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# ANALIZA UČINKOVITOSTI KOGENERACIJSKOGA PARNO-TURBINSKOG POSTROJENJA SNAGE 5,7 MW<sub>el</sub> EFFICIENCY ANALYSIS OF A STEAM TURBINE COGENERATION PLANT WITH CAPACITY 5,7 MW<sub>el</sub>

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**Sažetak:** U industriji, gdje se istovremeno u proizvodnom procesu koristi toplinska i električna energija, jedan od najučinkovitijih načina snabdijevanja energijom je zajednička proizvodnja toplinske i električne energije u kogeneracijskom parno-turbinskom postrojenju. Uz obnovljive izvore energije, kogeneracijska postrojenja su danas veoma poticani energetske sustavi. U INI-Maziva Rijeka ugrađeno je kogeneracijsko parno-turbinsko postrojenje snage 5,7 MW<sub>el</sub>. Za zajedničku proizvodnju toplinske i električne energije, ovo kogeneracijsko postrojenje ima ugrađenu kondenzacijsku turbinu s reguliranim oduzimanjem pare. U ovom su radu dani glavni tehnički podaci i analiza učinkovitosti toga kogeneracijskog parno-turbinskoga postrojenja.

**Ključne riječi:** – kogeneracija  
– parno-turbinsko postrojenje  
– učinkovitost

**Summary:** In industry, where heat and electric energy is to be used simultaneously, the most efficient way for energy supply is the combined production of heat and power in a cogeneration steam turbine plant. In addition to renewable energy, cogeneration plants are today very productive energy systems. In the INA-Maziva Rijeka refinery, a CHP plant has been built with a capacity of 5,7 MW<sub>el</sub>. For combined heat and power production, these cogeneration plants are equipped with a steam condensing turbine with one controlled and one non-controlled extraction. This paper presents the main technical characteristics and gives an efficiency analysis of this cogeneration steam turbine plant.

**Key words:** – cogeneration  
– steam turbine plant  
– efficiency

## 1. UVOD

U industriji i naseljenim mjestima, gdje istovremeno postoji potreba za toplinskom i električnom energijom, najjednostavniji je i najčešći način snabdijevanja ovim oblicima energije da se toplinska energija proizvodi u kotlovnica, a električna energija preuzima iz javne mreže. Međutim, znatno učinkovitija je zajednička proizvodnja toplinske i električne energije u kogeneracijskim parno-turbinskim postrojenjima. Odvojena proizvodnja toplinske energije je nepovoljna i s ekološkog stajališta jer se spaljuje gorivo i zagađuje okolina, a da se pri tome ne koristi mogućnost proizvodnje vrijedne električne energije.

Za kogeneracijska parno-turbinska postrojenja mogu se primjenjivati protutlačne parne turbine ili kondenzacijske turbine s reguliranim oduzimanjem pare [1-6].

## 1. INTRODUCTION

In the industry and in cities, where heat and electric energy is needed at the same time, the simplest and the most common method of energy supply is by separately producing heat in steam boilers, while electric energy is purchased from the outside power grid. However, a more efficient mode is the combined production of heat and power in cogeneration steam turbine plants. The separate production of heat and power is also unfavorable for the environment, because the burning of fuel pollutes the environment in this case without any production of worthy electric energy.

Back-pressure and condensing steam turbines with controlled extraction can be used for cogeneration steam turbine plants, [1-6].

The plants with back-pressure steam turbines are the

Postrojenja s protutlačnim parnim turbinama su najjednostavnija i najučinkovitija parno-turbinska postrojenja. Međutim, kod njih proizvodnja električne energije ovisi o potrebi toplinske energije. Kad nema potrošnje toplinske energije ne može se proizvoditi električna energija. S protutlačnim turbinama zadovoljava se potreba za toplinskom energijom, a u slučaju manjka, električna se energija preuzima iz vanjske elektroenergetske mreže, dok se u slučaju viška isporučuje u elektroenergetsku mrežu. Postrojenja s kondenzacijskim turbinama uz regulirana oduzimanja pare su složenija i manje učinkovita u odnosu na postrojenja s protutlačnim turbinama. Međutim, u njima se može proizvoditi toplinska i električna energija i u slučajevima kada nema potrebe za toplinskom energijom. Ovakva se postrojenja obično ugrađuju kada se želi iz vlastita izvora snabdijevati s potrebnom toplinskom i električnom energijom, bez ovisnosti od javne elektroenergetske mreže.

U rafinerijskim postrojenjima INA-Maziva Rijeka ugrađeno je 2006. godine kogeneracijsko parno-turbinsko postrojenje za proizvodnju toplinske i električne energije. Kogeneracijsko postrojenje ima ugrađenu kondenzacijsku turbinu s jednim reguliranim oduzimanjem pare, tako da može proizvoditi električnu energiju i kada nema potrebe za toplinskom energijom. Toplinska se energija koristi za tehnološke procese, a električna za pogon elektromotora i rasvjetu.

U ovom članku dan je prikaz toga kogeneracijskog parno-turbinskoga postrojenja namijenjenoga za zajedničku proizvodnju toplinske i električne energije. Prikazana je koncepcija kondenzacijske turbine s jednim reguliranim i jednim ne-reguliranim oduzimanjem pare. Analizirani su režimi rada i učinkovitost takvoga postrojenja uz prikaz i komentar rezultata.

## 2. OPIS KOGENERACIJSKOGA PARNO - TURBINSKOG POSTROJENJA

Kogeneracijsko parno-turbinsko postrojenje sastoji se od kondenzacijske turbine s jednim nereguliranim i jednim reguliranim oduzimanjem pare i generatora električne energije. Oduzimanja pare iz turbine koriste se za tehnološke potrebe u proizvodnim postrojenjima.

Osnovni tehnički podaci parno-turbinskoga agregata za zajedničku proizvodnju toplinske i električne energije jesu [7]:

### Turbina

- računski snaga.....5,7 MW
- maksimalna snaga.....6,0 MW
- brzina vrtnje.....9500 min<sup>-1</sup>
- tlak pare na ulazu u turbinu.....4,0 MPa
- temperatura pare na ulazu u turbinu..430 °C

simplest and the most efficient steam turbine plants. But, their production of electric energy depends on the use of heat energy. When heat is not needed for consumption, electric energy cannot be produced.

With back-pressure steam turbine plants, the consumption of heat energy has to be covered, while electric energy can be delivered to or purchased from the outside power grid.

Plants with condensing steam turbines that have controlled extractions are more complex and less efficient compared to systems with back-pressure steam turbines. But in these plants, electrical energy is dependent upon heat consumption. Such plants are usually installed in cases where heat and power have to be produced from the source plant and without dependence on a public power grid.

In refinery plants of INA-Maziva Rijeka, a cogeneration steam turbine plant was constructed during the year 2006, with the aim of producing heat and power for refinery needs. This cogeneration plant has a condensing steam turbine with one controlled extraction, so it can produce power also in cases when heating energy is not needed. Heating energy is used for refinery processes, while electric is used for the motor operation and for lighting.

A description of this cogeneration steam turbine plant for the combined production of heat and power is given in this article. A basic design is presented for the condensing steam turbine with one controlled and one non-controlled steam extraction. Working regimes and plant efficiency are analyzed with the presentation of results and relevant comments.

## 2. DESCRIPTION OF COGENERATION STEAM TURBINE PLANT

The cogeneration steam turbine plant consists of one condensing turbine with one non-controlled extraction, one controlled extraction, and one electric generator. Steam extracted from the turbine is used for process needs in refinery plants.

Basic technical data of the steam turbine for combined heat and power production are as follows [7]:

### Turbine

- nominal power.....5,7 MW
- maximum power.....6,0 MW
- speed of rotation.....9500 min<sup>-1</sup>
- inlet steam pressure.....4,0 MPa
- inlet steam temperature.....430 °C

- količina pare na ulazu u turbinu.....61 t/h
- tlak nereguliranog oduzimanja pare..1,78 MPa
- količina nereguliranoga oduzimanja..19 t/h
- tlak reguliranoga oduzimanja.....0,73 MPa
- količina reguliranoga oduzimanja.....29 t/h
- tlak u kondenzatoru pri temperaturi rashladne vode 27 °C.....22,5 kPa

#### Reduktor brzine vrtnje

- brzina vrtnje.....9500/1500 min<sup>-1</sup>

#### Generator

- brzina vrtnje.....1500 min<sup>-1</sup>
- faktor snage.....0,8
- maksimalna snaga.....7500 kVA
- napon .....6,3 kV.

Na slici 1. dan je prikaz osnovne toplinske sheme parno-turbinskoga postrojenja za zajedničku proizvodnju toplinske i električne energije. Svježa para iz generatora pare dovodi se u turbinu i ekspandira do nereguliranoga oduzimanja gdje se oduzima dio pare za toplinske potrošače višeg tlaka. Preostali dio pare ekspandira do reguliranoga oduzimanja gdje se oduzima dio pare za toplinske potrošače nižeg tlaka. Ostatak pare ekspandira do tlaka u kondenzatoru gdje se kondenzira. Iz kondenzatora se kondenzat, pomoću kondenzatne pumpe, odvodi u otplinjač i dalje pomoću napojne pumpe u regenerativni zagrijač te u generator pare. U otplinjaču se izdvaja kisik iz napojne vode da se spriječi odnosno smanji korozija u generatoru pare.

Parno-turbinsko postrojenje ima redukciju tlaka svježe pare na tlak nereguliranoga oduzimanja te redukciju tlaka do tlaka reguliranoga oduzimanja. Pomoću redukcijских stanica omogućen je rad toplinskih potrošača pri ispadu turbine iz pogona ili tijekom njena remonta.

Uzdužni presjek kondenzacijske turbine s oduzimanjima pare prikazan je na slici 2. Turbina ima pet akcijskih stupnjeva koji se sastoje od statorskih i rotorskih lopatica. Statorske lopatice su ugrađene u razdjelne stijene. Rotorske lopatice su ugrađene u rotorska kola. Iza prvoga stupnja turbine izvedeno je neregulirano oduzimanje pare.

- inlet steam quantity.....61 t/h
- no-controlled extr. pressure.....1,78 MPa
- no-controlled extr. quantity.....19 t/h
- controlled extr. pressure.....0,73 MPa
- controlled extr. quantity.....29 t/h
- condenser pressure for cooling water temperature 27 °C.....22,5 kPa

#### Gearbox

- speed of rotation.....9500/1500 min<sup>-1</sup>

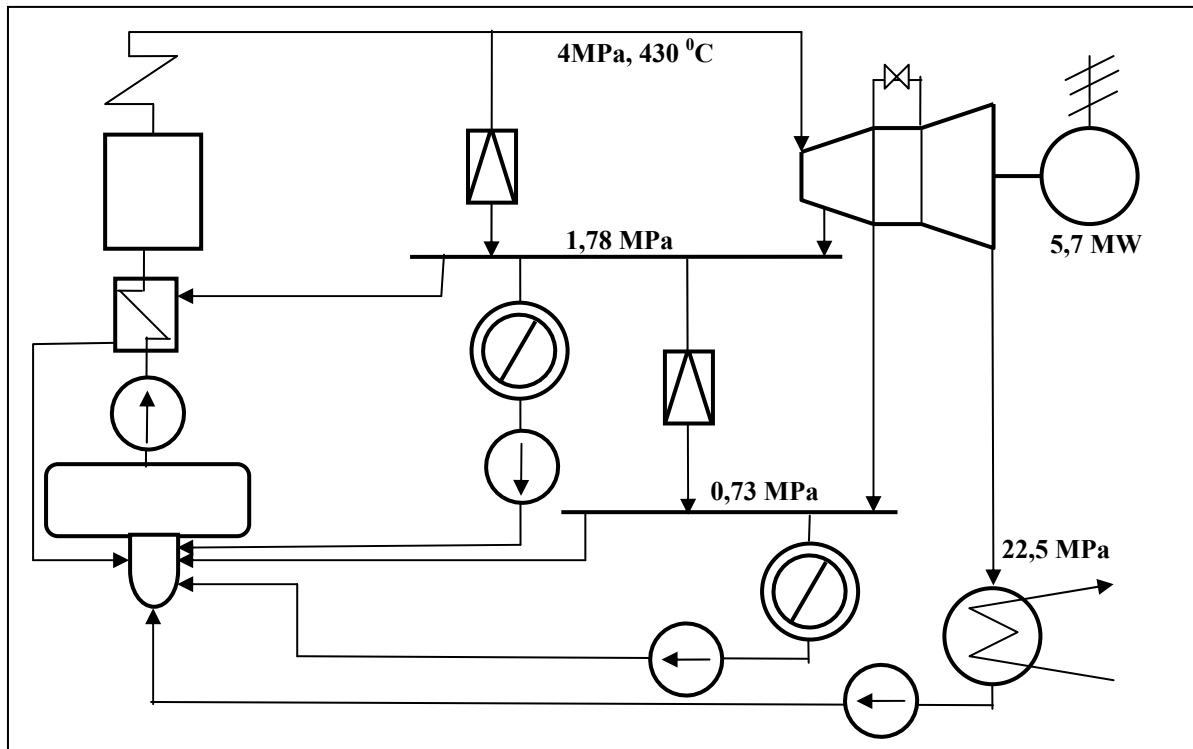
#### Electric generator

- speed of rotation.....1500 min<sup>-1</sup>
- capacity factor.....0,8
- maximum power.....7500 kVA
- voltage.....6,3 kV.

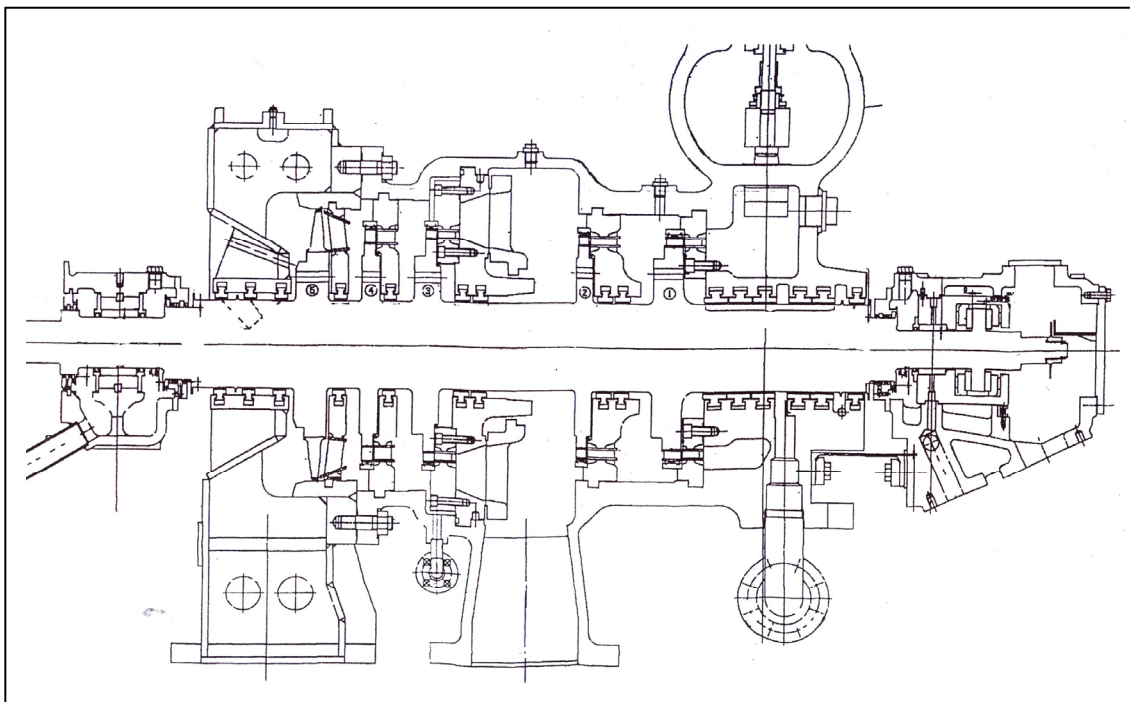
Figure 1 presents the basic scheme of a cogeneration steam turbine plant for combined production of heat and power. The steam from the boiler enters into the turbine where it expands to the non-controlled extraction where a part of steam is extracted for high-pressure heat consumers. The rest of the steam expands to the controlled extraction where the second part of the steam is extracted for low-pressure heat consumers. The remaining steam expands to the pressure in the condenser where it turns to liquid. From the condenser, the condensate is transported by pumps to the deareator and after that by feed pumps, through a regenerative feed heater, to the steam boiler. In the deareator, free oxygen has to be removed to prevent, i.e. to decrease, corrosion in the boiler.

The steam turbine plant is equipped with a station for pressure reduction to the pressure of non-controlled extraction, and also with another station for pressure reduction to the pressure of the controlled extraction. These reduction stations enable the operation of heat consumers in cases when the steam turbine is not in the operation due to maintenance or other reasons.

The longitudinal section through the condensing steam turbine with the extractions is presented in Figure 2. The steam turbine has five action stages consisting of stator and rotor blades. Stator blades are incorporated into distributing partitions. Rotor blades are incorporated into rotor wheels.



Slika 1. Osnovna toplinska shema kogeneracijskoga parno-turbinskog postrojenja  
 Figure 1. Basic scheme of cogeneration steam turbine plant



Slika 2. Uzdužni presjek kondenzacijske turbine s dva odzimanja pare, snage  $5,7 \text{ MW}_{el}$   
 Figure 2. Section through the condensing steam turbine with two extractions, capacity of  $5,7 \text{ MW}_{el}$

Regulirano oduzimanje pare izvedeno je iza drugoga stupnja turbine. Primjenom zakretne dijafragme skraćuje se turbina u odnosu na izvedbu s regulacijskim ventilima [8]. Neregulirano oduzimanje je jednostavnije u odnosu na regulirano oduzimanje. Međutim, kod njega se tlak pare mijenja s opterećenjem turbine, dok tlak pare reguliranoga oduzimanja ostaje konstantan. Neregulirano oduzimanje pare obično se primjenjuje kada je količina oduzimane pare manja od 30 % protočne količine.

Rotor turbine je oslonjen na dva radijalna klizna ležaja. Prednji ležaj je kombinirani radijalno-aksijalni za sprječavanje pomaka rotora u aksijalnom smjeru. Parna turbina, preko reduktora brzine vrtnje, pogoni električni generator koji je spojen s krutom spojkom. Za podmazivanje ležajeva turbine, reduktora i generatora, kao i za potrebe regulacije, ugrađen je zasebni uljni sustav.

Svježa para se dovodi u turbinu kroz ventil svježe pare i regulacijske ventile. Para u turbini ekspandira u prvom stupnju gdje se dio pare neregulirano oduzima za tehnološke potrebe. Preostala para ekspandira u drugom stupnju iz kojega se dio pare regulirano oduzima, također za tehnološke potrebe, a preostali dio pare ekspandira u ostalim stupnjevima do tlaka u kondenzatoru.

Na slici 3. dan je prikaz projektne krivulje ekspanzije pare u turbini za računski režim rada u Mollier-ovom h-s dijagramu za vodenu paru. Iz dijagrama je vidljivo da se neregulirano oduzimanje pare iz turbine izvodi kod tlaka 17,8 bar i regulirano oduzimanje kod tlaka 7,3 bar. Tlak pare na izlazu iz turbine i u kondenzatoru je 0,225 bar. Rashladna voda za kondenzator dobavlja se iz rashladnih tornjeva. Parni kondenzator je površinski izmjenjivač topline koji je projektiran tako da se jedna njegova polovica može čistiti dok druga normalno radi.

Projektni dijagram režima rada turbine za količinu regulirana oduzimanja pare 24 t/h do 36 t/h, pri zatvorenome nereguliranom oduzimanju pare, prikazan je na slici 4.

Iz dijagrama se može odrediti snagu turbine za određenu količinu ulazne i oduzimane pare.

The non-controlled steam extraction is made after the first turbine stage. The controlled steam extraction is made after the second turbine stage. With the use of a rotating diaphragm, the length of the turbine is decreased compared to the turbine with common regulating valves [8]. The non-controlled extraction is simpler, but in this case, the steam pressure changes with the varying of turbine load, while in controlled extraction the constant steam pressure is maintained. The non-controlled extraction is commonly used when the steam quantity of extracted steam is less than 30 % of the total steam flow.

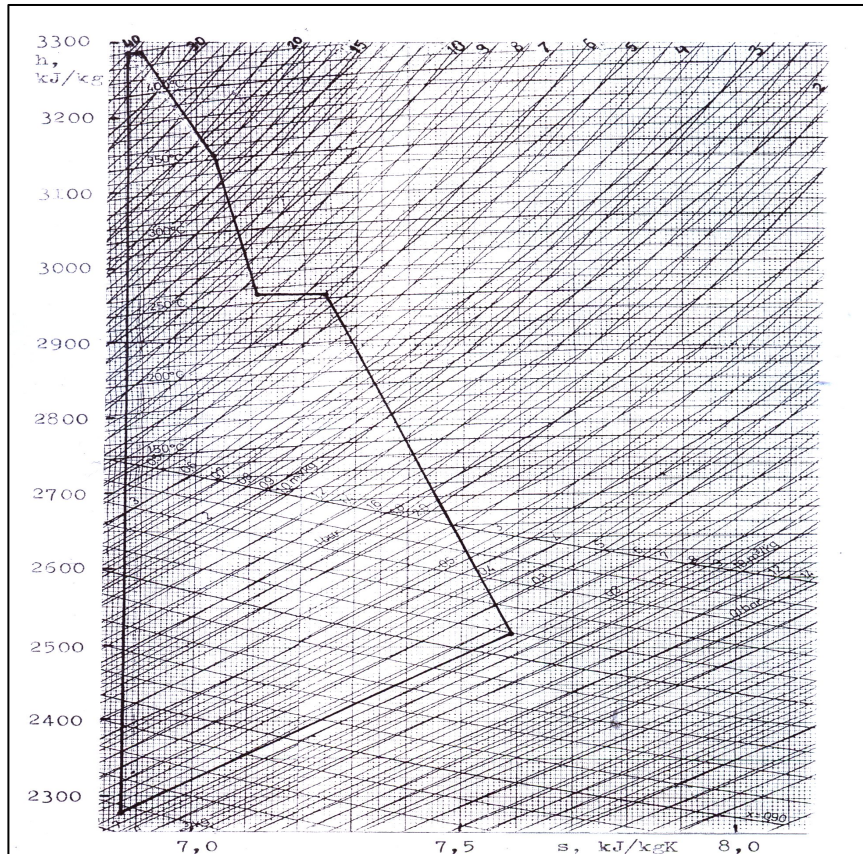
The rotor of the turbine is supported by two radial slide bearings. The front bearing is a combined axial-radial design to prevent any motion of the rotor in the axial direction. The steam turbine drives the electric generator through a gearbox connected with the rigid coupling. For the lubrication of the bearings, the gearbox and for the turbine control system, a separate oil system is included.

Fresh steam enters into the turbine through the main close valve and through control valves. Steam expands through the turbine first stage, where part of it is non-controllably extracted for consumers in the technological process. The rest of the steam expands through the turbine second stage, after which a part of it is controllably extracted for process users, as well. The remaining steam expands through other turbine stages to the condenser pressure.

Figure 3 shows the design expansion line of steam through the turbine in the Mollier's h-s diagram. It can be seen from the diagram that the non-controlled extraction is at the pressure of 17,8 bars, while the controlled extraction is performed at a pressure of 7,3 bars. The pressure in the turbine outlet and in the condenser is 0,225 bars. The cooling water for the condenser comes from the cooling towers. The steam condenser is made as a surface heat exchanger, designed to enable cleaning of one half, while the second half remains in normal operation.

The design diagram of turbine operating conditions is presented in Figure 4 for cases of controlled extractions between 24 t/h and 36 t/h and for zero flow through the non-controlled extraction.

The load of the turbine can be defined from the diagram on the basis of inlet and extracted steam quantity.



Slika 3. Mollier-ov  $h-s$  dijagram za proces pare u turbini  $5,7 \text{ MW}_{el}$

Figure 3. Mollier's  $h-s$  diagram of the process in the turbine capacity of  $5,7 \text{ MW}_{el}$

Na primjer, za količinu svježe pare na ulazu u turbinu  $55 \text{ t/h}$  i količinu reguliranog oduzimanja pare  $36 \text{ t/h}$ , električna snaga iznosi  $5 \text{ MW}$ . Maksimalna snaga turbo-agregata je  $6 \text{ MW}$ , maksimalna količina pare na ulazu u kondenzator iznosi  $15,5 \text{ t/h}$ , a minimalni protok pare u kondenzator je  $2,5 \text{ t/h}$ .

### 3. ANALIZA UČINKOVITOSTI KOGENERACIJSKOGA PARNO- TURBINSKOG POSTROJENJA

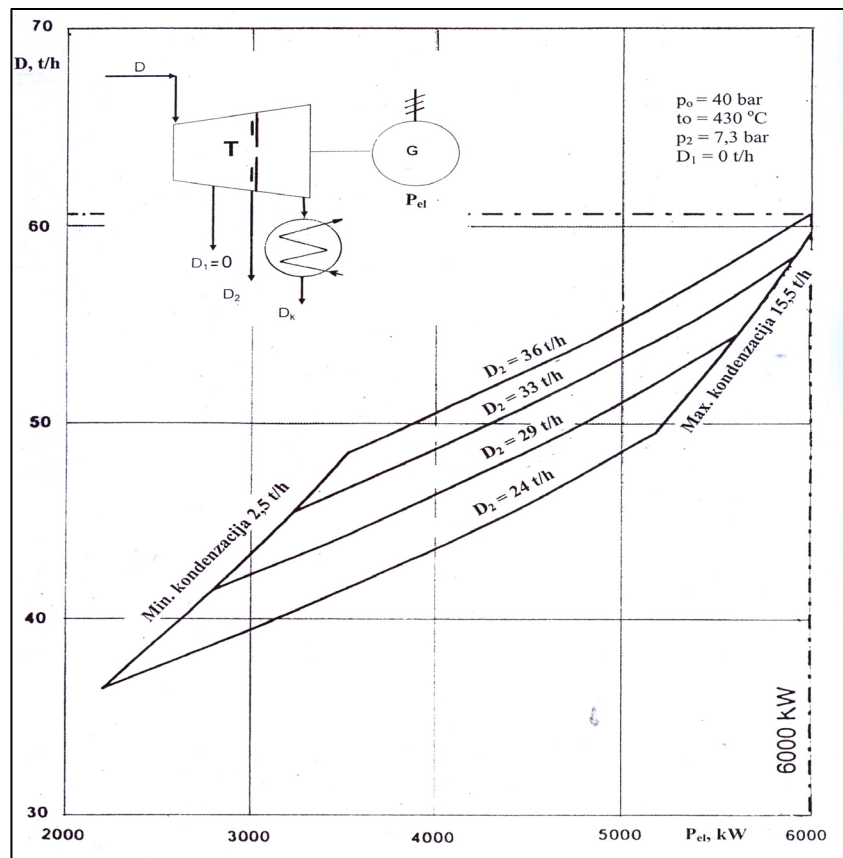
Analizirani su osnovni pokazatelji učinkovitosti parno-turbinskoga postrojenja u projektnome (računskome) režimu rada sa snagom na generatoru  $P_{el} = 5700 \text{ kW}$ . Projektни režim rada je osnovni režim na temelju kojega je proračunana i konstruirana parna turbina.

For example, in the case of an input steam quantity of  $55 \text{ t/h}$  and for the quantity of controlled extraction  $36 \text{ t/h}$ , the generated power in the turbine is  $5 \text{ MW}$ .

The maximum power of the turbo-generator is  $6 \text{ MW}$ , the maximum steam flow into the condenser is  $15,5 \text{ t/h}$ , while the minimum steam flow through the condenser is  $2,5 \text{ t/h}$ .

### 3. EFFICIENCY ANALYSIS OF THE COGENERATION STEAM TURBINE PLANT

The main efficiency indicators are analyzed for the described cogeneration steam turbine plant for the case of the design (calculating) operating regime with an output power of  $5700 \text{ kW}_{el}$ . The design regime is the basic operating regime for which the steam turbine is calculated and designed.



Slika 4. Dijagram rada turbine, snage 5,7 MW<sub>el</sub>, pri zatvorenome ne-reguliranom oduzimanju pare  
 Figure 4. The operation diagram of the turbine, capacity of 5,7 MW<sub>el</sub>, with closed non-controlled extraction

Jedan od osnovnih pokazatelja učinkovitosti rada parne turbine je njen unutarnji stupanj iskoristivosti  $\eta_i$ . On uzima u obzir sve gubitke strujanja pare u turbini, a jednak je omjeru stvarnoga (politropskoga)  $H_i$  i teoretskoga (izentropskoga) toplinskog pada u turbini:

One of the major efficiency indicators of the steam turbine is its internal efficiency,  $\eta_i$ . It includes all internal flow losses through the turbine and is presented as the ratio between the polytropic ( $H_i$ ) and isentropic ( $H_0$ ) heat drop through the turbine:

$$\eta_i = \frac{H_i}{H_0} = \frac{h_0}{h_0} \frac{h_k}{h_{kt}} = \frac{3285}{3285} \frac{2521}{2278} = 0,758, \quad (1)$$

gdje je  $h_0$ ,  $h_{kt}$ ,  $h_k$  - entalpija pare na ulazu u turbinu, entalpija na izlazu iz turbine kod teoretskoga i entalpija na izlazu iz turbine kod stvarnoga toplinskog pada. Proračunan unutarnji stupanj iskoristivosti turbine relativno je nizak.

where  $h_0$ ,  $h_{kt}$ , and  $h_k$  are the enthalpy of input steam, enthalpy of output steam at the theoretical level and at the real heat drop. This calculated internal efficiency is relatively low. For small condensing steam turbines with extractions, this internal efficiency is usually between 0,7 and 0,83, depending mainly on the design of turbine flow parts.

U kondenzacijsko-oduzimnim parnim turbinama manjih snaga obično iznosi 0,7 do 0,83, što ovisi najviše o konstrukciji protočnoga dijela turbine.

The basic indicator of the entire heat efficiency of the cogeneration steam turbine plant is the total efficiency  $\eta_{tot}$  which is the ratio between the sum of the output electric power  $P_{el}$  and heat  $Q_p$ , and of heat power  $Q_1$  given to fresh steam.

Osnovni pokazatelj učinkovitosti toplinskoga procesa kogeneracijskoga parno-turbinskog postrojenja je ukupni energetski stupanj iskoristivosti procesa  $\eta_{tot}$  koji je jednak omjeru zbroja dobivene električne  $P_{el}$  i toplinske snage  $Q_p$  te dovedene toplinske snage  $Q_1$  koja se predaje ulaznoj

It should be mentioned that the input power brought with

pari.  
Potrebno je napomenuti da je toplinska snaga dovedena s gorivom veća od toplinske snage  $Q_1$  za veličinu gubitaka u generatoru pare.

the fuel is greater than  $Q_1$  due to losses in the steam boiler.

$$\eta_{\text{tot}} = \frac{P_{\text{el}} + Q_p}{Q_1} = \frac{P_{\text{el}} + Q_{p1} + Q_{p2}}{Q_{1k} + Q_{1p1} + Q_{1p2}}. \quad (2)$$

Toplinska snaga, predana toplinskim potrošačima prvoga (ne-reguliranoga) oduzimanja pare  $Q_{p1}$ , može se odrediti pomoću izraza (3):

The heat power delivered to heat consumers through first (non-controlled) extraction  $Q_{p1}$  can be calculated by the equation (3):

$$Q_{p1} = D_1(h_{p1} - h_{p1'})\eta_p = 19(3146 - 881)0,9/3,6 = 10759 \text{ kW}, \quad (3)$$

gdje je  $D_1$  - količina pare prvoga oduzimanja;  $h_{p1}$  - entalpija pare prvoga oduzimanja;  $h_{p1'}$  - entalpija pare kondenzata na izlazu iz toplinskoga potrošača;  $\eta_p$  - stupanj iskoristivosti potrošača topline. Analogno se može odrediti toplinska snaga predana potrošačima drugoga (reguliranoga) oduzimanja pare prema izrazu (4).

where  $D_1$  is steam quantity at first extraction;  $h_{p1}$  is the enthalpy of first extracted steam;  $h_{p1'}$  is the enthalpy of condensate at the heat consumers outlet; and  $\eta_p$  is the efficiency of heat consumers. The heating power delivered to heat consumers through second (controlled) extraction can be calculated by equation (4):

$$Q_{p2} = D_2(h_{p2} - h_{p2'})\eta_p = 29(2970 - 705)0,9/3,6 = 16421 \text{ kW}, \quad (4)$$

gdje je  $D_2$  - količina pare drugoga oduzimanja;  $h_{p2}$  - entalpija pare drugoga oduzimanja;  $h_{p2'}$  - entalpija pare kondenzata na izlazu iz toplinskoga potrošača.

where  $D_2$  is steam quantity at second extraction;  $h_{p2}$  is the enthalpy of steam at second extraction; and  $h_{p2'}$  is the enthalpy of steam at the outlet of heat consumers.

Dovedene toplinske snage kondenzacijskoga protoka pare  $Q_{1k}$ , protoka pare prvoga (ne-reguliranoga) oduzimanja  $Q_{1p1}$  i protoka pare drugoga (reguliranoga) oduzimanja  $Q_{1p2}$  mogu se odrediti pomoću izraza (5), (6) i (7):

The inlet heating powers of steam to be condensed  $Q_{1k}$ , of steam to be extracted at first (non-controlled) extraction  $Q_{1p1}$  and of steam to be extracted at second (controlled) extraction  $Q_{1p2}$  can be defined by the equations (5), (6) and (7):

$$Q_{1k} = D_k(h_0 - h_{k'}) = 13(3285 - 263)/3,6 = 10913 \text{ kW}, \quad (5)$$

$$Q_{1p1} = D_1(h_0 - h_{p1'}) = 19(3285 - 881)/3,6 = 12688 \text{ kW}, \quad (6)$$

$$Q_{1p2} = D_2(h_0 - h_{p2'}) = 29(3285 - 705)/3,6 = 20783 \text{ kW}, \quad (7)$$

gdje je  $D_k$  - količina pare na ulazu u kondenzator;  $h_k$  - entalpija kondenzata na izlazu iz kondenzatora.

where  $D_k$  is steam quantity at the condenser inlet, and  $h_k$  in the enthalpy of condensate at the condenser outlet.

Uvrštavanjem dobivenih veličina određuje se ukupni energetske stupanj iskoristivosti kogeneracijskoga parno-turbinskog postrojenja:

By introducing defined values, the total energy efficiency of the cogeneration steam turbine plant can be calculated by the following:

$$\eta_{\text{tot}} = \frac{5700 + 10759 + 16421}{10913 + 12688 + 20783} = 0,741. \quad (8)$$

Ukupni energetske stupanj iskoristivosti visoko učinkovitih kogeneracijskih parno-turbinskih postrojenja može iznositi do 0,85 i više.

The total energy efficiency of highly efficient cogeneration steam turbine plants can reach 0,85 and even more.

Jedan od pokazatelja učinkovitosti kogeneracijskih parno-turbinskih postrojenja je specifična potrošnja pare po jedinici proizvedene električne energije, a koja u projektnome režimu rada, za razmatrani slučaj, iznosi:

One of indicators for the efficiency of cogeneration steam turbine plants is the specific steam consumption for produced electric energy, and for the considered case it is:



$$d_e = \frac{D}{P_{el}} = \frac{61000}{5700} = 10,7 \text{ kg/kWh.} \quad (9)$$

Jedan od osnovnih pokazatelja učinkovitosti rada kogeneracijskoga parno-turbinskog postrojenja je i specifična potrošnja topline. To je ustvari recipročna vrijednost ukupnoga energetskeg stupnja korisnosti, odnosno:

One of the main efficiency indicators for cogeneration steam turbine plants is the specific heat consumption. Basically, it is the reciprocal value of total energy efficiency, i.e.:

$$q_e = \frac{1}{\eta_{tot}} = \frac{3600}{0,741} = 4858 \text{ kJ/kWh.} \quad (10)$$

Specifična potrošnja topline kogeneracijskoga procesa pokazuje koliko topline treba dovesti u proces po jedinici proizvedene električne i toplinske energije.

Definicija ukupnoga energetskeg stupnja iskoristivosti ima manjkavost obzirom na drugi zakon termodinamike jer su s njime električna energija i toplina jednako vrijednovane, iako su one različite po kvaliteti i vrijednosti. Ova se manjkavost umanjuje uzimanjem u obzir utjecaj cijene električne i toplinske energije [9].

Umjesto ukupnoga energetskeg stupnja iskoristivosti, u nekim se slučajevima koristi ekvivalentni toplinski stupanj iskoristivosti koji je definiran kao odnos proizvedene električne energije i razlike topline dovedene gorivom i topline predane toplinskim potrošačima, prema izrazu (11):

The specific heat consumption of a cogeneration plant presents the inlet heat quantity consumed in the process per unit of produced energy (electric and heat).

This definition of the total energy efficiency has a deficiency in consideration to the second law of thermodynamics, because electrical and heat energy are here equally valued, although these two types of energy have different values and qualities. This defectiveness can be compensated by taking into account prices of electric energy and heat [9].

Instead of the total energy efficiency, the equivalent heat efficiency is considered in some cases, which is defined as the ratio between produced electric energy and the difference between the used fuel energy and heat delivered to heat consumers, according to the equation (11):

$$\eta_{ekv} = \frac{P_{el}}{Q_1 - Q_p} = \frac{P_{el}}{Q_1 - Q_{p1} - Q_{p2}} = \frac{5700}{44384 - 10759 - 16421} = 0,331. \quad (11)$$

Ustvari, u ovome se izrazu uzima u obzir ekvivalentno smanjenje potrošnje goriva, koje se postiže u usporedbi sa sustavom gdje se zasebno proizvodi električna i toplinska energija.

Specifična potrošnja topline, na temelju ekvivalentnoga toplinskog stupnja iskoristivosti, iznosi:

Basically, the equivalent decreasing of consumed fuel is taken in the consideration by this expression in comparison to the system where power and heat is produced separately.

The specific heat consumption, based on the equivalent heat efficiency, is as defined by the expression (12):

$$q_{ekv} = \frac{1}{\eta_{ekv}} = \frac{3600}{0,331} = 10876 \text{ kJ/kWh.} \quad (12)$$

Ova specifična toplina pokazuje koliko treba dovesti topline u kogeneracijskome procesu za jedinicu proizvedene električne energije.

Analizirajući izračunate pokazatelje učinkovitosti kogeneracijskoga parno-turbinskog postrojenja proizlazi da je učinkovitost ovog postrojenja relativno niska. To se može objasniti s relativno visokim tlakom prvoga (1,78 MPa) i drugoga (0,73 MPa) oduzimanja pare, kao i visokim tlakom u kondenzatoru (22,5 kPa). Kod ovakvih postrojenja, učinkovitost je to veća što su tlakovi oduzimate pare iz turbine i kondenzacije niži, te što manje pare odlazi u kondenzator na ukapljivanje. S nižim tlakom oduzimanja pare dobije se veći rad u turbini na

Therefore, the defined specific consumption of heat presents the quantity of heat to be consumed in the cogeneration system per unit of produced electric energy. By analysis of obtained efficiency indicators for the considered cogeneration steam turbine plant, it can be concluded that its efficiency is relatively low compared to similar plants. This fact can be explained with relatively high pressures of first (1,78 MPa) and of second (0,73 MPa) extractions and also with a relatively high condensation pressure (22,5 kPa). Such plants have better efficiencies when pressures of the extractions and of the condensation are as low as possible and also when the quantity of condensed steam is as low as possible. The

račun oduzimate pare. Međutim, na tlakove oduzimate pare se u radu turbine ne može utjecati jer su oni, u ovome slučaju, ovisni o potrebama potrošača topline, odnosno tehnološkoga procesa u rafinerijskome sustavu proizvodnje [10]. Tlak kondenzacije pare u kondenzatoru ovisi uglavnom o temperaturi rashladne vode, količini rashladne vode i o veličini rashladne površine kondenzatora. Na temperaturu rashladne vode za kondenzaciju pare ne može se utjecati jer ona prvenstveno ovisi o stanju okoline, odnosno o podneblju i godišnjem dobu. Kod ovoga postrojenja se za hlađenje kondenzatora koristi kružni rashladni sustav pomoću otvorenih rashladnih tornjeva.

Na količinu rashladne vode i veličinu rashladne površine kondenzatora može se utjecati tijekom projektiranja i odabira opreme. Što je veća količina rashladne vode i veća rashladna površina kondenzatora, niži će biti tlak kondenzacije i postići će se veći rad u turbini iz pare koja ekspanzira do tlaka u kondenzatoru. Međutim, u tome slučaju raste i cijena postrojenja, odnosno trošak investicije. Iz toga razloga, odabir tih parametara kod pojedinih slučajeva parno-turbinskih postrojenja treba biti temeljen na postupku optimizacije s kojim se treba uzeti u obzir izvedba hladnog kraja turbine, veličina kondenzatora, kapacitet rashladnoga sustava, odnosno s time u vezi učinkovitost i sveukupni troškovi rada postrojenja.

#### 4. ZAKLJUČAK

U INA - Maziva Rijeka ugrađeno je novo kogeneracijsko parno-turbinsko postrojenje za zajedničku proizvodnju toplinske i električne energije. U računskom režimu rada parno-turbinsko postrojenje daje toplinsku snagu 27,18 MW i električnu 5,7 MW. Kogeneracijsko parno-turbinsko postrojenje ima ugrađenu kondenzacijsku paru turbinu s jednim reguliranim i jednim ne-reguliranim oduzimanjem pare. Takva parno-turbinska postrojenja za zajedničku proizvodnju toplinske i električne energije imaju nižu ukupnu energetska učinkovitost u odnosu na postrojenja s protutlačnim turbinama. Međutim, parno-turbinska postrojenja s kondenzacijskim turbinama uz regulirana oduzimanja pare su veoma elastična u pogonu jer mogu proizvoditi potrebnu toplinsku energiju i željenu količinu električne energije neovisno o potrebi za toplinskom energijom. Povećanje učinkovitosti industrijskih kogeneracijskih parno-turbinskih postrojenja može se postići njihovim maksimalnim korištenjem za proizvodnju pare za razne potrebe u tehnološkim procesima proizvodnje. S primjenom kogeneracijskih postrojenja povećava se učinkovitost u odnosu na odvojenu proizvodnju toplinske i električne energije, a s time u vezi postiže se i proporcionalno smanjenje onečišćenja okoliša.

lower extraction pressure enables higher conversion of heat to work in the turbine. But in this case, the pressure of extractions during turbine operation is defined by requirements and characteristics of heat consumers, i.e. of consumers in the refinery process [10]. The pressure in the condenser depends mainly on the temperature and quantity of cooling water and also on the size of the condenser cooling surface. The temperature of cooling water is dependent on the ambient temperature, i.e. on the climate and season. In the considered case, the circulating cooling water system with the open cooling tower is provided to cool the steam condenser.

The quantity of cooling water and the size of the condenser cooling surface can be changed during the design and equipment selection. The greater the cooling water quantity and the condenser cooling surface, the lower the condensation pressure that can be achieved and the greater the work that can be obtained in the turbine from the steam expanding to the condenser pressure. Meanwhile, the investment cost is higher in this case. Due to this reason, the selection of these parameters for particular steam turbine plants has to be based on the optimization procedure which has to take into the consideration the design of low-temperature turbine parts, the condenser size, and the capacity of the water cooling system, as well as the efficiency and total costs of the plant operation.

#### 4. CONCLUSION

A new cogeneration steam turbine plant for the combined production of power and heat has been constructed at the INA – Maziva Rijeka refinery plant. In the case of design regime, the steam turbine plant gives a heat power of 27,1 MW and an electric power of 5,7 MW. The plant is equipped with a condensing steam turbine with one controlled and one non-controlled steam extraction. Such steam turbine plants for combined production of power and heat have a lower total energy efficiency in comparison with plants with back-pressure turbines. Meanwhile, steam turbine plants with condensing-extracting turbines are very elastic during operation, because they can produce required power and heat independent of the required heat energy.

The augmentation of efficiency of cogeneration steam turbine plants can be achieved by their maximum use for steam production to cover requirements in various industrial processes.

The use of cogeneration plants increases efficiency in comparison with the separate production of power and heat, and by this effect the simultaneous reduction of environment pollution is also very significant.

## LISTA SIMBOLA

- unutarnji stupanj korisnosti	$\eta_i$	
- teoretski toplinski pad	$H_0$	kJ/kg
- stvarni toplinski pad	$H_i$	kJ/kg
- entalpija ulazne pare	$h_0$	kJ/kg
- entalpija izlazne pare kod teoretskog toplinskog pada	$h_{kt}$	kJ/kg
- stvarna entalpija izlazne pare	$h_k$	kJ/kg
- ukupna energetska iskoristivost	$\eta_{tot}$	
- električna snaga	$P_{el}$	kW
- dobivena toplinska snaga	$Q_p$	kW
- toplinska snaga predana ulaznoj pari	$Q_1$	kW
- dovedena toplinska snaga potrošačima prvoga ne-reguliranog oduzimanja	$Q_{p1}$	kW
- količina pare prvoga oduzimanja	$D_1$	kg/s
- entalpija pare prvoga oduzimanja	$h_{p1}$	kJ/kg
- entalpija kondenzata prvoga oduzimanja	$h_{p1'}$	kJ/kg
- korisnost toplinskih potrošača	$\eta_p$	
- dovedena toplinska snaga potrošačima drugoga reguliranog oduz.	$Q_{p2}$	kW
- količina pare drugog oduzim.	$D_2$	kg/s
- entalpija pare drugog oduzim.	$h_{p2}$	kJ/kg
- entalpija kondenzata drugog oduzimanja	$h_{p2'}$	kJ/kg
- dovedena toplinska snaga kondenzacijskog protoka	$Q_{1k}$	kW
- količina pare u kondenzaciji	$D_k$	kg/s
- entalpija kondenzata na izlazu iz kondenzatora	$h_{k'}$	kJ/kg
- dovedena toplinska snaga prvoga oduzimanja	$Q_{1p1}$	kW
- dovedena toplinska snaga drugoga oduzimanja	$Q_{1p2}$	kW
- specifični utrošak pare	$d_e$	kg/kWh
- ulazna količina pare	$D$	kg/s
- specifični utrošak topline	$q_{ekv}$	kJ/kWh
- ekvivalentni toplinski stupanj korisnosti	$\eta_{ekv}$	
- ekvivalentni specifični utrošak topline	$q_{env}$	kJ/kWh

## LIST OF SYMBOLS

- internal efficiency
- theoretical heat drop
- real heat drop
- enthalpy of input steam
- enthalpy of output steam for theoretical heat drop
- real enthalpy of output steam
- total energy efficiency
- electric power
- output heat power
- heat power given to fresh steam
- heat power for heat consumers of first non-regulated extraction
- quantity of first extraction
- enthalpy of steam at first non-controlled extraction
- enthalpy of condensate after first non-controlled extraction
- efficiency of heat consumers
- input heat power for consumers of second controlled extraction
- quantity of second extraction
- enthalpy of steam at second controlled extraction
- enthalpy of condensate after second controlled extraction
- input heat power of steam to be condensed
- quantity of condensed steam
- enthalpy of condensate after condenser
- input heat power of first non-controlled extraction
- input heat power of second controlled extraction
- specific steam consumption
- input steam quantity
- specific heat consumption
- equivalent efficiency
- specific equivalent heat consumption

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