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Optimal heat load distribution between cogeneration steam turbine installations in combined heat and power (CHP) plants

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Abstract

The efficiency of thermal plants with steam turbine CHP depends on the heat load and the temperatures of incoming and outgoing district heating water. The distribution of the heat loads between the steam turbines and subsequent condensers at CHP systems influences significantly on the fuel consumption per unit generated energy. The aim of the present report is to develop an algorithm for modeling investigation and estimation of the optimal distribution of the heat load between cogeneration steam turbine units with different characteristics and schemes. The algorithm is applied for a thermal plant with two cogeneration units, containing a turbine with controlled *steam extraction and turbine with backpressure. The most effective work regimes of the investigated plant are determined in function of generated heat for the district heating*

Keywords: *cogeneration steam turbine, adjustable steam extraction, energy efficiency, fuel save*

1. **Introduction** controlled

Combined heat and power (CHP) production is accomplished in a single energy transforming facility. Most often steam turbine installations are employed with controlled (steam) extraction and back pressure. Combined heat and power production is more efficient than the separate production, accomplished in two separate installations. The electrical power in the separate method is generated from condensation steam turbine, and the heat is generated from a hot-water boiler.

According to EU directive 2004/8/EC [1] the energy efficiency of the CHP plants is estimated from the fuel economy achieved. Fuel economy is determined after comparison of the fuel consumption between the combined and separated method. The fuel consumption of the combined method is determined from heat and mass balance. The fuel consumption of the separated method is determined separately for each installation using reference efficiency coefficients of the condensation steam turbine and the hot-water boiler [2].

The CHP fuel economy is dependent on the consumption heat load $\dot{Q}_{DH}$, the temperature of the return τ_2 and supply district heating water τ_1. The control parameters of a heat-supply steam turbine installation are the consumption heat load $\dot{Q}_{DH}$ and the supply water temperature τ_1. The return water temperature τ_2 is uncontrolled parameter as it depends on the consumption heat load and the heat losses of the heat distribution [4, 8].

The purpose of the present report is to present a method for optimal distribution of the heat load between steam turbine installations that in most cases have different properties. The tools used for this purpose are mathematical and numerical modeling.

2. Problem setup

Optimal distribution of the heat load between consumers corresponds to the case when fuel economy is a maximum, $S_{total} = \max$. When studying the mode of operation of CHP plants it is necessary the fuel economy to be determined in percentage. In such case the objective function for concurrent operation of n steam turbines with different characteristics is:

$$S_{total} = S_1 \frac{\dot{Q}_{chp1}}{\sum_{i=1}^{n} \dot{Q}_{chpi}} + S_2 \frac{\dot{Q}_{chp2}}{\sum_{i=1}^{n} \dot{Q}_{chpi}} +....+ S_n \frac{\dot{Q}_{chpn}}{\sum_{i=1}^{n} \dot{Q}_{chpi}} = \max \tag{1}$$

where:

S_{total} is the fuel economy for the plant, %;

S_{chp1}, S_{chp2},…, $S_{chp\,n}$ – fuel economy achieved by the 1^{-st}, 2^{-nd} и n^{-th} steam turbine installation for CHP, %;

Q_{chp1}, Q_{chp2}, …, Q_{chpn} – heat load of the steam controlled extraction and boiler-condensers of the 1^{-st}, 2^{-nd} и n^{-th} steam turbine installation, MW.

$\sum_{i=1}^{n} \dot{Q}_{chpi} = \dot{Q}_{chp1} + \dot{Q}_{chp2} + ... + \dot{Q}_{chpn}$ - total heat load, MW;

The fuel economy for any CHP installation S, % could be determined by [2]:

$$S = \left(1 - \frac{F}{\frac{E}{EFF_p} + \frac{Q_{DH}}{EEF_q}} \right) \cdot 100 \tag{2}$$

where:

F is the fuel released energy, MWh;
E – electrical energy, produced by the CHP, MWh;
Q_{DH} – heat energy produced, MWh;
EFF_p – efficiency of electrical power generation of the replacement condenser block from the separated production;
EFF_q – efficiency of heat energy production from the hot-water boiler from the separated production.
In this study the following efficiency coefficients are used: for EFF_p = 0,33, and for EFF_q = 0,90, which correspond to the recommendations of EU directive 2004/8/EC [1]. For the calculations a virtual fuel was used (low heating value 29300 kJ/kg).

Limitations are imposed during the solution of equation (1), which are related to the technical characteristics of the steam turbine installations:

- Range of permissible values for the heat in relation to the properties of the turbine – ($\dot{Q}_{chp,min} \leq \dot{Q}_{chp} \leq \dot{Q}_{chp,max}$);
- Range of steam pressure in the regulated steam extraction or in the boiler-condenser at the turbine installations - ($p_{ext,\,min} \leq p_{ext} \leq p_{ext,\,max}$);

Maximum flow rate of the supply district heating water through the boiler installation or boiler condenser - ($G \leq G_{max}$).

3. Case studied

The studied installation is a CHP plant including industrial steam turbine PT-30-90/10 and a steam turbine PR-66-130/10. The first turbine delivers district heat by directing steam from a controlled (steam) extraction to a district heat exchanger where it heats the district heating water. For industrial consumers steam is directed via controlled (steam) extraction from the turbine. For the second installation (backpressure steam turbine) the district heating water is heated by the steam that enters the boiler-condenser. The maximum heat load that both installations can together supply to the consumers is 166,75 MW and it corresponds to the individual installations' maximum heat load where the controlled steam extraction turbine has 36,75 MW and the other one has 130 MW.

The flow of heat and water in the installation is shown on figure 1. The district heating water that enters the plant (G_{DH}) is split in two flows. The one (G_{DHE}) is heated in the district heat exchanger with steam from the controlled steam extraction; the other (G_{BC}) is heated in the boiler condenser of the PR turbine. Afterwards the two flows are mixed in a collector, where the district heating supply water temperature τ_1 is formed.

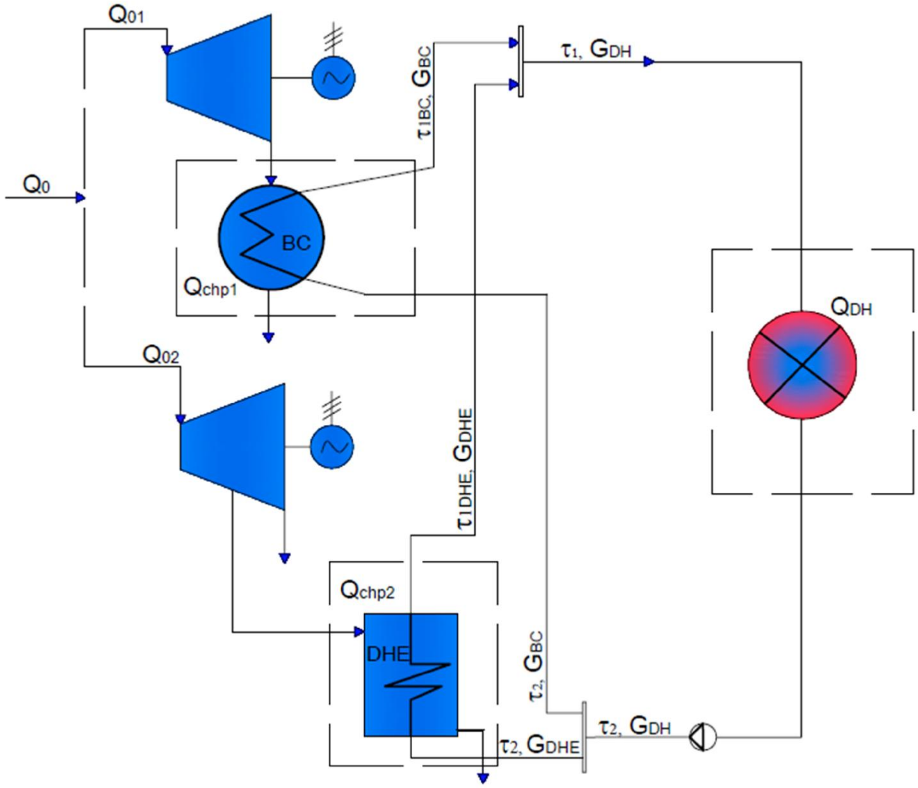


Figure 1 The flow of heat and water in the CHP plant

The problem is solved using the decomposition principle, after which the energy efficiency of each installation is studied separately based on a mathematical model created after analysis of the results from numerical predictions of the CHP operation. The derived mathematical relationships are used for distributing of the heat load between the installations according to the defined objective function (1).

4. Simulation and mathematical modeling

Simulation models for the two steam turbine systems were developed by ***GateCycle*** software**.** Created simulation models are validated by comparing the results obtained by solving them with data as the real operation and the technical documentation of installations [6].

For the mathematical description of the fuel economy of cogeneration plants can be used a second order polynomial [3], as the variables that are involved in it are heat load on the customers $\dot{Q}_{DH}$, temperature of the outgoing τ_1 and incoming τ_2 district heating water :

$$S\left(\tau_1,\tau_2,\dot{Q}_{DH}\right) = b_0 + b_1\tau_1 + b_2\tau_2 + b_3\dot{Q}_{DH} + b_{11}\tau_1^2 + b_{22}\tau_2^2 + b_{33}\dot{Q}_{DH}^2 + b_4\tau_1\tau_2\dot{Q}_{DH} \qquad (3)$$

where:

$S(\tau_1, \tau_2, \dot{Q}_{DH})$ are fuel economy of CHP installation, %;

τ_1 – temperature of the outgoing district heating water, ^oC;

τ_2 – temperature of the incoming district heating water, ^oC;

$\dot{Q}_{DH}$ – heat load production from CHP unit for district heating system, MW;

b_0, b_1, b_2, b_3, b_{11}, b_{22}, b_{33}, b_4 - coefficients of the regression equation.

The verification of the adequacy of the model can be performed according to the criterion of Fischer as the examine the significance of the coefficient of multiple correlation [7]

4.1. Simulation and mathematical modeling on the cogeneration steam turbine PT-30-90/10

Basic flow diagram of cogeneration steam turbine PT-30-90/10 by ***GateCycle*** is present figure 2. Nominal electricity power for this installation is 30 MW. It has two controlled steam extraction and condensing section. CHP installation of this type can reach full electrical power regardless of the outputting heat load through controlled steam extraction.

For the compilation of the simulation model used data from the technical documentation of the turbine. The main elements include models are: steam generator, steam turbine, electrical generator, condenser, four feedwater heaters, deaerator, two controlled steam extraction – industrial steam extraction and district heating steam extraction, district heat exchangers and feedwater pumps.

The steam turbine have high pressure (HPS) and low pressure section (LPS). On the simulation scheme the steam turbine is present by tree section, which is necessary to modeling controlled first steam extraction. Parameters of the steam, which is entered into the model are the temperature and pressure at the inlet of the turbine (t_o=535 ^oC, p_o=8,83 MPa). Steam pressure at the exit of the turbine depends on the mode of operation of the condenser. For LPS set lower and upper limits of steam flow through it. Lower limit is 5,4 kg/s and upper is 12,4 kg/s. Value for isentropic efficiency is 81 %. With the tools provided by the program set up limits of change of steam pressure in controlled steam extractions. These limits are consistent with the technical documentation of the CHP installation. In the modeling un controlled steam extractions set up steam pressure for nominal regime of the turbine. When evaluating variable operating modes, the pressure in the un controlled steam extractions is determined by the equation of Flügel-Stodola. In the model in steam generator are input pressure and temperature on outlet steam. For the condenser model is set heat transfer area (A=600 m^2) and nominal steam pressure p_c= 5 kPa. The parameter enter in district heat exchanger are heat transfer area (A=1700 m^2) and maximal flow of district water through it (G_{DHE}=233 kg/s). In the deaerator model is chosen constant pressure mode. The pressure in deaerator is 1,08 MPa. In the model generator relies its efficiency - 96%. The modeling of the condensate pump to set desired pressure on the water outlet.

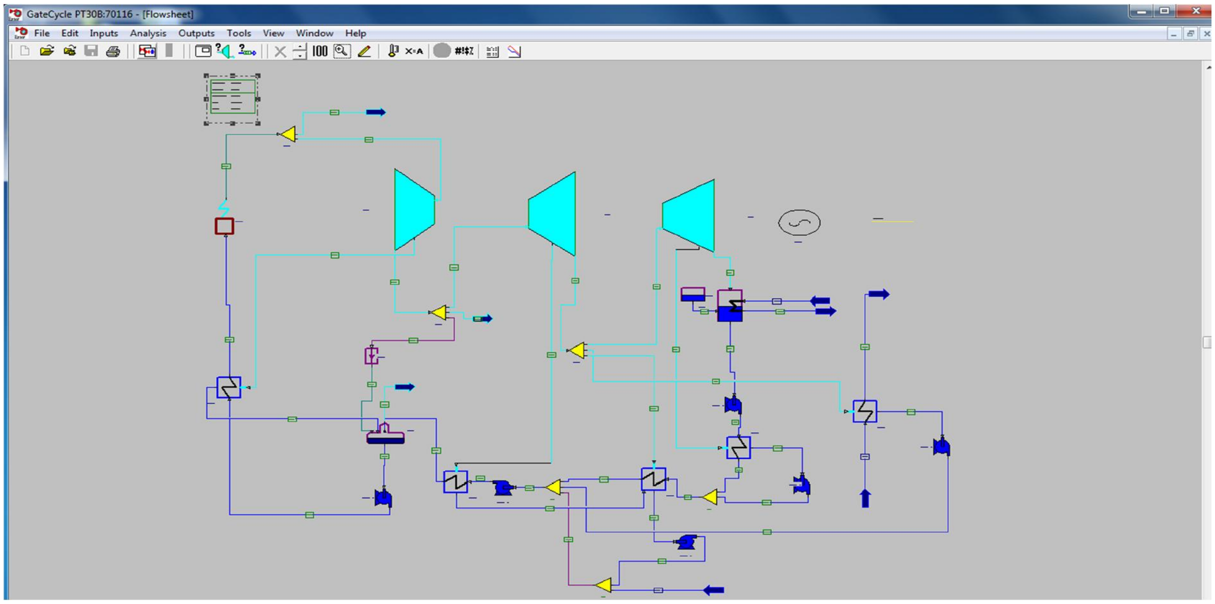


Figure 2 Simulation scheme on cogeneration steam turbine PT-30-90/10 by ***GateCycle***

In order to validate the model was performed calculations for the design mode of the plant, and the results were compared with data of the technical documentation of the turbine - table 1.

Table 1

Cogeneration steam turbine	PT-30-90/10		
	Date from technical documentation	Simulation modeling result	difference, %
Inlet steam pressure, $p_{o,}$ MPa	8,80	8,80	-
Inlet steam temperature, t_o, ^oC	535	535	-
Electricity power, P, MW	30	30	-
Inlet steam flow, D_o, kg/s	51	51,8	1,5
Industrial controlled steam extraction flow , $D_{industrial}$,kg/s	17	17,2	1,1
Water flow from industrial consummators, kg/s	5,56	5,56	-
Steam pressure in industrial controlled extraction, $p_{industrial}$, MPa	1,18	1,15	2,6
District heating controlled steam extraction flow, D_{DH}, kg/s	17	17,2	1,2
District heating controlled steam extraction flow, p_{DH}, MPa	0,20	0,20	-
Steam pressure in condenser, p_c, kPa	5,00	5,19	3,8
Feedwater temperature, t_{FW}, ^oC	230,0	230,0	-
Specific fuel consumption , g/kWh	186	190	2,1

The accuracy of the model is considered adequate if the deviation of the simulation results is within ± 5% [5]. It is seen that the results obtained from the simulation model deviate from the dates specified in the technical documentation within limits. Therefore, the model can be used for research and other modes of steam turbine plant.

Investigate are modes of operation in which the temperature on the incoming district water varies from 50 ° C to 70 ° C, and in the LPS of the steam turbine passes steam flow, which is necessary for its cooling. The thermal load of consummators in heating systems varies from 22 to 36,75 MW and corresponds to the capabilities of the installation concerned to outputting heat.

Constraints for studied modes of installation are:

- Change of steam pressure in the controlled steam extraction p_{DH} from 0,12 MPa to 0,25 MPa;
- District heating water flow, G_{DHE} <233 kg/s;

The results of the simulation calculations for various modes of operation are presented in table 2.

Table 2

№	τ_1, °C	τ_2, °C	Q_{DH}, MW	S, %
1	120	70	36,75	24,44
2	118	70	36, 75	24,69
…………………………………………………………………………….				
27	115	65	35,00	24,32
28	113	65	35,00	24,38
…………………………………………………………………………….				
53	110	60	30,00	22,65
54	108	60	30,00	22,83
…………………………………………………………………………….				
77	105	55	25,00	22,19
78	103	55	25,00	22,41
…………………………………………………………………………….				
107	98	50	22,00	22,16
108	96	50	22,00	22,38

The coefficient of multiple correlation on the equal (4) is e R_{xy}=0,985. According to Fisher criterion it is significant (F^*=403,2 $F(\alpha,\nu_1,\nu_2)$= 2,10). Therefore, the regression equation can be used to assess the fuel economy which results from the operation of the steam turbine PT-30-90/10.

4.2. Simulation and mathematical modeling on the cogeneration steam turbine PR-66-130/10

On the figure 3 is present basic flow diagram on cogeneration steam turbine PR-66-130/10 by software for simulation modeling ***GeteCycle***. This cogeneration installation is backpressure steam turbine with controlled steam extraction. Nominal electricity power for this installation is 66 MW. Electrical power depends on the outputting heat load in district heating systems. This is due to lack of production of electrical energy by a condensation method.

For creation of the simulation model data from the technical documentation of the PR-66-130/10 turbine is used. Regenerative feedwater heating are using four heat exchangers (two have a low pressure and two high pressure). Operation pressure for deaerator unit is 1,08 MPa. This installation delivers heat for domestic and industrial consumers. For domestic heat load are outputting by the boiler-condenser. In the boiler-condenser is heated district heating water by steam from last turbine stage.

Technological heat load are supply by industrial steam extraction. The steam pressure in extraction changes from 0,80 to 1,30 MPa. Initial steam parameters for cogeneration turbine are temperature and pressure (t_o=530 ^{o}C, p_o=12,75 MPa). For LPS in the steam turbine model initiate lower and upper limit for through steam flow. These limits correspond to the minimum (80 MW) and the maximum (130 MW) heat load on boiler-condenser. In the boiler-condenser model is initiate heat transfer area (A=2200 m^2), limits to change steam pressure, the maximum temperature levels on district heat water (outgoing and incoming) and maximal district heat water flow through it. . Other equipment of the thermal scheme are modeled similarly as other steam turbine installation.

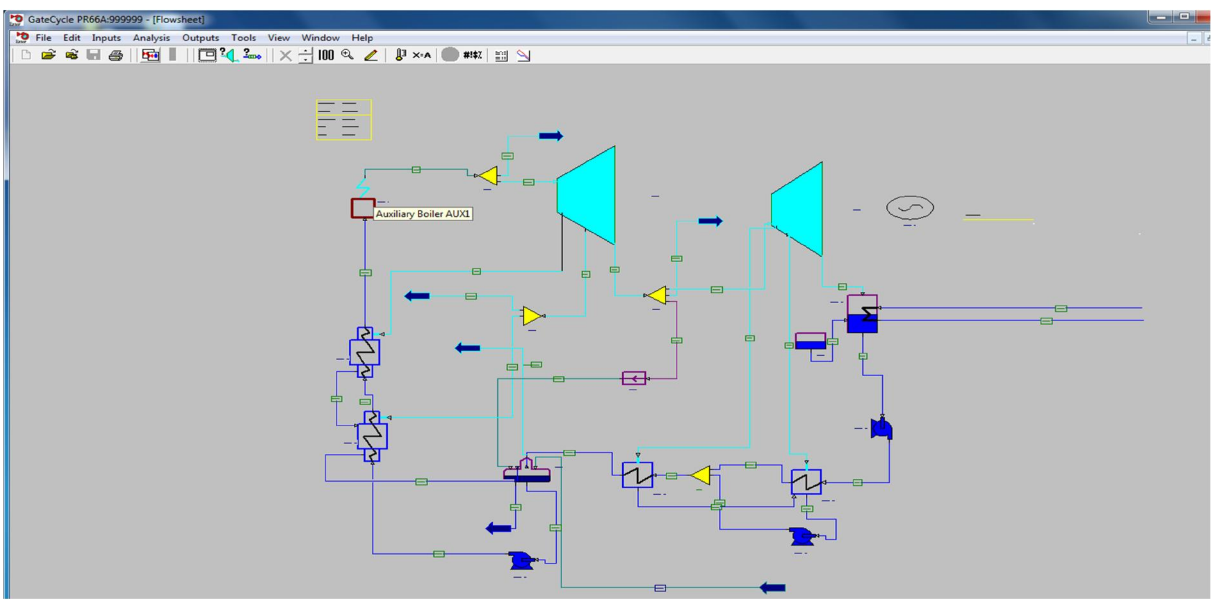


Figure 3 Simulation scheme on cogeneration steam turbine PR-66-130/10 by ***GateCycle***

For the validation of the model is perform the calculation the design mode of the cogeneration installation, the results obtained were compared with data of the technical documentation of the turbine - table 3.

Table 3

Cogeneration steam turbine	PR-66-130-10		
	Date from technical documentation	Simulation modeling result	difference, %
Inlet steam pressure, p_o, MPa	12,75	12,75	-
Inlet steam temperature, t_o, $_o$C	540	540	-
Electricity power, P, MW	66	66	-
Inlet steam flow, D_o, kg/s	123	123.85	1.5
Industrial controlled steam extraction flow, $D_{industrial}$, kg/s	40	40	-
Water flow from industrial consummators, kg/s	5	5,12	2,4
Steam pressure in industrial controlled extraction, $p_{industrial}$, MPa	1,18	1,18	-
Steam flow through boiler-condenser, D_{BC}, kg/s	64	65,2	1,9
Steam pressure at boiler-condenser, p_{BC}, MPa	0,20	0,20	-
Feedwater temperature, t_{FW}, ^{o}C	224	221	1,3
Specific fuel consumption , g/kWh	148	151	2,0

It is evident that the results obtained from the simulation model deviate from the dates specified in the technical documentation within limits (± 5%). Therefore, the model can be used for research and other modes of steam turbine plant.

Researches modes of operation in which the temperature of the opposite network water is changing from 50 ° C to 70 ° C, and the heat consumer loads from 80 to 130 MW. Constraints under which the calculations were performed are:

- Steam pressure into boiler-condenser is change in the range 0,10 ÷ 0,25 MPa;
- Flow of district heating water through $G_{BC} \leq 722$ kg/s;

The results of the simulation calculations for various modes of operation are presented in table 4.

Table 4

№	τ_1,°C	τ_2, °C	Q_{DH}, MW	S, %
1	120	70	130,00	27,38
2	118	70	130,00	27,60
……………………				
29	115	65	120,00	28,10
28	113	65	120,00	28,31
……………………				
61	110	60	110,00	28,47
62	108	60	110,00	28,68
……………………				
103	105	55	100,00	28,94
104	103	55	100,00	29,05
……………………				
197	100	50	80,00	28,85
198	98	50	80,00	29,06

To determine the coefficients of the regression equation (3) is performed out of the obtained data in table 4 using the method of least squares. The regression equation for determining the fuel economy on the CHP turbine PR-66-130/10 acquired type:

$$S\left(\tau_1,\tau_2,\dot{Q}_{DH}\right)= 27,45-5,25.10^{-2}\tau_1 + 2,00.10^{-1}\tau_2 + 6,31.10^{-2}\dot{Q}_{DH} - \\ -2,70.10^{-4}\tau_1^2 - 2,70.10^{-4}\tau_2^2 + -2,3.10^{-4}\dot{Q}_{DH}^2 + 6,10.10^{-7}\tau_1\tau_2\dot{Q}_{DH} \quad (5)$$

The coefficient of multiple correlation on the equal (5) R=0,989. According to Fisher criterion it is a significant (F^*=1056,2, $F(\alpha,\nu_1,\nu_2)$= 2,056). Consequently, obtained regression dependence can be used for evaluating the fuel economy, which is implemented at operation of steam turbine system PR-66-130/10.

5. Optimal heat load distribution between cogeneration steam turbine

The simulating scheme by ***GateCycle*** CHP plant is presented on figure 4. It including industrial with controlled extraction steam turbine PT-30-90/10 and industrial-backpressure steam turbine PR-66-130/10

In creating models of the plant data were used technical documentation for both turbine installations. Common connection between steam turbine installations in the scheme is the tract of district heating water. In the inlet collector district heating water entered in CHP plant. Water inlet Collector splits into two streams. One of them is heating in boiler-condenser on PR-66-130/10 and other heating in district heat exchanger on PT-30-90/10. The limits for district heating water to equipment in plant are entered in model for incoming collector. The temperature of the water to district heating users is obtained after solving of model for output collector.

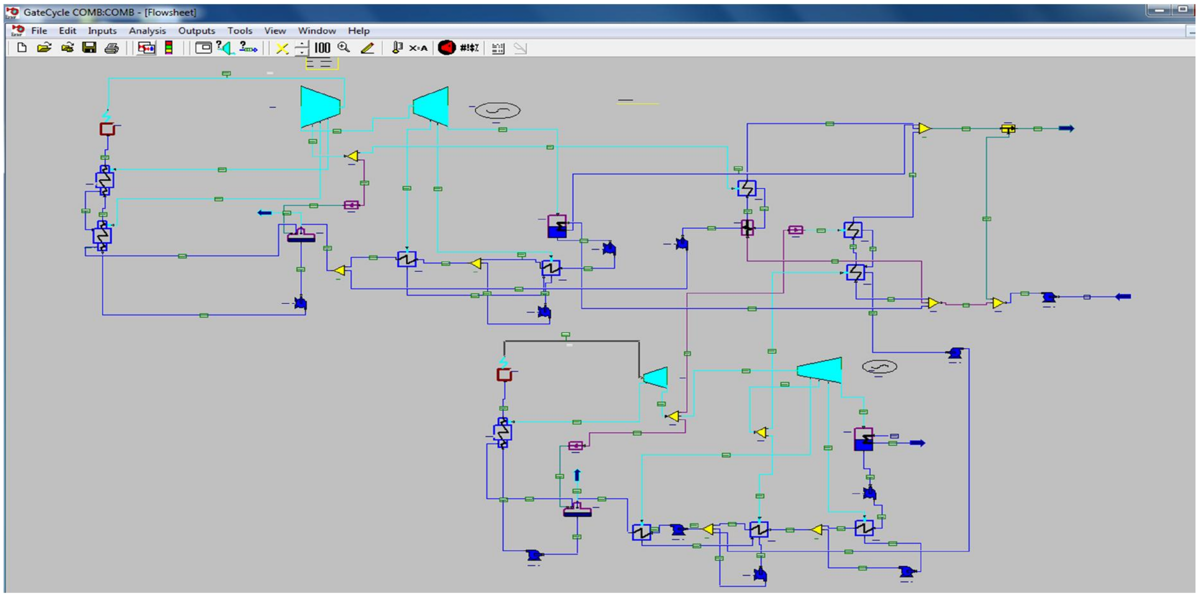


Figure 4. Simulation scheme on CHP plant by ***GateCycle***

The validation of the simulation model is made on the basis of exploitation data for mode with a total heat load 147 MW, in which the turbine PR-66-130/10 is loaded with 125 MW, and the remaining 22 MW is provided by other PT-30-90/10. The results of simulation calculations and data operation mode are given in table 5.

Table . 5

	Date from exploitation	Simulation modeling result	difference, %
Inlet steam flow for cogenerations turns , D_o, kg/s	102,2	97,6	-4,5
Overall electricity power, P, MW	72,5	69,9	-3,7
Temperature level of incoming district heating water , τ_2, ^oC	55	55	-
Temperature level of outgoing district heating water, τ_1, ^oC	94,8	96,8	2,1
Fuel economy, S_{total}, %	27,9	28,8	3,1

It is evident that the results obtained from the simulation model deviate from operational data within acceptable limits (± 5%). Therefore, the model can be applied to the study of other modes.

The optimal heat load distribution between these cogeneration steam turbine are obtained after solving after the objective function:

$$S_{total} = S_{PT}\frac{\dot{Q}_{chp}^{PT}}{\dot{Q}_{chp}^{PT}+\dot{Q}_{chp}^{PR}} + S_{PR}\frac{\dot{Q}_{chp}^{PR}}{\dot{Q}_{chp}^{PT}+\dot{Q}_{chp}^{PR}} = \max \qquad (6)$$

where:

S_{PT} is fuel economy for PT-30-90/10, defined by the equation (4) %;

S_{PR} - defined by the equation PR-66-130/10, defined by the equation (5) %;

$\dot{Q}_{chp}^{PT}$ - heat load outputting from cogeneration steam turbine with controlled extraction PT-30-90/10, MW;

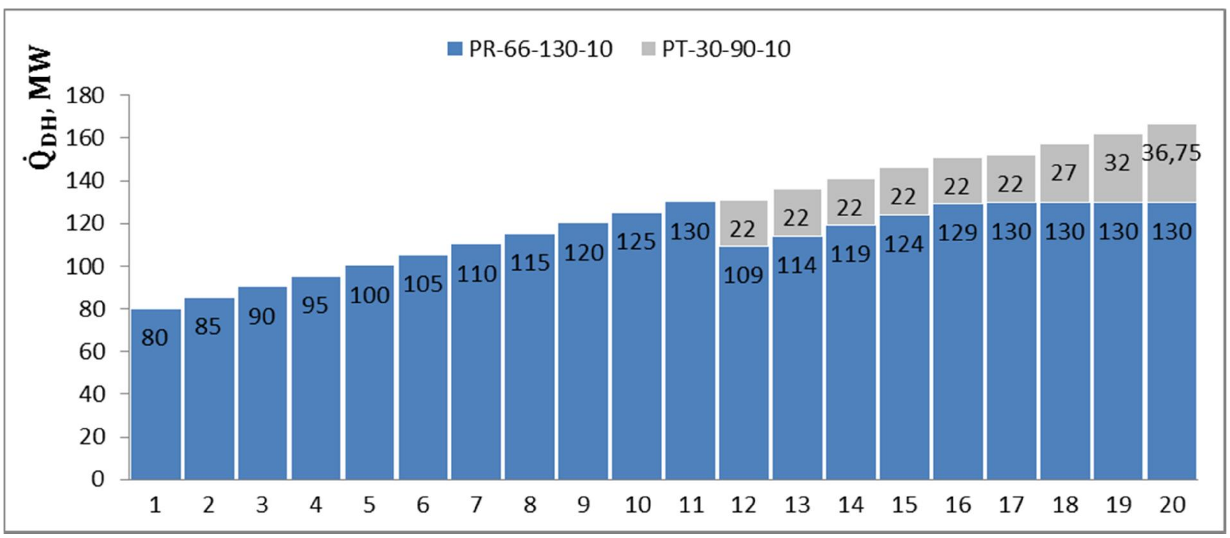
$\dot{Q}_{chp}^{RT}$ - heat load outputting from backpressure steam turbine PT-66-130/10, MW.

Objective function is solved for the mode in which the thermal load is changing from 80 to 166,75 MW, and temperature level on incoming district heating water is changing from 50 to 70 ^{o}C.

The limitations under which the problem is solved are:

- Steam pressure in controlled extraction for PT-30-90/10 is change from MPa, and steam pressure in boiler-condenser is change form 0,12 MPa to 0,25
- Flow district heating water thought district heat exchanger (G_{DHE}) must not exceed 233 kg/s, and flow through boiler-condenser (G_{BC}) - 722 kg/s

Distribution heat load between these steam turbine for operation mods with maximal fuel economy are present on figure**.**



Фиг.5. Structure of the heat load distribution between cogeneration steam turbine in plants for optimal mode.

The heat load of 80 MW is the minimum thermal load that backpressure steam turbine can outputting by boiler-condenser. Backpressure steam turbine operated independently to full load (130 MW), explained by greater fuel economy, which this installation realized. When the load increases above 130 MW is needed in the heat source to distribute the heat load between steam turbine installations. For example, if consumption in heating systems of 131 MW required heat load of backpressure turbine system to be reduced to 109 MW, which is explained by the minimum heat load of the other PT-30-90/10 turbine of 22 MW. By increasing the consumption of heat, the thermal load of the controlled steam extraction turbine remains constant, while backpressure is loaded to its full heat output due to its greater economy. If the heat load of 152 MW backpressure steam turbine realize their full thermal output of 130 MW, and the remaining 22 MW is provided by PT-30-90/10. By increasing the heat load in excess of 152 MW is gradually loaded steam turbine with controlled extraction.

Changing of fuel economy in joint work of the two turbines, depending on the district heating load and the temperature level of the incoming water τ_2, is presented on figure 6.

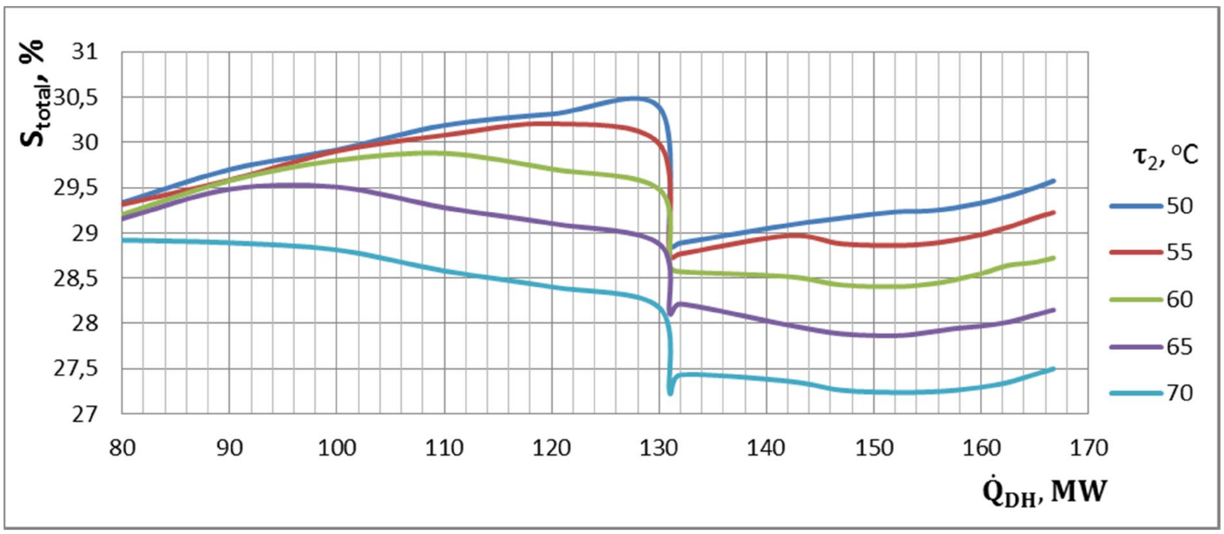


Figure 6. Variation of fuel economy, depending on the heat load and the temperature of incoming district heating water at the optimal mode.

When heat load is changed from 80 to 130 MW, the maximal fuel economy is changed form 28,9 to 30,4%. For this case PT-30-90/10 does not output heat load for district heating. At the heat load of 131 MW fuel economy decreases due to the load of 22 MW of steam turbine with controlled extraction. Fuel economy in this mode is amended in the range of 27,2 to 28,9 %. The higher value corresponds to the temperature of incoming water from 50 °C and the lower temperature of 70 °C. When both of systems are fully loaded and the temperature of the water at the input of the plant is 50 °C, fuel economy in their joint work reaches 29.6%. At increase in temperature of the water network to the opposite 70 ° C reduced the fuel economy by about 2%.

By the simulation model of the plant is performed research on the optimal distribution of the heat load between the both turbines. Research is the amendment of these magnitudes:

- Temperature level on outgoing district heating water – τ_1, °C;
- Total electrical power from CHP plant– P, MW;

Changes on the temperature level of district heating water for optimal heat load distribution is presented on Figure 7.

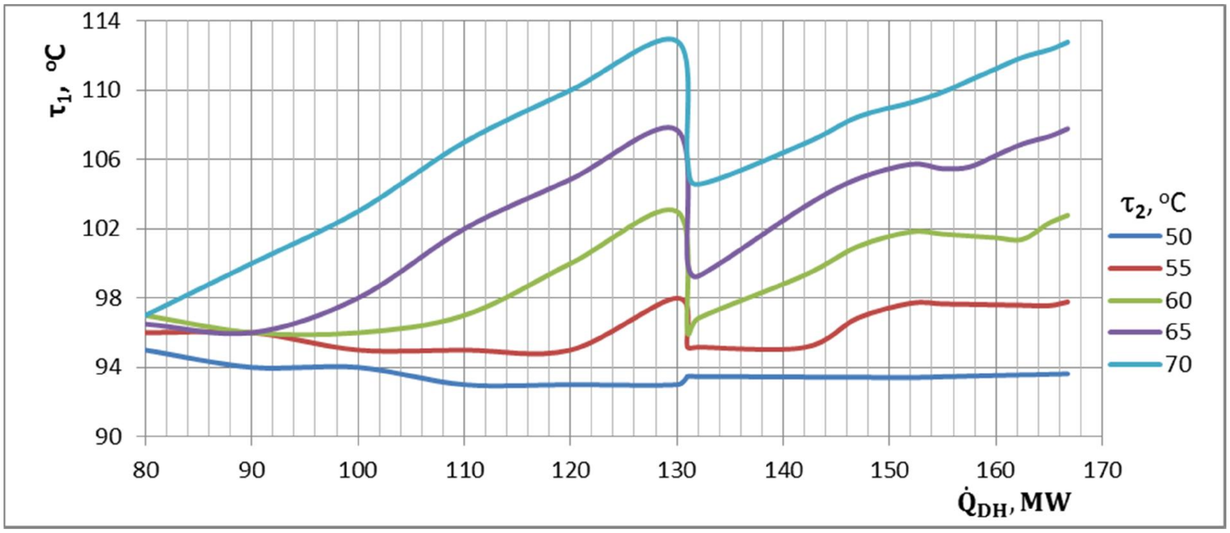


Figure 7. Changes of level temperature outgoing water fore operation modes with maximal fuel economy

Seen to be that variation of the heat load of 80 to 130 MW water temperature to consumers depends on the capabilities of backpressure steam turbine to heat water. The inclusion of the heat loads in PT-30-90/10 130 MW reduces the temperature level for outgoing district heating water and this change is larger at a higher inlet temperature. At the increase of the heat load, the temperature of water supply network increases. When the thermal load reaches the maximum temperature of the water supply network is changing from 94 ^{o}C. to 113 ^{o}C at changing the temperature on incoming water from 50 ^{o}C. to 70 ^{o}C.

Electrical power outputting from both steam turbine for operation mode with maximal fuel economy is presented on Figure 8.

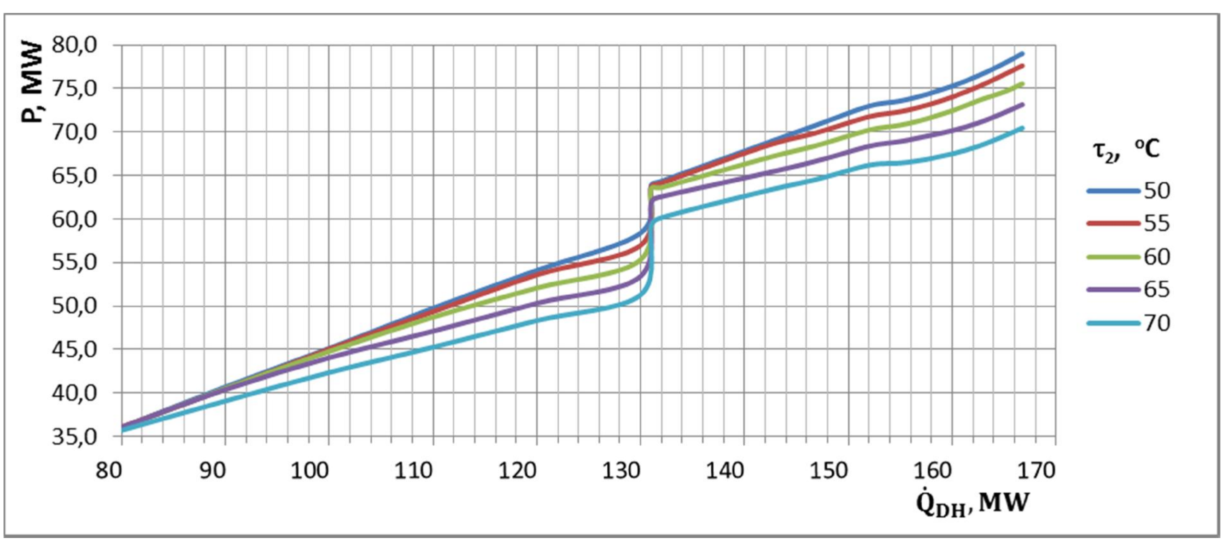


Figure 8. Changes of outputting electrical power in joint work of both of steam turbine

When the heat load is provided to consumers only by backpressure steam turbine plant, electric power is changing from 35,8 MW to 58,4 MW. A low value corresponds to the minimum heat load and the temperature of the incoming water from 70 ^oC. Electrical power of 58,4 MW realize for 130 MW heat load on boiler-condenser and incoming water temperature 50 ° C. When the heat load of 131 MW, the electric power generated by the turbine PT-30-90-10 is from 23 to 25% of total electric power, depending on the temperature level of the incoming water from district heating. At the maximum heat load and water temperature at the plant inlet 50 ^oC electrical power reaches 79 MW and gradually decreases with increasing temperature and at 70 ^oC it is equal to 70,4 MW.

6. Conclusion

Developed are simulation models for combined heat and power installations with regulated steam extraction PT-30-90/10 and backpressure PR-66-130/10. After models validation the efficiency was studied of the steam turbine installations at conditions different from the design ones. The numerical results are used for development of mathematical models for prediction of fuel economy and optimization of the installations operation under different consumer heat demands and temperature of supply and return district heating water of the installations.

An approach was suggested for optimizing the heat load distribution between the steam turbine installations with regulated steam reduction PT-30-90/10 and steam turbine with backpressure PR-66-130/10 to achieve maximum fuel economy.

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