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Influence of temperature of return district water on the performance of a backpressure steam turbine installation

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Abstract. The district heating systems supply heat to a wide range of consumers. In the heat source of such systems, highly efficient technologies are used for the combined production of electrical and thermal energy mainly based on steam turbine installations with backpressure turbines or turbines with adjustable steam extractions. Combined production leads to a reduction in fuel consumption (fuel saving) compared to the separate production of the two energy products. The fuel saving resulting from cogeneration reduces carbon dioxide emissions. Combined production affects the amount of fuel saved, leading to a reduction in emitted emissions, both the size of the heat load realize to consumers and the temperature of the water that enters from the return pipeline of the district heating systems into the heat source. In backpressure steam turbine installations, the district water is heated by the steam that enters the boiler-condenser, and in steam turbine installations with adjustable steam extraction, it is heated in a district heater by steam extracted from the turbine. The purpose of this paper is to study the influence of the temperature of return district heating water on the performance of a backpressure steam turbine installation for cogeneration.

Introduction

Combined production of thermal and electrical energy is implemented in thermal power plants, which allows for the efficient use of primary energy resources and the reduction of carbon emissions in the environment. The thermal energy generated at the source is delivered to domestic and industrial consumers through the district heating system. The industrial load is mostly constant throughout the year, and the parameters of the steam through which it is supplied remain constant.

The domestic load has two components – heating and domestic hot water supply. The heating load is variable, seasonal and mainly depends on the outside air temperature. The load for domestic hot water supply is year-round, almost independent of the outside temperature and is delivered to consumers with a constant temperature of the district heating water.

The main parameters that determine the mode of operation of the district heating system are

- flow of district water (G, kg/s);
- temperature of supply district water (τ_1,˚C);
- temperature of return district water (τ_2.˚C).

These parameters determine the heat load Q_{DHS} that is supplied to the consumers and they are related by the following equation:

$$Q_{DHS} = Gc_p(\tau_1 - \tau_2) \quad (1)$$

where: c_p is specific heat capacity, kJ/kg ˚C.

The change of each of the parameters: G, τ_1, τ_2 leads to a pressure change in the boiler-condenser, which affects the thermal efficiency of backpressure steam turbine installations.

The controllable parameters of the heat source are the temperature of the supply water to the district heating system (τ_1) and the flow of district water (G). The temperature of the return district water (τ_2) is an uncontrollable parameter for the heat source, the value of which is the resultant magnitude of heat consumption in the district heating system.

The temperature of the return district water is input to the heat source and has the value of τ_2. In backpressure steam turbine installations, it is heated in a boiler-condenser by the steam after the turbine, whereas in steam turbine installations with adjustable steam extraction, heating is carried out in a boiler system with steam generated in one or more turbine steam extractions [1-3].

The change in the temperature of the return district water leads to a change in the pressure in the boiler-condenser. This influence can be expressed by the following formula:

$$t_s = \tau_2 + \Delta\tau + \delta t \tag{2}$$

where:

t_s - saturation temperature of the vapor in the boiler-condenser, ˚C

$\Delta\tau$ - heating magnitude of the district water, ˚C;

δt – the temperature difference of the flows in the heat exchanger, ˚C

The saturation temperature of the vapor (t_s) unambiguously determines the steam pressure in the boiler-condenser.

As the pressure in the boiler-condenser decreases, the processed enthalpy drop of the turbine increases and the relative production of electrical energy on the basis of heat consumption (power to heat ratio) increases. The power to heat ratio is defined as the ratio of the received electrical energy by the combined method P_{DHS} to the released heat for the district heating system Q_{DHS} from the steam turbine installation [4, 5]. At a set heat load of the heat supply system, this indicator depends on the operating mode of the turbine. The main mode factor is the steam pressure in the boiler-condenser.

In the district heating system, a qualitative-quantitative regulation of heat loads is applied, which is characterized by a change in the flow and in the temperature of the district water depending on the outside air temperature (t_{out}, ˚C) [1, 2, 6].

The temperature graph of the district heating system of the city of Sofia is presented in Fig. 1. The calculation temperature graph for the applied qualitative-quantitative regulation of heat loads is 150/70 ˚C. This means that when the calculated temperature of the outside air is reached, the district water at the outlet of the heat source has a temperature of 150 ˚C, and the temperature of the water in the return heat pipe is 70 ˚C.

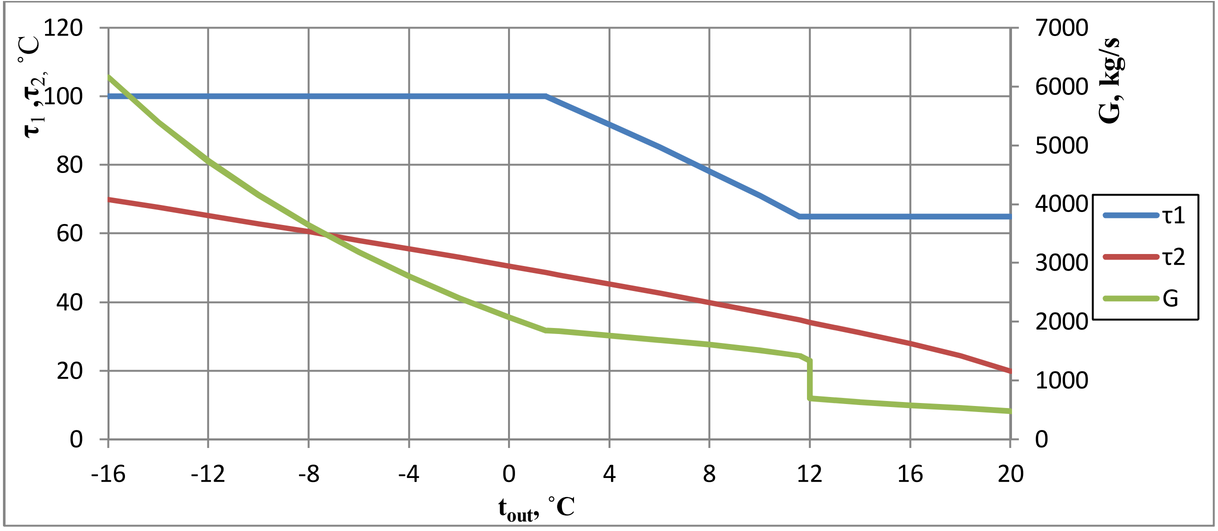

Fig.1 The temperature graph of the district heating system of the city of Sofia

The temperature graph is characterized by two "cut-offs", where the temperature of the supply district water is kept constant despite the change in the outside temperature. At the left part of the graph (low outside temperatures), the temperature graph cut-off at 100 °C and the district water supply temperature is maintained at this level at lower outside temperatures. In order to meet the heat load under these conditions, the flow of district water in the heat supply system increases. These modes are characterized by lower heat losses (due to the lower temperature) and by a higher consumption of electrical energy in the heat supply from the source to the consumers.

At the right part of the graph, the temperature cut-off is at 65 °C and the district water temperature is maintained at this level at higher outside temperatures. The break in the temperature graph in this case is necessitated by the need to heat the water for domestic needs to the normative value of 55 °C.

At outside temperatures higher than 12 °C, the heat supply in the district heating system is terminated, and heat is released only for domestic hot water supply.

In order to assess the influence of the temperature of the return district water on the performance of the combined production of the installation, it is necessary to determine the energy efficiency indicators of this kind of technology.

An unequivocal assessment of the perfection of combined production gives the fuel saving indicator (ΔF, MWh) [4], which is obtained in comparison with the separate production of the same amount of heat and electricity. This indicator is determined by the difference between the energy equivalent of the fuel input in the installation for separate production technology (F_{SHP}, MWh) and the energy equivalent of the cogeneration unit (F_{CHP}, MWh). The consumption fuel from the combined production unit depends on the size of the release heat load to the consumers and the temperature graph of the district heating system. The determination of the energy input with fuel in the separate method of production is performed on the basis of reference efficiency values for the production of electrical and thermal energy from the replacement technologies [7]. These values depend on the type of fuel used in the cogeneration unit. The energy equivalent of the fuel input in both technologies is determined at the same volumes of thermal and electrical energy production. Fuel saving is calculated using the equation:

$$\Delta F = F_{SHP} - F_{CHP} \tag{3}$$

As a result of the fuel saving in the cogeneration, the emitted emissions are reduced compared to the separate production of electricity and heat energy. The carbon emissions saving (ΔE_{CO2}, kg) from the cogeneration production is determined based on the obtained fuel saving and the specific emission factor (f_{CO2}, kg_{CO2}/MWh), the value of which depends on the type of fuel used [8-10]. The carbon emissions saving as a result of the operation of the cogeneration unit is given by equation:

$$\Delta E_{CO2} = \Delta F \cdot f_{CO2} \tag{4}$$

In a series of studies, the economic effect and environmental benefits of lowering the temperature of the return district water have been determined [11-14], where the object of analysis is only the district heating system.

The present development aims to study the influence of the temperature variation of the return district water inlet for heating in the heat source on the performance indicators of a backpressure cogeneration steam turbine.

To obtain numerical data, a simulation study was performed using a verified and validated model of a backpressure steam turbine installation [15].

Simulation model of a cogeneration installation

The studied cogeneration installation, which releases heat to consumers, is VPR-66-130/10. It is a backpressure steam turbine with a maximum electrical power of 66 MW and releases thermal energy for domestic and industrial heats consumers. The thermal energy for industrial consumers is supplied by steam from an adjustable steam extraction turbine, and thermal energy for domestic users is supplied by district water, which is heated in the boiler-condenser by steam which, before entering the boiler-condenser, has produced electrical energy at the terminals of the generator.

The developed simulation model of the steam turbine installation in the GateCycle environment is shown in Fig.2

In the simulation environment, the steam turbine is presented as a two-cylinder using the tools available in the software. This is required in order to simulate the adjustable steam extraction of the steam turbine. When modeling the individual elements, values of a constructive and regime character are introduced according to the documentation of the steam turbine installation. For example, for the boiler-condenser of the installation, design parameters such as number of flow passes, heating surface, inner and outer diameter of the pipes are input.

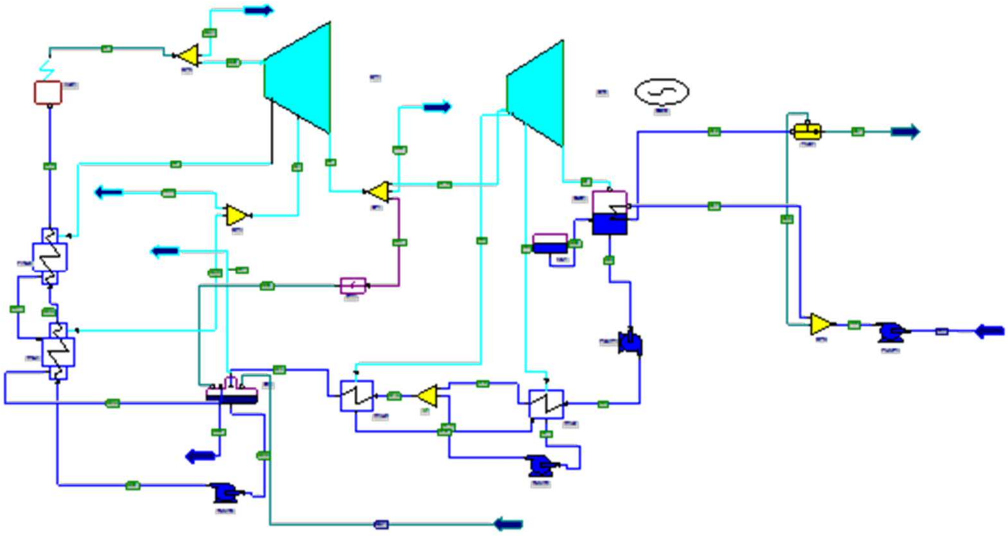

Fig. 2. Visualization of heat scheme on VPR-66-130/10 by simulation software GateCycle.

The development of the model of the steam turbine plant is shown in detail elsewhere [15]. On the basis of data from the technical documentation of the turbine, simulation calculations of characteristic operating modes were performed and the accuracy of the model was evaluated.

Input data for the study

The input data for solving the simulation model of the steam turbine plant are:

- inlet steam pressure - $p_o = 13$ MPa;
- inlet steam temperature - $t_o = 535\ ^{o}C$
- maximum heating of the district water in the boiler-condenser - $\Delta\tau = 50\ ^{o}C$;
- maximum flow of district water through the boiler-condenser - G = 722 kg/s;
- steam pressure variation limits in the boiler from 0.1 to 0.25 MPa;
- maximum steam flow in the boiler-condenser- 63 kg/s.

The mode of operation of the backpressure steam turbine installation is considered, in which 130 MW of heat load is released to consumers through the boiler-condenser. Industrial steam extraction is not operating and heat for industrial users is not released.

For the purpose of the study, the temperature of the return district water changes in the range from 50 ^{o}C to 70 ^{o}C. The value of 50 ^{o}C is typical for the end of the heating season, as well as when releasing heat only for domestic hot water supply (summer mode). At the design temperature of the outside air, the temperature of the district water in the return heat pipe reaches the upper limit of the considered temperature interval - 70 ^{o}C.

The flow of district water through the boiler-condenser is changed to meet the heat load and corresponds to the passport data of the turbine.

Results of the simulation study

By the simulation model, multivariate calculations of the operating modes of the steam turbine installation were performed. The following quantities were calculated:

- electrical power of the steam turbine at different load modes - P, MW;
- electrical power of the steam turbine, which is developed as a result of the heat released in district heating system – P_{DHS}, MW;
- electrical power resulting from the regenerative heating of the main condensate – P_{REG}, MW;
- flow of district water through boiler-compensator - G, kg/s;
- steam pressure change in change boiler-compensator - p_{BC}, MPa;
- power to heat ratio – P_{DHS}/Q_{DHS}.

The obtained results are presented graphically depending on the temperature of the return district water τ_2 and magnitude of its heating in the boiler-condenser $\Delta\tau$

The change in the electric power P_{DSH} of the steam turbine unit, produced by the combined method, when releasing heat to consumers, is shown in Fig.3.

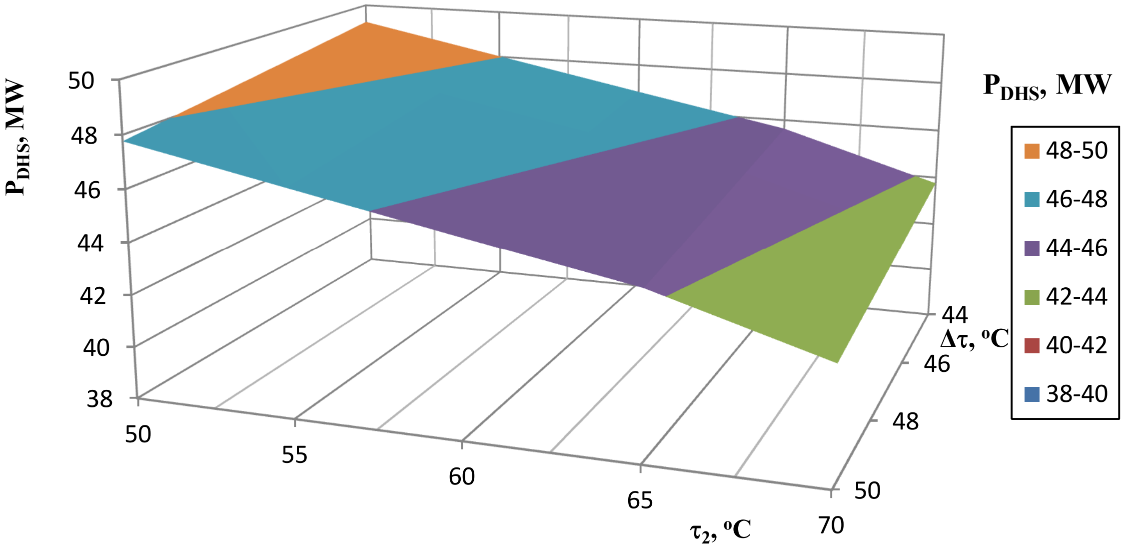

Fig. 3. Change of the electric power of the steam turbine installation P_{DSH} at a heat load of the consumers Q_{DHS}=130 MW depending on the temperature of the return district water and the magnitude of the heating of the water in the boiler-condenser.

It can be seen that as the temperature of the return district water decreases, the electric power (P_{DHS}) obtained by the combined method increases.

For the considered heat load and maximum district water heating, the electric power of the P_{DHS} steam turbine plant increases from 42.35 to 47.76 MW when the temperature of the return district water decreases from 70 °C to 50 °C. The increase in electrical power is due to the lower steam pressure in the boiler-condenser in this mode and, accordingly, to an increase in the available enthalpy drop for the steam turbine. The change in steam pressure in the boiler-condenser p_{BC} when the temperature of the return district water changes is shown in Fig. 4.

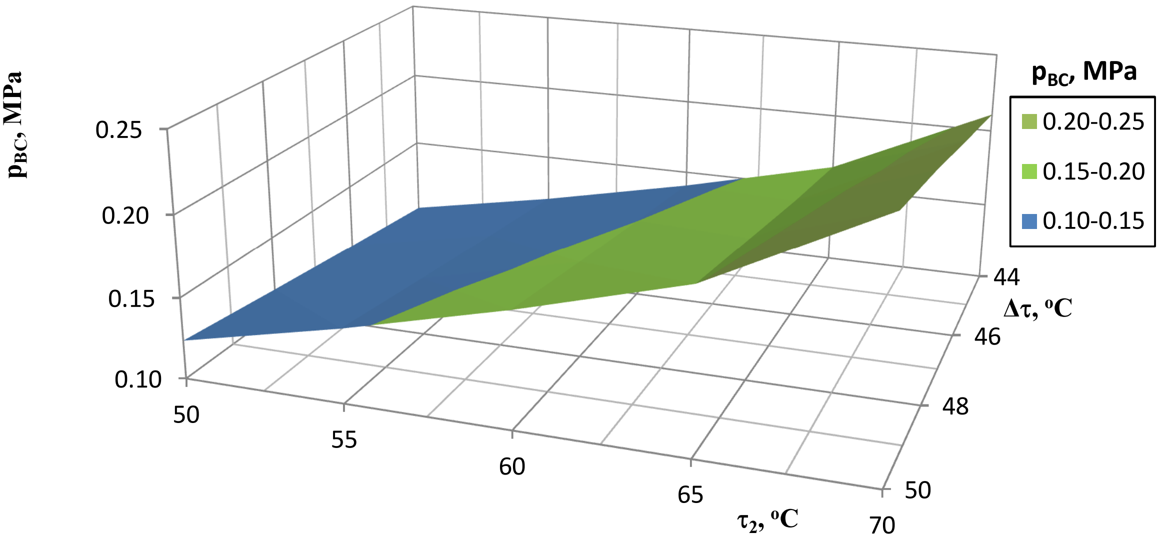

Fig. 4. Change of the steam pressure in the boiler-condenser depending on the temperature of the return district water and the magnitude of the heating of the water in the boiler-condenser.

The steam pressure in the boiler-condenser has changed in the interval from 0.12 to 0.25 MPa. At a temperature of 50 ˚C of the return district water and magnitude of the heating of 44 ˚C, the steam pressure is 0.12 MPa

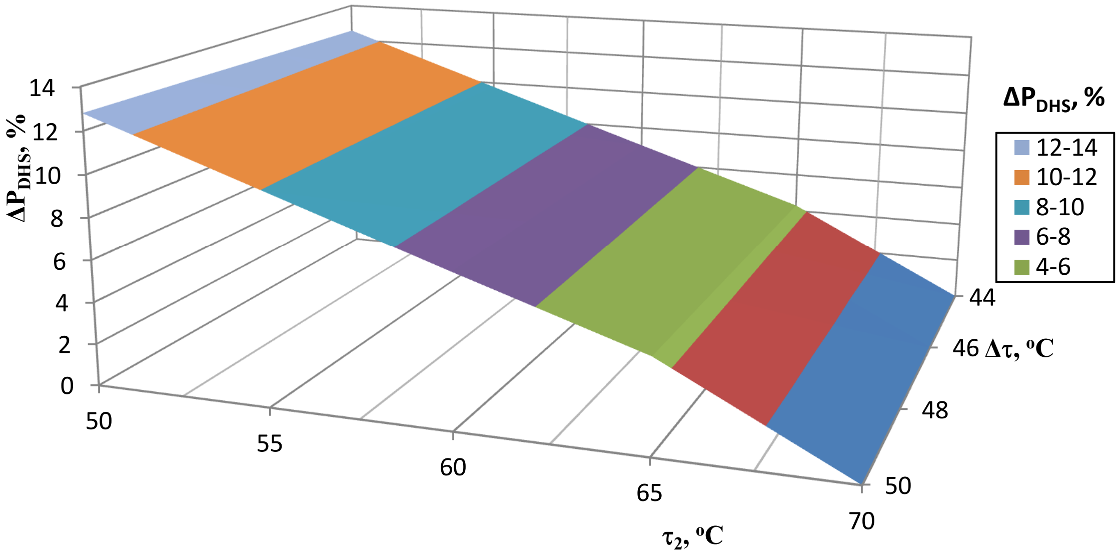

Fig. 5. Relative change of electric power at a heat load of the consumers Q_{DHS}=130 MW as a function of temperature of the return district water and the magnitude of the heating of the water in the boiler-condenser.

Fig. 5 presents the relative change in electrical power in percentages (ΔP_{DHS}, %) when the temperature of the return district water decreases from 70 ˚C to 50 ˚C. It can be seen that the combined electrical power increases as the temperature of return district water decreases. It reaches maximum value at a temperature of the return district water of 50 ˚C. The maximum value is 12.8% higher compared to the combined electrical power obtained at a temperature of 70 ˚C.

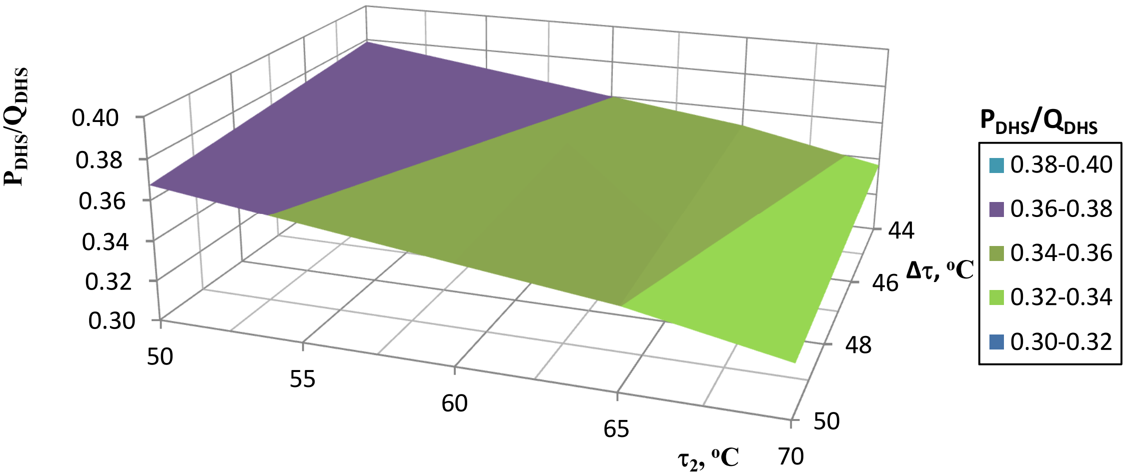

Fig. 6. Change of the power to heat ratio at a heat load of the consumers Q_{DHS}=130 MW depending on the temperature of the return district water and the magnitude of the heating of the water in the boiler-condenser.

The power to heat ratio at variable magnitude of the heating of the district water in the boiler-condenser and variable temperature of the return district water is shown in Fig. 6. It can be seen that this magnitude increases with the decrease of the temperature of the incoming district water from the heat supply systems. The change of the indicator is in the interval from 0.320 to 0.380. The higher value corresponds to power to heat ratio of 49.24 MW, which is reached at a temperature of the district water at the boiler inlet of 50 ˚C and a steam pressure of 0.12 MPa.

The carbon dioxide emissions savings as a result of the operation mode of the cogeneration unit are shown in Fig.7. Their value is obtained after determining the fuel savings resulting from the combined heat and power generation of the backpressure steam turbine. The reference values of the replacement capacities for the production of thermal and electrical energy, as well as the emission factor corresponding to the natural gas fuel.

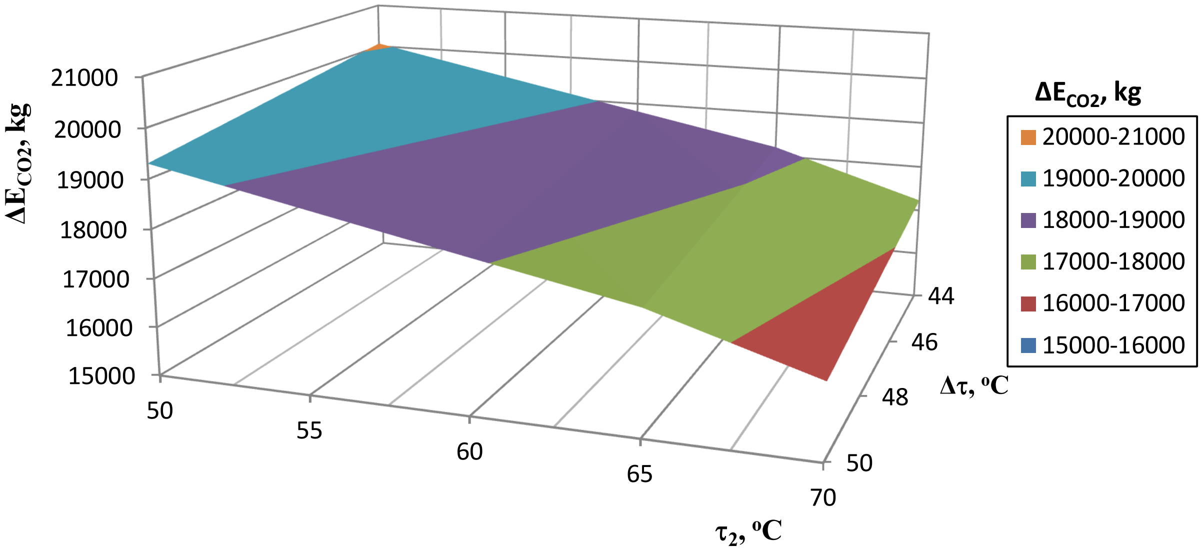

Fig. 7. Change in the emmision savings at a heat load of the consumers Q_{DHS}=130 MW depending on the temperature of the return district water and the magnitude of the heating of the water in the boiler-condenser.

From the obtained results for the emission saving of carbon dioxide, it can be seen that they increase with the decrease in the temperature of the return district water of the heat supply system. This is due to the increased fuel saving in these modes of operation of the steam turbine installation.

At a heat load of the district heating system of 130 MW and 6000 hours of annual operation of the cogeneration plant, reducing the temperature of the return district water at the inlet of the boiler-condenser from 70 ˚C to 50 ˚C saves around 16300 tons of carbon emissions from the combustion of natural gas. These emissions correspond to a fuel saving of 10,000 tons (coal equivalent).

Analysis of the obtained results

In this study, the influence of the temperature of the return district water on the operation of a backpressure steam turbine installation VPR-66-130/10 is investigated. The study was performed by simulation modeling using a validated and verified model of the steam turbine installation. The multivariate calculations were performed for typical modes of operation of the district heating system of the city of Sofia.

The obtained numerical results show that a decrease in the temperature of the return district water, the production of electrical energy obtained from combined production increases. This is due to the increase in the processed enthalpy drop from the backpressure steam turbine.

From the results obtained in the study for the maximum heat load, which is released to the heat consumers through the boiler-condenser on the cogeneration unit, it can be seen that with a decrease in the temperature of the water in the return pipe by 1 °C, the electrical power of the steam turbine increases by 0.370 MW.

Lowering the temperature of the return district water increases fuel economy and reduces carbon dioxide emissions from the cogeneration unit. For the considered heat load of the district heat supply system with an annual duration of operation of 6000 hours, the decrease in the temperature of the return district water by 1 °C leads to the conditional fuel economy of 515 t coal equivalent. The fuel saved reduces carbon dioxide emissions by about 842 t, when using natural gas from the cogeneration unit.

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