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Thermoeconomic analysis of supercritical coal fired power plant using RRM method

Analiza termoekonomiczna nadkrytycznego bloku węglowego przy użyci metody RRM

The availability of low-cost energy is a key factor for development of each country. On the other hand a strategic priority for the European Union is to prevent dangerous climate change. According to binding legislation the EU has committed to cut its greenhouse gas emissions to 20% below 1990 levels in 2020. Renewable sources of energy seem like the simplest answers to that expectation, rather than carbon-intensive fossil fuels. However, the relatively high costs of some renewable technologies coupled with inherent limitations suggest that fossil fuels, especially coal, will remain a dominant source of electricity at least in the near future. Therefore in power generation industry there is a need to identify the most cost effective power generation technologies considering process, economic, and regulatory conditions. Before making a decision, each company, operating in the energy sector has to assess whether the expenditures for new generation plant are reasonable and which of the available technologies is the most cost-effective choice. In the near future the Polish energy sector will require substantial investments. It results from the growth of Polish economy as well as from aging of the existing power plants and industrial installations [8].

Cost estimation of the investment is a specific subject and a problem of its own nature. During the initial planning of investments a rough cost estimates are necessary to decide between alternative designs and for a given project evaluation. Generally, the economic evaluation of the specified plant capacities is based on the total capital costs, total operating costs and revenues from sales of generated electricity. Especially that decisions which concern financial expenses are characterized by certain of risk, which must by estimated. This kind of analysis is very important in energy sector, where unit investment cost is high, and it payback period extends over many years.

A variety of cost models such as simple payback period (SPBP), Discounted Pay Back Period (DPBP), internal rate or return (IRR) and net present value (NPV) calculations are used in some energy production studies. The drawbacks of traditional methods result from their simplified methodologies, which take into account the total amount of investment only and may not

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give correct answers if the costs of investment of competing projects are not equal. One of the most advanced procedures used in the financial analysis of power systems is the method of Revenue Requirement Method (RRM). This method allows for a detailed estimation of the cost of investment, thereby provides the estimation of the minimum acceptable cost recovery to the investor. In this method, the costs and revenues are equalized, so that the present value of the required income reflects future costs [1]. Despite some objections formulated among the others by Linda [2] and Awerbuch [3] on too many stringent financial and operational assumptions it seems that this method is currently the most advanced one and allows for the most accurate estimation of the economic effects of investments in power industry. Its value is also reflected in the fact that it is used by such institutions as EPRI (Electric Power Research Institute) and NREL (National Renewable Energy Laboratory).

The main aim of the paper is to present assumptions of the procedure developed at Institute of Thermal Machinery Czestochowa University of Technology on the basis of RRM method. The calculation algorithm was coded in the commercial Microsoft Office Excel program. It was combined with the heat- and mass-balance commercial software package IPSEpro. The second objective of this study was to analyze the conceptual plant designs and to evaluate the economy of different power plant designs under various infrastructural constraints. Some factors, which allow to measure the economic effects, like levelled main product unit cost (MPUC) and levelled fuel unit cost (LFC) were considered. Prior to economical analysis heat and mass balances for various plant designs were performed and assessed based on efficiency. These analyzes were applied to a conceptual 900 MW power unit for ultra-supercritical parameters proposed within the National Strategic Research Programme "Advanced Technologies for Energy Generation" [13].

Characteristic of cost calculation method (RRM)

The RRM method examines the various elements of the cost of plant investment and operation. These elements include carrying charges and expenses. Carrying charges consist of book depreciation, property and income taxes, return on equity, return on debt, and insurance. Expenses include fuel, operating and maintenance costs. The main assumption of this method is to project costs over the plant useful life. The general decision rule is to choose the best alternative for which the present value of the investment revenue requirement is the lowest [9]. The method defines some costing metrics, which allows for reliable comparison of various power technologies on a similar basis. For this purpose the total revenue requiems parameter (TRR), the levelled unit cost of a product (MPUC) and the levelized fuel unit cost (LFC) are most often used.

The RRM method requires several assumptions. The base year is the first year of capital expenditure. The costs are expressed in mixed, current-year currency over the entire capital expenditure period, which is assumed to last between three and five years for most of power plants. Important are also financial assumptions, characteristic for energy sector, like the average nominal escalation rate of fuel cost and the required number of labour positions for operating and maintenance. One of the most important assumptions of RRM is that, all financial data and parameters are taken for the year of calculation [1]. In carrying out economic calculations the accurate estimation of Purchase Equipment Cost (PEC) is the very important step, since most of the components of total capital investment (TCI) are based on PEC. It is apparent that the accuracy of cost estimates depends on the amount and quality of the available cost information. The best cost estimates can be obtained through manufactures quotations, and when the data are hardly available the prices can be obtained from the literature data or from charts giving correlations of the costs plotted versus the equipment or item size. Then PEC costs are supplemented by other onsite and offsite investment costs as well as indirect costs. All of these items make up the Fixed Capital Cost (FCI). To have the Total Cost Investment (TCI) other outlays (OO), consisting of startup costs, working capital, licensing costs, research and development and allowance for funds used during construction must be taken into account [1]. Of course all cost data used in economic analysis must be brought to the same reference year.

When TCI is estimated, the calculations are carried out for book and tax life. Next the Total Revenue Requirement factor for each year of operation is calculated, based on following estimation:

$$TRR = TCR + ROI + ITX + OTXI + FC + O\&M \qquad (1)$$

where :

TRR – annual Total Revenue Requirement
TCR – annual Total Capital Cost
ROI – annual minimum return on investment
ITX – annual income taxes
FC – annual fuel cost
$O\&M$ – annual operating and maintenance cost

For known TRR the levelled calculations can be carried out. That process allows to calculate several variable expenditures to constant value within the prescribed time period. The levelled process can be carried out in two ways:

- for current currency price
- for constant currency price

According to Bejan [1] levelled method should be used for long time period and short time period. For energy issues 20 and 10 years periods are usually assumed. However, the caution is necessary for investment based on long term criteria, due to their sensitivity to late years results as well as to the risk that some of the analysed installation might never materialize (due to technological change or new governmental regulation). For this reason the year by year analysis should be still based on book and tax life for long and short time period, but short levelization periods should be applied as basis for decision making.

The thermal system usually produces one main product. However, if the system produces the additional by-product the levelled procedure for it must also be applied. Than the levelized unit cost is calculated according to:

$$MPUC = \frac{TRR - BPV}{MPQ} \qquad (2)$$

where :

$MPUC$ – evelled Main Product Unit Cost
BPV – annual levelled By-Product Value
MPQ – annual Main Product Quantity

The calculation algorithm described above was coded in the commercial MO Excel program. It was integrated with the heat- and mass-balance commercial software package IPSEpro. For the purpose of fluent estimation of PEC costs a new library, called APP_ECO_Lib was created. It is based on the library developed by (product of IPSE) within European GTPOM project [12], but was extended at ITM by new correlations and updated equipment prices.

Description of power unit for ultra-supercritical parameters

The demand for more efficient cycles than the conventional subcritical steam plant pushes up the level of the live and reheated steam parameters. Current status of the technology achieves efficiencies of 45% (lower heating value (LHV) basis) with live steam parameters limited to about 30 MPa and 600°C. This limit is mainly imposed by the materials of the boiler and high pressure turbine components. However, prospects of technology development aim at 700°C and higher pressures in the near future. As a response to this need, a conceptual 900 MW power unit for ultra-supercritical parameters within the National Strategic Research Programme "Advanced Technologies for Energy Generation" was proposed. The research described in [10, 11] discussed various structural modification of this initial power unit. For the purpose of this work three cases were considered. The reference case (case 1), presented in Fig.1a, has a structure typical for ultra-supercritical steam cycle. It consists of boiler, three main turbine sections (HP, IP, LP), condenser, preheaters of low and high pressure regeneration system, an additional mixing exchanger, deaerator, and an external motor to supply a feed water pump. The second case (case 2), presented in Fig.1b, was modified according to AD700 concept [4] by addition of so called Tuning Turbine (TT), which solves a problem of very high steam bleed temperatures and the exergy loss in high and intermediate pressure regenerative heaters. For the last case (case 3), presented in Fig.1c, the structure was further extended by an additional use of a double steam reheat. The values of basic parameters are shown in Tab.1. Fig. 1 presents the structure of all three cases, which in detail were developed and analysed in [5, 6] using heat- and mass-balance commercial software package IPSEpro. As a main parameter the gross power generation efficiency (η_{ge}) defined as:

$$\eta_{ge} = \frac{P_T}{Q_{in}} \tag{3}$$

was used. In equation (3) P_T is the generated power and Q_{in} is the heat input to the steam cycle.

Although the two modifications of the thermal cycle seem minor, they have strong impact on the water/steam parameters. Fig. 2 shows efficiency distribution for each of the cases considered. It was observed that the additional Tuning Turbine caused an increase in the efficiency of 0.14%. Addition of a double steam reheat gives the rise of efficiency around 1.12%. It seems therefore that these two modifications are justifiable from the viewpoint of thermodynamics. Further on, the use of secondary superheat is certainly advantageous, since it improves the efficiency of thermal cycle, reduces the total heat transfer surface area, reduces the live steam flux and provides clear benefits of performance. It should be noted however, that the introduction of Tuning Turbine and a double reheat increases the complexity of power unit structure, which may cause the rise of investment costs.

Table 1

The value of basic parameter of considered cases

Parameters	Case 1	Case 2	Case 3	Unit
t_{ps}	702	702	702	°C
t_{pp}	721	721	721	°C
t_{pwp}	-	-	721	°C
t_{wz}	330	330	332	°C
$p_{pś}$	357.5	357.5	382.5	bar
p_{pp}	75	75	130	bar
p_{pwp}	-	-	29.9	bar
η_{ge}	51.97	52.11	53.23	%
P	900	900	900	MW

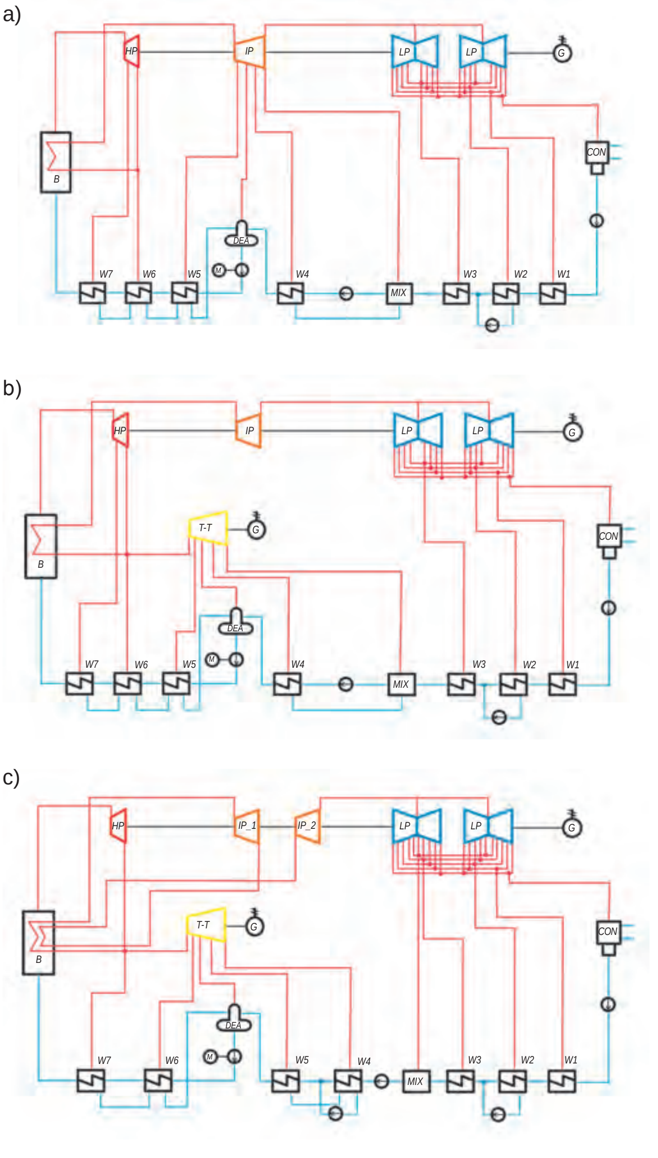

Fig. 1. The scheme of considered cases:
a) case 1, b) case 2 and c) case 3

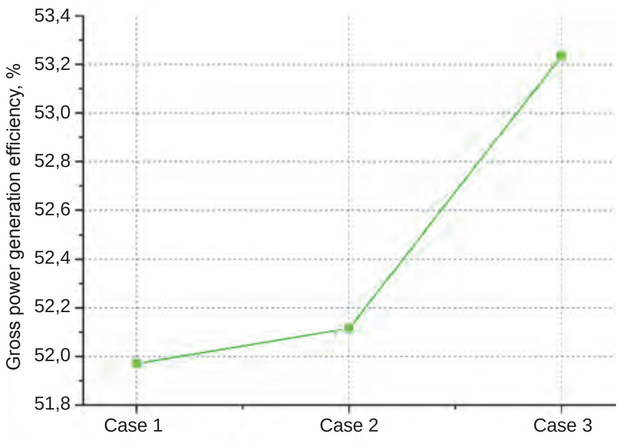

Fig. 2. The gross power production efficiency for considered cases

Evaluation of the power plant economics

The economic evaluation of three specified designs of ultra-supercritical power plant is based on the total capital investment, total operating costs and total revenue requirement for sales of generated electricity. For the course of calculations the 2013 was taken as a reference year for financial data. Following the suggestion of Bejan [1] the analyses were carried on for long and short time periods, but levelization was conducted for 10 years period and constant currency price. It was assumed that average capacity factor is 85%, average caloric value of fuel is 23MJ/kg. The unit cost of fuel was assumed to be equal 400 PLN/tonne, the averaged labour rate equals 35PLN/h and the number of labour position was calculated the estimate that 2 MW of generated power required 1 employee. For each calculation the generation power was constant and equal 900MW.

The first task was to compare basic economical quantities for all cases. The parameters like boiler, TCI, MPUC, FC were chosen as the main parameters. The results are shown in Fig.3, where the percent change of the costs compared to reference case (case 1) are given. It may clearly be seen that application of TT and second reheat leads to reduction of main costs. This is due to the rise of efficiency, which causes the reduction of generated heat flux, that in turn leads to decrease of investment costs of a boiler. Additionally, the reduction of boiler power causes the decrease of fuel demand and so LCF. The above analysis shows that the development of the power plant by second reheat together with tunning turbine is economically justified.

Fig. 4 presents the variation of the main equipments prices. Boiler price as well as costs of the turbine and preheaters are the main cost components of TCI and MPUC. For these items a material factor related to steam parameters is very important. The data presented in Fig. 4 present the change of percentage share of particular cost components expressed as TCI percentage. It is seen that the purchase cost of the turbine and of the boiler are dominant reaching nearly 8%. For the turbine the cheapest solution was obtained for case 2. It is caused by moving the hot turbine bleeds to a separate TT that decreases the steam mass flux in the main circuit. For case 3 the turbine prices raises again, which is caused by significant extension of low pressure part. Purchase cost of condenser and deaerator represented a small part of TCI, but quite significant are the expenditures for the regenerative heaters (around 3% of TCI). Here, bleeds temperature and pressure play the main role, which strongly correlates with a material used for construction of preheaters. In our new library APP_ECO_Lib the type of materials was taken into account and expressed by a material factor. Those characteristics are especially important for preheater W7, where very expensive high-temperature alloys are used.

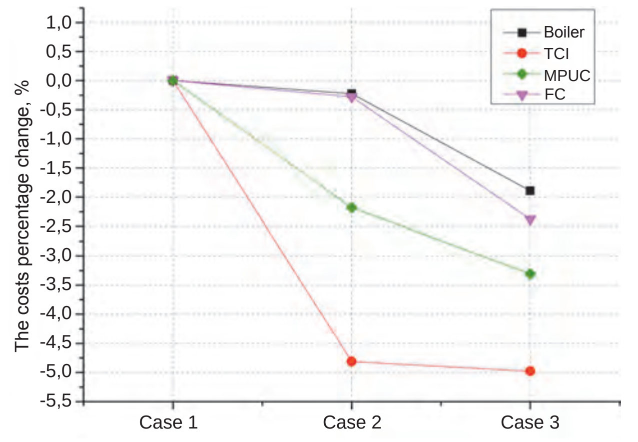

Fig. 3. Comparison of basic economical quantities

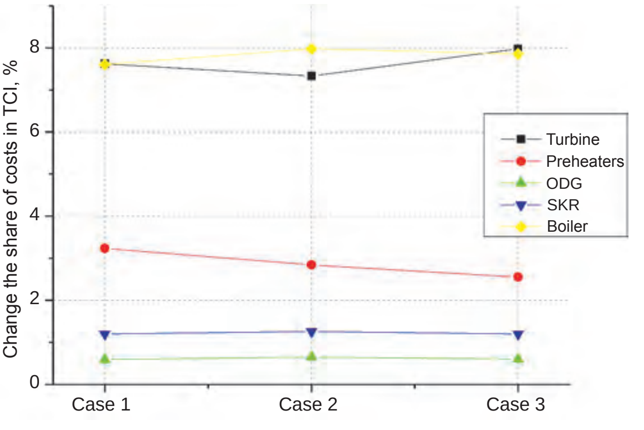

Fig. 4. The change of purchase cost of main power unit elements

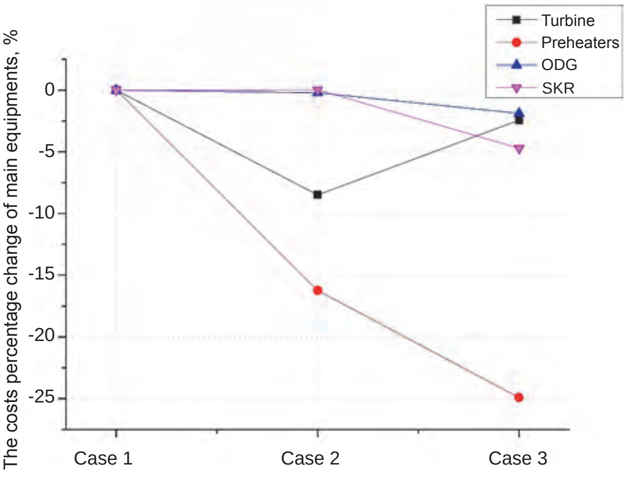

Fig. 5. The influence of purchase cost for main unit power elements as a term of reference case

Supplementary information is provided by the data in Fig. 5. It presents the percentage change of main equipments prices relative to the reference case. Again it is shown that the highest reduction of purchase cost was obtained for regenerative heaters. In this case the cost was decreased by 16% for case 2 and by 25% for case 3. The analysis performed by Dong Energy [4] also indicated this element of the power plant as one of the most impacting in the overall cost reduction in the case of ultra-supercritical steam cycle supplemented with TT. Structural modification of the initial power unit has an influence of the cost of deaerator and condenser. The cost of deaerator is mainly dependent on outcome mass flux, while for condenser it mainly depends on heat exchange area.

Summary

In this paper the economical analysis for a novel concept of ultra-supercritical coal-fired steam cycle was under consideration. The calculations were performed with IPSEpro and RRM method. The three cases with different structure configuration were analysis. From the viewpoint of thermodynamic the case 3 is a most effective system. The increase of efficiency seems to be sufficient to compensate investment cost associated with structural change. It should be mentioned of some of calculation uncertainty related with material factors. It was shown that material factors can rapidly increase with rise of working medium parameters (like temperature or pressure). The analyses have shown that calculations for critical and under-critical steam cycles are sufficiently reliable. However recently is lack of data for new materials with will be use for ultra-supercritical steam cycle, that is way calculation for this cases can be burdened with systematic error.

The results presented in this paper were obtained from research work co-financed by the National Centre of Research and Development in the framework of Contract SP/E/1/67484/10 – Strategic Research Programme – Advanced technologies for energy generation: Development of a technology for highly efficient zero-emission coal-fired power units integrated with CO_2 capture.

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