THERMODYNAMIC ANALYSIS OF COMBINED CYCLE POWER PLANT

Glazar, V.*, Mrzljak, V. and Gubic, T.
*Author for correspondence
Faculty of Engineering,
University of Rijeka,
Vukovarska 58,
51000 Rijeka,
Croatia,
E-mail: vladimir.glazar@riteh.hr

ABSTRACT

Although development in electrical power production continuously shifts to renewables, power plants based on conventional fuels should not be neglected. Market requirements and their operational flexibility are just some of the reasons for this kind of plant to be worth investigated and explored. In this paper, the combined cycle power plant is analyzed. Analyzed plant size and operating parameters were based on an existing plant located in the north of Croatia. The power plant consists of two blocks that can operate independently of each other. Each block consists of 30 MWe gas turbine and 10 MWe steam turbine. The gas and steam part of the plant is connected with a heat recovery steam generator where the flue gases from the gas turbine deliver heat to the water and the steam which are then used in the steam turbine part of the process.

In this paper thermal calculation of a combined cycle power plant is performed. The technical description of the energy system is followed by the energy balance calculation of the gas turbine and the energy balance equation of the steam turbine. Calculations are made in two ways, analytically by standard thermodynamic procedures and by using modern commercial computer-based calculation software. The results obtained by both methods are analyzed and compared, followed by discussion and conclusion.

INTRODUCTION

The combined cycle power plant consists of at least one gas turbine (GT) process, at least one steam turbine (ST) process, and its connection by heat recovery steam generator (HRSG) [1]. The idea of combining gas and steam turbine processes arises from the high temperature and high mass flow rate of flue gases, which exit the gas turbine process [2].

In simple combined cycle process flue gases from GT in HRSG heat up water and produce superheated steam without the usage of any additional fuel. Therefore, fuel consumption occurs only in GT combustion chambers.

The complex combined cycle process involves additional fuel consumption in fuel burners, usually mounted at the HRSG inlet. In such a process, the temperature of flue gases from GT is not sufficient for all necessary heating processes inside HRSG [3].

NOMENCLATURE

Abbreviations

CC	Combustion Chambers
CON	Condenser
ECO	Economizer
EG	Electricity Generator
EVAP	Evaporator
GT	Gas Turbine
HRSG	Heat Recovery Steam Generator
REJ	Rejected
ST	Steam Turbine
SUP	Superheater
TC	Turbo-compressor

Latin symbols

h	[kJ kg^{-1}]	Specific enthalpy
H_{low}	[MJ kg^{-1}]	Fuel lower heating value
$\dot{m}$	[kg s^{-1}]	Mass flow rate
P	[MW]	Power
$\dot{Q}$	[MW]	Heat transfer

Greek symbols

η	[%]	Efficiency
Δ	[-]	Difference

Regardless of the combined cycle process type, superheated steam in such processes is produced at very low cost, because the fuel amount for steam production is low (fuel in additional burners before HRSG) or equal to zero (when only GT combustion chambers use fuel).

It is important to note that HRSG which connect gas and steam processes in combined power plants is a very complex component which is a theme of many kinds of research [4] and optimizations [5].

A combination of GT and ST processes resulted in high overall efficiency of the combined cycle (60% or more) [6], much higher when compared to single GT or single ST processes. High overall efficiency is the most important reason why combined cycle power plants are in intensive usage and development nowadays. Many researchers deal with combined power plants or its integral components to optimize their performances and additionally increase overall efficiency.

Several authors presented a performance analysis of combined cycle power plants [7] in order to obtain its optimum operation [8]. Liu and Karimi [9] presented a new operating strategy for a combined cycle power plant which increases overall plant efficiency and reduces pollutant emissions.

Exergy analysis of combined cycle power plants [10] is often used tool for detecting power plant major losses and provides techniques for its minimization [11]. Energy, exergy and economic analyses (3E) can provide even a financial background of the combined power plant and its components [12].

Recent researches about combined power plants are based on implementing solar heating systems into the power plant in order to reduce fuel consumption and further increase overall efficiency [13, 14].

In this paper, operating parameters of the combined power plant will be calculated by using two different approaches: first with analytical calculations and second by use of simulations modeled with the commercial computer program.

COMBINED CYCLE POWER PLANT DESCRIPTION

Analyzed combined cycle power plant is used for electricity production only; waste heat from HRSG is not recuperated than rejected to the environment. The power plant consists of two identical blocks, Figure 1.

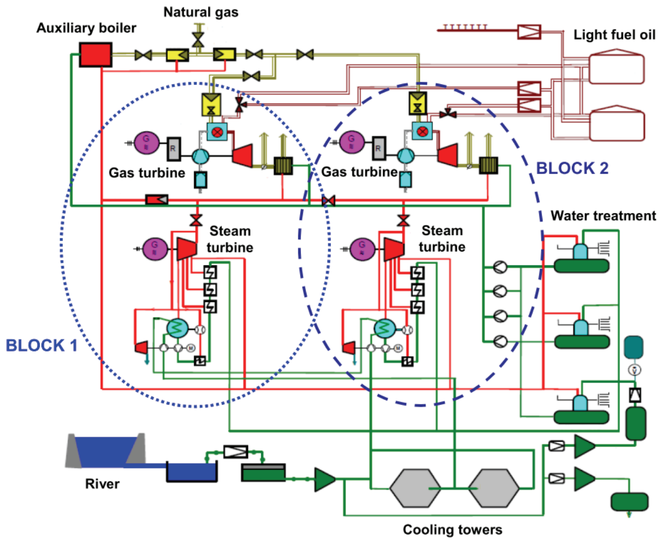

Figure 1 The scheme of combined cycle power plant [15]

Each block has one gas turbine (producer Westinghouse, USA) with a nominal power of 30 MWe and one steam turbine (producer Jugoturbina, Croatia) with a nominal power of 10 MWe. Main producer specifications of the gas turbine are presented in Table 1, while the main producer specifications of a steam turbine are presented in Table 2. Gas and steam turbines are connected in each block by HRSG (producer Cockerill, Belgium) whose main specifications are presented in Table 3.

Both gas turbines have a possibility of stand-alone operation regardless of steam process of the plant - in such operating regime flue gases from gas turbines are rejected directly to the environment. Steam pipelines between HRSG's and steam turbines are connected between blocks in a way that any gas turbine can operate with any steam turbine what enables cross-flow operation (in the case of malfunction or during the maintenance process).

Table 1 Main gas turbine (GT) producer specifications

Type	W-251-B1
Nominal power	31.5 MWe
Maximum power	40.0 MWe
Air pressure after turbo-compressor	10 bar
Air temperature after turbo-compressor	~ 340 °C
Flue gases temperature - turbine inlet	1019 °C
Flue gases temperature - turbine outlet	480 °C - 500 °C
Rotation speed	80.9 s^{-1}
Efficiency (gas process)	28 %
Number of turbine stages	3
Number of turbo-compressor stages	18

Primary fuel is natural gas, while the power plant has also the possibility to operate with light fuel oil as auxiliary fuel. Light fuel oil is rarely used due to a more negative impact on the environment (when compared to natural gas).

Table 2 Main steam turbine (ST) producer specifications

Type	Action / two Curtiss stages
Number of action stages	17
Nominal power	11.5 MWe
Maximum power	12.5 MWe
The nominal pressure of steam at the turbine inlet	36 bar, maximum 43 bar
The nominal temperature of steam at the turbine inlet	435 °C, maximum 450 °C
Rotation speed	50 s^{-1}
Efficiency (steam process)	27 %

The combined cycle power plant is used as a peak power plant due to fast starting and operation flexibility. During the load increase from a dead state to full load, gas turbines require around 20 minutes and the entire combined block requires around 90 minutes. Additional insurance of possible gas turbine(s) malfunction offers auxiliary boiler for HRSG drive which can operate also with natural gas or light fuel oil.

Table 3 Main producer specifications of HRSG

Dimensions of a spiral-brass tubes	Ø 31.8 mm x 4mm
Operating pressure	41 bar
Operating temperature	440 °C

In analytical calculations and simulation, only one block of analysed combined cycle power plant is used. The obtained operating parameters are valid for one gas and one steam turbine as well as for one HRSG and steam condenser. The power plant overall thermal efficiency is the overall thermal efficiency of each block. HRSG does not use any additional fuel - heating of all the components is performed only with flue gases from GT (simple combined cycle).

ANALYTICAL POWER PLANT CALCULATIONS

Analytical power plant calculations can be performed by using known equations of thermodynamics [16, 17]. In this case, combined power plant analytical calculations will be performed for the following plant operating parameters: Air mass flow rate through GT process, GT turbo-compressor power, Heat delivered in GT combustion chambers, Fuel consumption, Water/steam mass flow rate through HRSG, Heat exchanged in HRSG economizer, Heat exchanged in HRSG evaporator, Heat exchanged in HRSG superheater, Heat rejected in steam condenser and Block (plant) overall thermal efficiency. Inputs used in analytical calculations refer to data of gas turbine and its process (Table 4) and to data of the steam turbine and its process (Table 5).

Table 4 Analytical calculations/Simulation model inputs for gas turbine (GT)

Environment air temperature	20 °C
Environment air pressure	1 bar
Air pressure after turbo-compressor	10 bar
Flue gases temperature at the turbine inlet	1019 °C
Flue gases pressure after expansion	1.03 bar
The lower heating value of natural gas	50015 kJ kg^{-1}
The lower heating value of light fuel oil	42948 kJ kg^{-1}
Turbine/turbo-compressor isentropic effic.	91 %
Gas turbine mechanical efficiency	99 %
Electricity generator efficiency	98 %
Combustion chambers efficiency	94 %
Flue gases temp. at the HRSG outlet	240 °C
HRSG efficiency	97 %
Gas turbine produced power	30 MWe

Specific enthalpy of the operating medium in each characteristic operating point of the gas turbine process and the steam turbine process can be calculated from the input data (Table 4 and Table 5) by using NIST-Refprop 9.0 software [18]. NIST-Refprop 9.0 allows calculation of thermodynamic data for each operating medium used in combined power plant - air, flue gases and water/steam. For each operating medium, at any characteristic operating point, NIST-Refprop 9.0 requires knowledge of two properties (for example pressure and temperature) to calculate all the others.

Table 5 Analytical calculations/Simulation model inputs for steam turbine (ST)

The steam temperature at the turbine inlet	435 °C
Steam pressure at the turbine inlet	36 bar
Steam pressure - first extraction	10 bar
Steam pressure - second extraction	3 bar
Steam pressure - third extraction	1 bar
Condenser pressure	0.04 bar
Condensation temperature	28.979 °C
Specific steam turbine outlet losses	30 kJ/kg
Turbine isentropic efficiency	95 %
Turbine mechanical efficiency	99 %
Turbine produced power	10 MWe

Specific enthalpy of air after turbo-compressor is calculated from known turbo-compressor pressure ratio, air inlet temperature and turbo-compressor isentropic efficiency. Specific enthalpy of flue gases after GT is calculated from the known GT pressure ratio, flue gas temperature at the GT inlet and GT isentropic efficiency.

In all the components of HRSG, the same pressure of water/steam is assumed as at the ST inlet (36 bar). The water/steam saturation line represents the limits between which operate each HRSG component. Steam condensation in condenser occurs at constant pressure and temperature.

The whole analytical calculation of combined power plant operating parameters, which will be compared with operating parameters obtained by the simulation model, is simplified. For example, it is assumed that throughout GT process circulates only the mass flow of air - which is a fact for turbo-compressor, but not for the turbine (throughout the turbine circulate the sum of air and fuel mass flows), etc. Equations for the analytical power plant calculation are:

Air mass flow rate through the GT process:

$$\dot{m}_{\mathrm{air}} = \frac{P_{\mathrm{GT}}}{\Delta h_{\mathrm{GT}} - \Delta h_{\mathrm{TC}}} \tag{1}$$

GT turbo-compressor power:

$$P_{\mathrm{TC}} = \dot{m}_{\mathrm{air}} \cdot \Delta h_{\mathrm{TC}} \tag{2}$$

Heat delivered in GT combustion chambers:

$$\dot{Q}_{\mathrm{CC}} = \dot{m}_{\mathrm{air}} \cdot \Delta h_{\mathrm{CC}} \tag{3}$$

Fuel consumption:

$$\dot{m}_{\mathrm{fuel}} = \frac{P_{\mathrm{GT}}}{H_{\mathrm{low}} \cdot \eta_{\mathrm{CC}} \cdot \eta_{\mathrm{EG}} \cdot \eta_{\mathrm{mechanical}} \cdot \eta_{\mathrm{GT}}} \tag{4}$$

where η_{GT} is gas turbine efficiency calculated as:

$$\eta_{\mathrm{GT}} = \frac{\Delta h_{\mathrm{GT}} - \Delta h_{\mathrm{TC}}}{\Delta h_{\mathrm{CC}}} \tag{5}$$

Water/steam mass flow rate through HRSG:

$$\dot{Q}_{\mathrm{flue\ gases}} \cdot \eta_{\mathrm{HRSG}} = \dot{Q}_{\mathrm{water/steam}} \tag{6}$$

Heat amount transferred from flue gases to water is:

$$\dot{Q}_{\mathrm{flue\ gases}} = \dot{m}_{\mathrm{air}} \cdot \Delta h_{\mathrm{HRSG}} \tag{7}$$

where Δh_{HRSG} is the specific enthalpy difference of flue gases at the HRSG inlet and outlet,

$$\dot{m}_{\mathrm{water/steam}} = \frac{\dot{Q}_{\mathrm{flue\ gases}} \cdot \eta_{\mathrm{HRSG}}}{\Delta h_{\mathrm{water/steam}}} \tag{8}$$

where $\Delta h_{\mathrm{water/steam}}$ is the specific enthalpy difference of steam/water at HRSG outlet and inlet.

Heat exchanged in HRSG economizer:

$$\dot{Q}_{\mathrm{ECO}} = \dot{m}_{\mathrm{water/steam}} \cdot \Delta h_{\mathrm{ECO,water}} \tag{9}$$

Heat exchanged in HRSG evaporator:

$$\dot{Q}_{\mathrm{EVAP}} = \dot{m}_{\mathrm{water/steam}} \cdot \Delta h_{\mathrm{EVAP,water/steam}} \tag{10}$$

Heat exchanged in HRSG superheater:

$$\dot{Q}_{\mathrm{SUP}} = \dot{m}_{\mathrm{water/steam}} \cdot \Delta h_{\mathrm{SUP,steam}} \tag{11}$$

Heat rejected in steam condenser:

$$\dot{Q}_{\mathrm{REJ}} = \left(\dot{m}_{\mathrm{water/steam}} - \dot{m}_{\mathrm{extracted}}\right) \cdot \Delta h_{\mathrm{CON}} \tag{12}$$

where $\dot{m}_{\mathrm{extracted}}$ is cumulative steam mass flow rate extracted from ST (ST has three extractions with a note that the first extraction leads steam to deaerator and high-pressure feed water heater). Steam mass flow rate extracted at each ST extraction is calculated according to each feed water heater energy balance.

Block (plant) overall thermal efficiency:

$$\eta_{\mathrm{block\ (plant)}} = \frac{P_{\mathrm{GT}} + P_{\mathrm{ST}}}{\dot{Q}_{\mathrm{CC}}} \tag{13}$$

It should be noted that combined cycle power plant block can operate only with one fuel (natural gas or light fuel oil), not with a combination of fuels. Both fuels were taken into account in order to determine which fuel gives higher block (power plant) overall thermal efficiency. Therefore, two analytical calculations were performed - first with natural gas and second with light fuel oil.

VALIDATION

In order to the validate results acquired with analytical calculation, the comparison has been done with previously published data [19]. At the rated output of both combined cycle power blocks, which includes gas turbine and steam turbine produced electrical power (63 MWe) natural gas consumption is 2.79 kg s^{-1}. According to available measurements [19], each block uses approximately 1.395 kg s^{-1}. Calculated natural gas consumption is 1.32 kg s^{-1} per block. Data for light fuel oil were not available as a power plant, due to ecology demands, works only with natural gas as fuel.

It can be seen that analytical simulation results coincide well with the measured fuel consumption at maximum load and that deviations are within an acceptable range. Differences are smaller than ±0.05 kg s^{-1}, which can be taken as an assertion of used analytical simulation validity. Therefore, it can be concluded that the described analytical model can be used for the comparison with the computer simulation program.

POWER PLANT SIMULATION MODEL

The simulation model is developed in a computer simulation program, which allows simulation of analyzed combined power plant stationary state. The simulation computer program uses known mathematical expressions for mathematical modelling of different thermodynamic phenomena. All the expressions are based on basic laws of mass, energy and momentum balance. Given the fact that a number of unknowns occur in relation to the number of set equations, the equation systems become analytically unsolvable and must be solved by numerical methods. The mathematical model is solved by the iterative procedure using the Newton-Raphson method with convergence criteria for all components set to 10^{-4}.

The simulation model is made by selecting and linking each individual plant component. Also, several components from the heat process require additional electrical, hydraulic and control components to ensure proper simulation.

The simulation model of one combined power plant block is simplified in a way that system for chemical preparation of water and heat consumers unrelated to the energy process are excluded. Similar duplicate parts are also omitted because they were used only in a case of overhaul or accident (for example reserve pumps or auxiliary boiler). The nominal heat load is simulated. The simulation model is based on the principle of achieving maximum overall thermal efficiency.

Each simulation program requires manually defined inputs for proper calculation. The program returns an error if the number of inputs or its definition is not proper. For this simulation model input parameters are defined for the GT process presented in Table 4 and for the ST process presented in Table 5 (the same as in analytical calculations). Similar to analytical calculations, two simulations were performed - first when the power plant block operates with natural gas and the second when it operates with light fuel oil.

COMPARISON OF RESULTS OBTAINED ANALYTICALLY AND WITH SIMULATION MODEL

After performing analytical calculations and two simulations obtained operating parameters were compared and presented in Table 6.

Table 6 Comparison of results - analytical calculation vs. simulation model

Operating parameter	Sim. model	Analytic. Calc.	Diff.
Air mass flow rate through the GT process, kg s^{-1}	97.92	95.73	2.24 %
GT turbo-compressor power, MW	29.71	29.97	0.85%
Heat delivered in GT comb. Chambers, MW	84.09	75.81	9.85 %
Natural gas consumption, kg s^{-1}	1.68	1.67	0.65 %
Light fuel oil cons., kg s^{-1}	1.97	1.95	1.32 %
Water/steam mass flow rate through HRSG, kg s^{-1}	10.2	9.66	5.29 %
Heat exchanged in HRSG economizer, MW	0.88	0.82	6.45 %
Heat exchanged in HRSG evaporator, MW	19.88	18.83	5.25 %
Heat exchanged in HRSG superheater, MW	5.11	4.84	5.14 %
Heat rejected in the steam condenser, MW	15.77	15.99	1.37 %
Block (plant) overall thermal efficiency - natural gas, %	47.53	52.6	5.07 %
Block (plant) overall thermal efficiency - light fuel oil, %	47.11	52.6	5.49 %

The percentage difference between the simulation model and analytical calculations for the majority of observed operating parameters is around 5 % or lower. The only notable difference (9.85 %) can be seen in heat delivered to GT combustion chambers because the simulation model calculates higher fuel consumption (for both fuels) which consequentially leads to higher air mass flow rate through GT combustion chambers. Also, a significant part of the presented differences is surely the result of simplifications used in the analytical calculations. This comparison shows that analytical calculations can be used for general analysis of any power plant (as well as observed combined power plant) or in the general analysis of power plant components. Detailed calculations, optimizations and plant upgrades are much easier and faster by using some commercial or non-commercial simulation programs.

THE EFFECT OF ENVIRONMENTAL TEMPERATURE ON THE POWER PLANT CHARACTERISTICS

Based on the built model, an analysis of environmental air temperature influence on power plant operating parameters was conducted. The observed parameters were: GT turbo-compressor power, fuel consumption (for natural gas as fuel) and the power plant thermal efficiency. The process analysis was modeled in a way that a constant value of all parameters was provided except for the inlet air temperature and the temperature of the cooling water. Consequently, the steam condensation temperature and the pressure in the steam part of the process were changing. The maximum power of the plant was 40 MW. The assumed difference between the cooling water and the condensation temperature was 5°C, and the assumed difference between the cooling water temperature and the ambient air was also 5°C.

The environmental temperature range was based on the technical regulation for this region [20], according to which the external design temperature for the heating period is -9.9 ° C, while the external design temperature in the cooling period is 27.1°C. In the analysis, the environmental temperature ranged from -10°C to 30°C with a step of 1°C. Figure 2 gives GT turbo-compressor power dependence on the environmental temperature for constant maximum block (plant) overall power output (40 MWe).

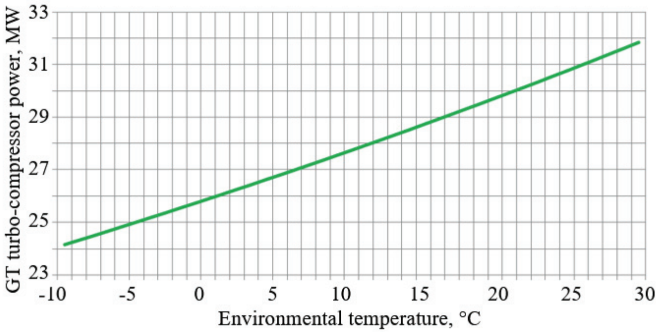

Figure 2 GT turbo-compressor power dependence on the environmental temperature

Increased air temperature results in lower compressor output. The amount of compressed air is dependent on the density of the air entering the compressor, which decreases in correlation with the rise of air temperature. To get the same volume of air at higher temperatures, GT turbo-compressor power increases. Due to the change of air density and decrease of compressor output, fuel consumption rises. Figure 3 gives fuel consumption dependence (for natural gas) on the environmental temperature.

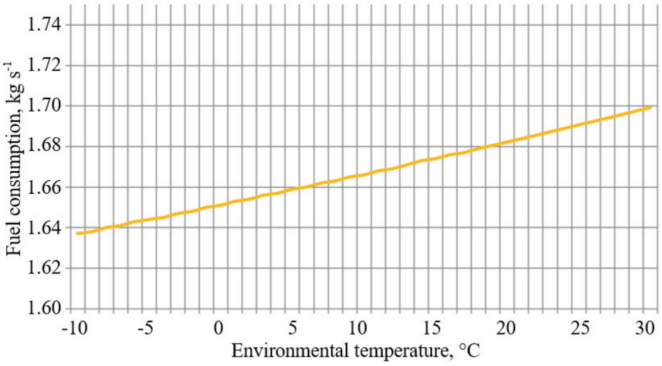

Figure 3 Fuel consumption dependence on the environmental temperature

Power plant thermal efficiency change due to environmental temperature change is shown in Figure 4 and for seasonal changes of temperature in Figure 5.

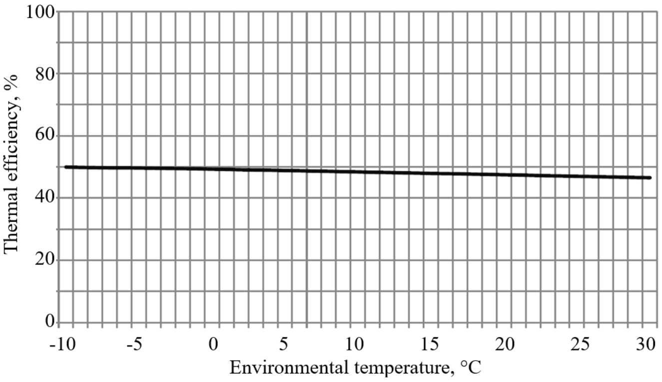

Figure 4 Power plant thermal efficiency dependence on the environmental temperature

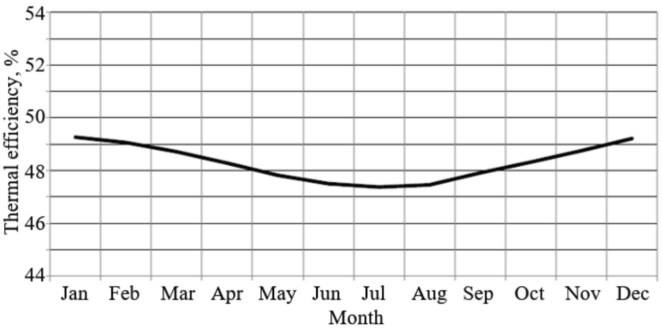

Figure 5 Power plant thermal efficiency change due to seasonal changes

The change in air temperature affects the power plant thermal efficiency. The explanation of such a relationship of the mentioned sizes is the fact that the rise of air temperature results with an increase of its specific volume and with the consequential increase of the work required for the compression stage.

CONCLUSION

The paper presents a thermodynamic analysis of the combined power plant located in the north of Croatia. Analyzed combined power plant has two identical blocks and each consists of one gas and one steam turbine processes. In each block, one HRSG is mounted which connects gas and steam turbine processes.

Comparison of results obtained with analytical calculations and by use of commercial computer program shows that simplified analytical calculations can be used for general analysis of combined power plant, while detailed calculations, optimizations and plant upgrades are much easier and faster by using simulation models.

For the analyzed combined power plant, analytical calculations resulted in the same overall thermal efficiency (52.60 %), regardless of used fuel in plant operation. On the other hand, the simulation model gives a slightly higher plant overall thermal efficiency when the plant operates with natural gas (47.53 %) in comparison with light fuel oil (47.11 %).

ACKNOWLEDGMENT

This work has been supported in part by the Croatian Science Foundation under the project IP-2018-01-3739 and in part by the University of Rijeka under the project number 17.10.2.1.05.

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