\begin{aligned} n_{\text{product}} &= n_{\text{product,start}} + |v_{\text{product}}| \cdot \xi = \\ &= n_{\text{product,0}} + |v_{\text{product}}| \cdot \xi \end{aligned} \quad (4)$$

or

$$n_{\text{product}} = |v_{\text{product}}| \cdot \xi$$

for products obtained from a given chemical reaction. The last relation is valid, if no reacting substance that has been earlier marked as a reaction product does occur in the reaction mixture at the start of a process.

By presence of non-reactive substances in a process, the inerts, additionally yields

$$n_{\text{inert}} = n_{\text{inert,start}} = n_{\text{inert,0}}$$

Is then the reaction intensity parameter  $l_{\text{reac}}$  equal to zero, there is no process. Is it, however, equal to one, the equilibrium state will be reached. Equations (3)–(4) can be written down according to the definition equation (2) as follows

$$\begin{aligned} n_{\text{substrate}} &= n_{\text{substrate,start}} - |v_{\text{substrate}}| \cdot l_{\text{reac}} \cdot \xi^* = \\ &= n_{\text{substrate,0}} - |v_{\text{substrate}}| \cdot l_{\text{reac}} \cdot \xi^* \end{aligned}$$

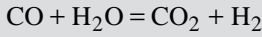
and

$$\begin{aligned} n_{\text{product}} &= n_{\text{product,start}} + |v_{\text{product}}| \cdot l_{\text{reac}} \cdot \xi^* = \\ &= n_{\text{product,0}} + |v_{\text{product}}| \cdot l_{\text{reac}} \cdot \xi^* \end{aligned}$$

After computing the value of  $\xi^*$  in an equilibrium state, the “real” extent of reaction can be determined and the appropriate quantities of reactants in a resulting reacting mixture.

### 3. AN OVERALL COMPUTING EXAMPLE FOR THE REACTION INTENSITY PARAMETER

It will be analyzed the so-called water-gas-shift reaction



that occurs at the temperature 1100 K. The intensity parameter value will be chosen to be  $\nu_{\text{reac}}=0.9$ , which is up to the process kinetics. The composition of the reacting mixture at the end of the process should be determined (Example 15.6 from [7]).

For the temperature 1100 K the reaction equilibrium constant equals to  $K=1$ , and there is

$$K = \frac{x_{\text{H}_2}^* \cdot x_{\text{CO}_2}^*}{x_{\text{CO}}^* \cdot x_{\text{H}_2\text{O}}^*}$$

If there are at the start of the process 1 kmol  $\text{H}_2\text{O}$  and 1 kmol  $\text{CO}$  (the stoichiometric mixture), then the amounts of reactants in equilibrium can be determined with help of the extent of reaction, i.e.

$$\begin{aligned} n_{\text{CO}} &= n_{\text{CO,start}} - \xi = 1 - \xi & n_{\text{H}_2\text{O}} &= n_{\text{H}_2\text{O,start}} - \xi = 1 - \xi \\ n_{\text{H}_2} &= n_{\text{H}_2,start} + \xi = \xi & n_{\text{CO}_2} &= n_{\text{CO,start}} + \xi = \xi \end{aligned}$$

and

$$\begin{aligned} n &= \sum n_i = n_{\text{CO}} + n_{\text{H}_2\text{O}} + n_{\text{H}_2} + n_{\text{CO}_2} = \\ &= \sum n_{i,\text{start}} + \xi \sum \nu_i = 1 - \xi + 1 - \xi + \xi + \xi = 2 \end{aligned}$$

where from

$$x_{\text{CO}} = \frac{n_{\text{CO}}}{n} = \frac{1-\xi}{2} \quad x_{\text{H}_2\text{O}} = \frac{n_{\text{H}_2\text{O}}}{n} = \frac{1-\xi}{2} \quad (5)$$

$$x_{\text{H}_2} = \frac{n_{\text{H}_2}}{n} = \frac{\xi}{2} \quad x_{\text{CO}_2} = \frac{n_{\text{CO}_2}}{n} = \frac{\xi}{2} \quad (6)$$

It is obvious, that in the equilibrium state yields  $\xi = \xi^*$ . It follows then

$$K = \frac{x_{\text{H}_2}^* \cdot x_{\text{CO}_2}^*}{x_{\text{CO}}^* \cdot x_{\text{H}_2\text{O}}^*} = \frac{(\xi^*)^2}{(1-\xi^*)^2} = 1 \quad (7)$$

and as a result

$$\xi^* = 0.5.$$

But according to equation (2) there is

$$\xi = \nu_{\text{reac}} \cdot \xi^* = 0.9 \cdot 0.5 = 0.45$$

and the mole fractions of reactants in the „real“ reacting mixture at the end state of the process are up to the given value of the reaction intensity parameter  $\nu_{\text{reac}}$ , taking into account process kinetics. With equations (5)–(6) they equal to

$$x_{\text{CO}} = \frac{n_{\text{CO}}}{n} = \frac{1-\xi}{2} = \frac{1-0.45}{2} = 0.275$$

$$x_{\text{H}_2\text{O}} = \frac{n_{\text{H}_2\text{O}}}{n} = \frac{1-\xi}{2} = \frac{1-0.45}{2} = 0.275$$

$$x_{\text{H}_2} = \frac{n_{\text{H}_2}}{n} = \frac{\xi}{2} = \frac{0.45}{2} = 0.225$$

$$x_{\text{CO}_2} = \frac{n_{\text{CO}_2}}{n} = \frac{\xi}{2} = \frac{0.45}{2} = 0.225.$$

In the equilibrium state these fractions were equal to

$$x_{\text{CO}}^* = \frac{n_{\text{CO}}^*}{n^*} = \frac{1-\xi^*}{2} = \frac{1-0.5}{2} = 0.250$$

$$x_{\text{H}_2\text{O}}^* = \frac{n_{\text{H}_2\text{O}}^*}{n^*} = \frac{1-\xi^*}{2} = \frac{1-0.5}{2} = 0.250$$

$$x_{\text{H}_2}^* = \frac{n_{\text{H}_2}^*}{n^*} = \frac{\xi^*}{2} = \frac{0.5}{2} = 0.250$$

$$x_{\text{CO}_2}^* = \frac{n_{\text{CO}_2}^*}{n^*} = \frac{\xi^*}{2} = \frac{0.5}{2} = 0.250.$$

The above water-gas-shift reaction, as an equimolar one ( $n = n^*$ ), gives the same already computed values for an arbitrary chosen process pressure. At the temperature e.g.  $T=1650$  K, the molar fractions, however, are different. The appropriate equilibrium constant equals to  $K=0.316$ , and according to the equation (7) the extent of the reaction at equilibrium will be  $\xi^*=0.36$ . Hence, in the equilibrium state there is:

$$x_{\text{CO}}^* = 0.320 \quad x_{\text{H}_2\text{O}}^* = 0.320 \quad x_{\text{H}_2}^* = 0.180 \quad x_{\text{CO}_2}^* = 0.180$$

and in the given „real“ process, where  $\xi = \nu_{\text{reac}} \cdot \xi^* = 0.9 \cdot 0.36 = 0.324$  yields:

$$x_{\text{CO}} = 0.338 \quad x_{\text{H}_2\text{O}} = 0.338 \quad x_{\text{H}_2} = 0.162 \quad x_{\text{CO}_2} = 0.162.$$

The method allows taking into account the special behavior of processes that do not reach their equilibrium state because of their kinetics. If there are inert substances in the reacting mixture, just like nitrogen (from the air), the amount of the last substance equals to 2 kmol for the stoichiometric water-gas-shift reaction, the equation (7) will be solved in the same manner and the resulting value of

the extent of the reaction will be either equal to  $\xi^* = 0.5$  (resp.  $\xi^* = 0.36$ ). The nitrogen molar fraction will be the same at the start of a process and at its end (equimolarity). The computed values of molar fractions will be then by assumed amount of 2 kmol nitrogen  $N_2$  (and 1 kmol CO or/and 1 kmol  $H_2O$ ) two times less.

In the case, the reacting mixture at the start is not a stoichiometric one; the computing procedure should be made in a little bit different way. If there are 1 kmol  $H_2O$  and 2 kmol CO, i.e.

$$n_{H_2O,start} = 1 \text{ kmol} \quad \text{and} \quad n_{CO,start} = 2 \text{ kmol}$$

taken to the reaction process, there are then in total 3 kmol at the start, equations (4)–(5) will be to:

$$\begin{aligned} x_{CO} &= \frac{n_{CO}}{n} = \frac{1-\xi}{3} & x_{H_2O} &= \frac{n_{H_2O}}{n} = \frac{2-\xi}{3} \\ x_{H_2} &= \frac{n_{H_2}}{n} = \frac{\xi}{3} & x_{CO_2} &= \frac{n_{CO_2}}{n} = \frac{\xi}{3} \end{aligned} \quad (8)$$

and the equation (7) for  $T = 1100$  K will be to

$$K = \frac{x_{H_2}^* \cdot x_{CO_2}^*}{x_{CO}^* \cdot x_{H_2O}^*} = \frac{(\xi^*)^2}{(1-\xi^*)(2-\xi^*)} = 1.$$

The solution for the process temperature  $T = 1100$  K gives  $\xi^* = 0.667$ . Taking into account the process intensity it follows  $\xi = \nu_{\text{reac}} \cdot \xi^* = 0.9 \cdot 0.667 = 0.6003$ , and with equations (8):

$$\begin{aligned} x_{CO} &= 0.1332 & x_{H_2O} &= 0.4666 \\ x_{H_2} &= 0.2001 & x_{CO_2} &= 0.2001 \end{aligned}$$

whereby:

$$\begin{aligned} x_{CO}^* &= 0.1110 & x_{H_2O}^* &= 0.4443 \\ x_{H_2}^* &= 0.2223 & x_{CO_2}^* &= 0.2223. \end{aligned}$$

Very similar should be proceeded in the case, in which there are some reaction products in the reacting mixture at the start of the process. If there are for example 1 kmol  $H_2O$ , 1 kmol CO and 1 kmol  $CO_2$  at the start, then in an every moment of the process there will be also:

$$\begin{aligned} x_{CO} &= \frac{n_{CO}}{n} = \frac{1-\xi}{3} & x_{H_2O} &= \frac{n_{H_2O}}{n} = \frac{1-\xi}{3} \\ x_{H_2} &= \frac{n_{H_2}}{n} = \frac{\xi}{3} & x_{CO_2} &= \frac{n_{CO_2}}{n} = \frac{1+\xi}{3} \end{aligned}$$

and the equation (7) will be to

$$K = \frac{x_{H_2}^* \cdot x_{CO_2}^*}{x_{CO}^* \cdot x_{H_2O}^*} = \frac{(1-\xi^*) \cdot \xi^*}{(1-\xi^*)(2-\xi^*)} = 1.$$

The solution gives the value of  $\xi^* = 0.333$ , and hence  $\xi = 0.9 \cdot 0.333 = 0.2997$ . Using this result there will be at the end:

$$\begin{aligned} x_{CO} &= 0.2334 & x_{H_2O} &= 0.2334 \\ x_{H_2} &= 0.0999 & x_{CO_2} &= 0.4332 \end{aligned}$$

or in the case of full equilibrium:

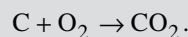
$$\begin{aligned} x_{CO}^* &= 0.2223 & x_{H_2O}^* &= 0.2223 \\ x_{H_2}^* &= 0.1110 & x_{CO_2}^* &= 0.4443. \end{aligned}$$

Herewith all the typical cases of simple chemical reactions could be discussed.

Another dimensionless parameter for the chemical reaction determining in a model is the appropriate thermal efficiency, which can be formulated in the same manner, just like it was by the heat exchanging processes. This thermal efficiency refers to the heat absorbed or created in a given chemical process.

#### 4. COAL COMBUSTION AND THE EXERGY ANALYSIS OF THE SYSTEM

According to the definition the combustion is a very rapid chemical oxidation reaction, the equilibrium of which lies at the side of products. The appropriate symbolic notation is thereafter to



The extent of this chemical reaction is in the assumed equilibrium state obviously equal to one. It simplifies significantly appropriate calculations. Thus, there is no need to give any reaction intensity parameter or it will be simply assumed  $\nu_{\text{reac}} = 1$ .

The exergy analysis of a typical gas turbine has been already presented in [8–9] by the author. For the following computations the relations from these contributions will be applied, and the same values of dimensionless parameters will be taken into account, namely:

$$\begin{aligned} \text{air compression} & \eta_{m, \text{aircomp}} = 0.95, \\ \text{intensity of heat exchange} & \nu_{\text{hex}} = 0.75, \\ \text{thermal efficiency of heat exchanger} & \eta_{\text{hex}} = 1 \text{ (no heat losses),} \\ \text{intensity of chemical reaction (C + O}_2 \rightarrow \text{CO}_2) & \nu_{\text{reac}} = 1, \\ \text{thermal efficiency of chemical reaction} & \eta_{\text{reac}} = 1 \text{ (no heat losses),} \\ \text{expansion in a turbine} & \eta_{m, \text{turb}} = 0.95. \end{aligned}$$

**Table 1**

The coal fed gas turbine – process pressure  $p = 10$  bar

Process temperature	=	1200 K	1300 K	1400 K	1500 K	1600 K	1700 K	1800 K	1900 K	2000 K
Thermal efficiency	$\eta_{th}$	0.403	0.434	0.460	0.482	0.500	0.516	0.530	0.542	0.553
Exergy efficiency	$\eta_{ex}$	0.528	0.555	0.577	0.594	0.608	0.619	0.629	0.637	0.644
Thermodynamic effectivity	$\varepsilon_{\Sigma}$	0.841	0.848	0.854	0.859	0.864	0.868	0.871	0.875	0.877
Expansion in a turbine	$\varepsilon_{turb}$	0.934	0.936	0.937	0.937	0.938	0.939	0.940	0.940	0.941
	$\gamma_{turb}$	0.366	0.364	0.361	0.359	0.357	0.355	0.353	0.351	0.350
Air compression	$\varepsilon_{aircomp}$	0.917	0.917	0.917	0.917	0.917	0.939	0.917	0.917	0.917
	$\gamma_{aircomp}$	0.192	0.176	0.163	0.151	0.141	0.132	0.124	0.117	0.111
Regenerative heat exchange	$\varepsilon_{hex}$	0.972	0.958	0.947	0.938	0.931	0.926	0.921	0.917	0.914
	$\gamma_{hex}$	0.020	0.033	0.045	0.055	0.065	0.074	0.082	0.089	0.096
Combustion reaction	$\varepsilon_{reac}$	0.720	0.737	0.752	0.764	0.776	0.786	0.795	0.803	0.810
	$\gamma_{reac}$	0.422	0.427	0.431	0.435	0.437	0.439	0.441	0.442	0.444

**Table 2**

The coal fed gas turbine – process pressure  $p = 20$  bar

Process temperature	=	1200 K	1300 K	1400 K	1500 K	1600 K	1700 K	1800 K	1900 K	2000 K
Thermal efficiency	$\eta_{th}$	0.395	0.417	0.433	0.444	0.460	0.483	0.502	0.520	0.535
Exergy efficiency	$\eta_{ex}$	0.517	0.533	0.542	0.548	0.559	0.579	0.596	0.611	0.624
Thermodynamic effectivity	$\varepsilon_{\Sigma}$	0.857	0.858	0.860	0.862	0.865	0.870	0.874	0.878	0.881
Expansion in a turbine	$\varepsilon_{turb}$	0.933	0.934	0.935	0.936	0.937	0.938	0.939	0.939	0.940
	$\gamma_{turb}$	0.403	0.396	0.391	0.386	0.384	0.383	0.382	0.381	0.380
Air compression	$\varepsilon_{aircomp}$	0.921	0.921	0.921	0.921	0.921	0.921	0.921	0.921	0.921
	$\gamma_{aircomp}$	0.258	0.234	0.215	0.198	0.185	0.173	0.163	0.155	0.146
Regenerative heat exchange	$\varepsilon_{hex}$	_*	_*	_*	_*	0.996	0.986	0.978	0.971	0.965
	$\gamma_{hex}$					0.003	0.011	0.019	0.026	0.033
Combustion reaction	$\varepsilon_{reac}$	0.719	0.737	0.752	0.765	0.776	0.786	0.795	0.803	0.810
	$\gamma_{reac}$	0.339	0.369	0.394	0.415	0.428	0.432	0.436	0.439	0.441

\* no regenerative heat exchange because of  $T_{turb} < T_{aircomp}$

So, the whole system can be univocally determined, e.g. [10]. The results are presented in Tables 1 and 2, once for the pressure 10 bar, and another for 20 bar.

The thermal system efficiency has been determined according to

$$\eta_{th} = \frac{L_{t,turb} - L_{t,aircomp}}{Q_{reac}}$$

and the exergy one

$$\eta_{ex} = \frac{L_{t,turb} - L_{t,aircomp}}{E_{Q_{reac}}} = \frac{T}{T - T_0} \cdot \frac{L_{t,turb} - L_{t,aircomp}}{Q_{reac}} = \frac{T}{T - T_0} \cdot \eta_{th}$$

whereby  $T$  is the combustion temperature. Additionally the concept of the thermodynamic effectivity of a process and of the system has been applied, [8] and [10]. In particular formulas have been used, which were already presented and discussed in [9].

The whole system effectivity, which is shown in Figure 1, can be determined with help of the formula

$$\varepsilon_{\Sigma} = \sum \gamma_i \varepsilon_i = \gamma_{turb} \varepsilon_{turb} + \gamma_{aircomp} \varepsilon_{aircomp} + \gamma_{hex} \varepsilon_{hex} + \gamma_{reac} \varepsilon_{reac}$$

whereby  $\gamma_i$  is the mathematical weights factor of the in  $i$ -th process diminishing exergies.  $\varepsilon_i$  is the particular  $i$ -th process thermodynamic effectivity.

## 5. CONCLUSIONS

There are presented computing results of the coal fed gas turbine, namely rating quotients, especially also the quotients based on the exergy balance. Taken separately they have no direct importance for the practice but taken together they show the method, which can be used in further investigations of the so-called clean combustion systems.

As a special problem the modeling of chemical reactions with help of the only one dimensionless parameter, the process intensity, has been presented as an example and discussed. The method suits very well for thermodynamic analyzes of complex power systems, in which chemical reaction are taken into account. Especially it is important for

the solid fuels (coal) gasifying chemical reactions. Similar to the heat exchange processes, the thermal efficiency can be given as the next dimensionless parameter for chemical reactions: it will be important for the heat absorbed or created during the particular chemical reaction: value one – no heat losses, value zero – the whole heat amount created or absorbed lost without any effect. Simultaneous chemical reactions can be in the same manner determined by the appropriate dimensionless parameters, and also calculated (e.g. [11]), which will be shown in next contributions.

#### Main symbols:

- $E$  – exergy,
- $\gamma$  – mathematical weights factor,
- $\varepsilon$  – thermodynamic effectivity,
- $\tau$  – intensity parameter,
- $\eta$  – efficiency quotient.

#### Superscript

- \* – state of equilibrium.

#### Subscripts:

- A, B, C – reactant A, B or C,
- aircomp – air compression,
- ex – exergy,
- hex – heat exchange,
- m – polytropic,
- reac – chemical reaction,
- th – thermal,
- turb – turbine,
- $\infty$  – infinity.

#### Acknowledgement

Worked out within the research project *Evaluation, Verification and Interpretation of the Environmental Loads of the Czech Republic – INTERVIRON 2B06068*.

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