TECHNIC AND ECONOMIC INDICATORS ANALYSIS FOR A COGENERATION SYSTEM WITH HEAT RECOVERY THROUGH FLUE GASES FROM PROCESS FURNACES

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Abstract: Cogeneration systems groups condensing turbine with heat recovery through flue gases from process furnaces have found application in the chemical industry, in refineries and large petrochemical plants, which are equipped with independent boilers for steam production. In principle, the three networks of refineries are required superheated steam corresponding to three pressure ranges: low pressure p=3....6 bar, medium pressure p=12 ... 25 bar high pressure and p=30... 60 bar. In this paper the authors conducted a study on the technical and economic performance on operation of such cogeneration system, taking into account that, for technical and economic parameters calculation using constructive-functional parameter values that differ for the three types of pressure analysis.

Keywords: technical and economic parameters, cogeneration, heat recovery, study.

1. INTRODUCTION

Cogeneration is the production of two forms of energy (electricity and heat) simultaneously, using the same equipment and the same as fuel.

A cogeneration power system allows local production of electricity at lower costs than those actually achieved in separate production systems and simultaneously thermal energy through recovery.

The main goals of cogeneration are: ensuring the final solution feasible for various energy optimization problems (electricity and heat), low energy consumption, obtaining a reasonable autonomy for electrical and thermal, last but not least, installing electricity and heat generation systems with a high reliability.

Cogeneration finds applications in the following areas: hot water industries, steam, hot air, chilled water, kings and heat systems, tertiary (hospitals, clinics, offices, hotels, airports) and isolated buildings (houses, weather stations, etc.).

At European level, cogeneration has a relatively high degree of expansion, reaching the Member States of the European Union about 70% of all food sources in large-scale development in the European Union cogeneration systems, standing following reasons: cogeneration used technologies to produce the two forms of energy, cogeneration go along with the concept of distributed generation of electricity, as in urban areas coexist with a thermal load electricity needed for household or industrial - that it cogeneration plants can cover local, thus avoiding transmission losses of electricity from the national grid distance to the place of consumption, cogeneration reduces carbon dioxide emissions by about 350 million tons Europe reduce its dependence on energy resources 1200 PJ /year;

In response to increased electricity production in industrial applications exclusively, in Romania the cogeneration was developed starting with year 1950.

For heating applications first cogeneration systems appeared in 1960 and expanded especially after 1970 as a result of increasing cumulative energy requirements and increasing the number of multi-family housing type.

Optimization studies conducted in 60 and 70 years felt that the sizing of cogeneration installation at a (45... 60)% of peak heat load is a load solution for energy production acceptable in one year, so depreciation investment to be made in a reasonable time. Cover peak load is made from hot water boilers (CAF).

Industrial development in our country and around the world that takes place under modernization continuous of the processes and increasing concerns for rational use of energy of all types.

Rational use of energy problem is very complex, being a strict interdependence of various fields of technology, the economic, environmental, social development and so on, following the rational energy: saving the primary energy resources that are limited, reducing investment and operating costs for primary energy extraction plants and to transform it into other forms of energy or transforming the various intermediate forms of energy, and transportation that facilities fuel distribution, electricity and heat, reducing the cost of industrial production, especially in the intensive where energy costs have a significant share in total expenditure, reducing emissions into the environment as harmful gases from various processes and process units.

Some thermal cycles are usually proposed to compose cogeneration schemes: steam cycle with heat recovery steam generators and steam turbines, gas cycle gas turbine (with or without heat recovery) conjunction cycles - as a composition of the previous cycles of internal combustion engines, particularly the one made from diesel engines [8].

A cogeneration power system allows local electricity production at lower costs comparing to actually achieved in separate production systems and simultaneously the heat, recovery, the main goals of cogeneration are: ensuring final solution feasible for various energy optimization problems (electricity and heat), low energy consumption, obtain reasonable electrical and thermal autonomy and, last but not least, the installation of production of electricity and heat with high reliability.

In present, combined heat and power plays an important role in most national strategies aimed at saving energy and reducing CO2 emissions, depending very much on the performance of installations for combined production of the two forms of energy (efficiency, recovery electricity and heat, number of hours) and baseline characteristics.

2. INDUSTRIAL COGENERATION SYSTEMS WITH STEAM TURBINE

Characterized by a much higher value for the heat comparing coefficient with urban cogeneration systems, industrial cogeneration systems can be economically efficient depending on the nature, heat demand and its simultaneity with electricity demand.
Industrial cogeneration technologies based on steam turbines lead to specific aspects regarding choosing the production of two forms of energy, on the one hand, depending on the actual technical condition of existing facilities, the remaining lifetimes and their economic efficiency assumed for a 15-20 years perspective, on the other hand, depending on availability perspective (for a minimum 40 years) of fuel used today.
Industrial consumers mainly use steam because of its qualities, it is preferred to other heat agents for heating and relaxation processes in turbines and other uses. Depending on the use you have, the steam must have certain qualities that they possess certain conditions imposed by temperature, pressure and position on phase equilibrium curves.
The main industrial cogeneration systems are made by groups of backpressure up parameters (Figure 1) to raised up parameters turbine generators groups (Figure 2) with adjustable sockets condensing groups (Figure 3) and, more recently, with condensing turbine groups with heat recovery from flue gases through process furnaces (figure 4) [2], [6], [7].

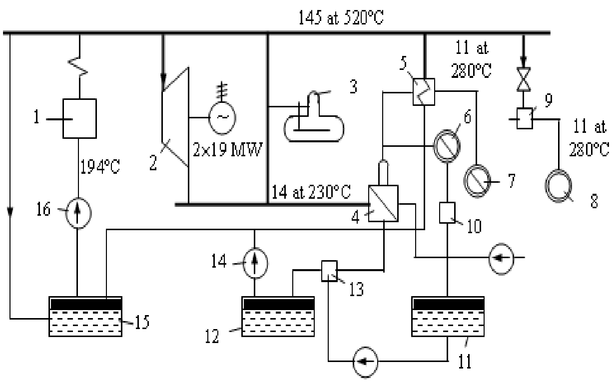

Fig.1. Cogeneration system with backpressure groups with high parameters: 1 - forced crossing boiler, 2 - backpressure turbine, 3 - heat accumulator, 4 - battery steam transformers, 5 - super heater, 6,7,8 - steam consumer group 9 - reduction-cooling station, 10 - total demineralization plant, 11.12 - pressure condensate reservoirs, 13 - getter; 14 - power pump, 15 - starting tank, 16 - water pump boiler

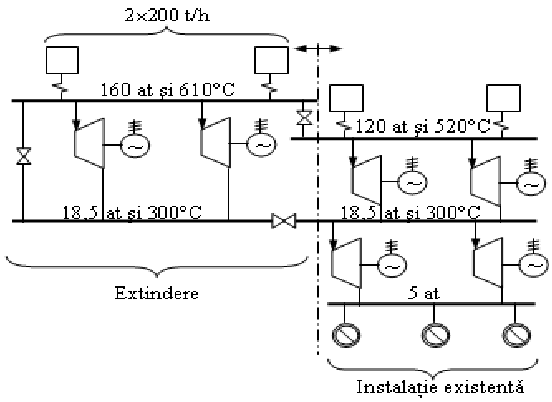

Fig.2. Cogeneration system with backpressure groups with raised parameters

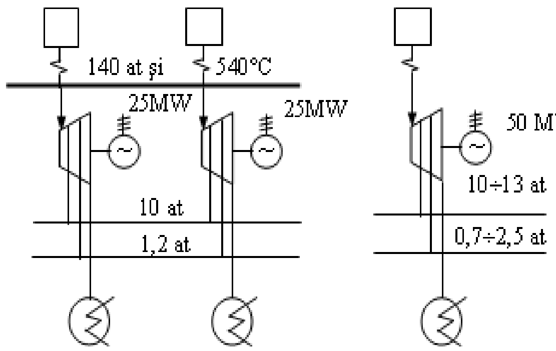

Fig.3. Cogeneration system with condensing groups with adjustable sockets of 25 MW and 50 MW expansion group

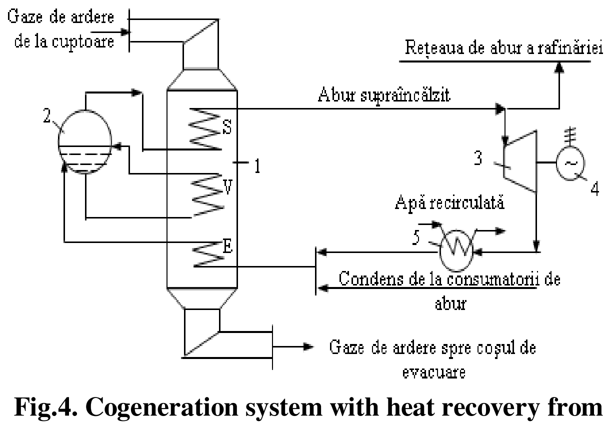

Fig.4. Cogeneration system with heat recovery from flue gases: 1 - recovery boiler, 2 - cylinder, 3 - turbine 4 - generator, 5 - turbine condenser E - saver, V - evaporator, S – super heater

Energy analysis of the energy systems with combined production of electricity and heat performance are based on diagrams illustrating some basic parameters, needed for comparing the separate production technologies.

3. THERMODYNAMICS INDICATORS OF INDUSTRIAL COGENERATION SYSTEMS WITH STEAM TURBINE

Analyzing in terms of thermodynamic, the electrical and thermal cogeneration systems with steam turbine can be determined [3], [5]:

1 Heat exchanger thermal efficiency for heat production:

$$\eta_t = \frac{Q_u}{Q_i} \tag{1}$$

Where:
Q_u - the amount of heat used [kW];
Q_i - the amount of heat introduced into the device, [kW].

2. Corresponding heat losses of electricity in heating cycle [kW]:

$$\Delta Q = \Delta y_p \cdot \left(q_{CTE} - q_{CET}\right) \cdot Q_i \cdot 10^{-6} \tag{2}$$

3. Thermodynamic efficiency of the heat exchanger:

$$\eta_{tot} = \frac{Q_i}{Q_i + \Delta Q} \tag{3}$$

4. Cogeneration index:

$$y_p = \frac{P_p}{Q_p} \tag{4}$$

Where:
P_p - electric power produced by the steam flow relaxation [kW];
Q_p - heat flow supplied from turbine [Gcal / h].

5. Reducing cogeneration index due to final temperature difference in heat exchanger:

$$\Delta y_p = \frac{\Delta i \cdot \eta_m \cdot \eta_g}{\left(i_2 - i_{2s}\right) \cdot 860 \cdot 10^{-6}} \tag{5}$$

Where:
Δ_i - heat exchanger enthalpy change [kJ / kg];
η_m - turbine mechanical efficiency [%];
η_g - generator efficiency [%];
i_2 - enthalpy steam turbine at the end of the real relaxation, [kcal / kgf];
i_{2S} - enthalpy steam turbine at the end of detente in the saturation temperature [kcal/kgf].

6. The total efficiency of the heat exchanger:

$$\eta_{tot} = \frac{Q_u}{Q_i + \Delta Q} \tag{6}$$

7. Power generation efficiency cogeneration system:

$$\eta_{Coge} = \eta_c \cdot \frac{1 + B}{1 + B \cdot \eta_c} \tag{7}$$

Where:
B – energetically coefficient expressed as the ratio of energy produced by steam power outlets and the power produced by steam condenser;
ηc - under pure efficiency condensing boiler [%].
8. Fuel economy:

$$\Delta B = \left[\left(\frac{1}{\eta_{CT}} - \frac{1}{\eta_C \cdot \eta_R}\right) + Y \cdot \left(q_{CTE} - q_{TCET}\right)\right] \cdot \frac{1}{H_i} \cdot Q_T \cdot - \frac{E - E_T}{H_i} \cdot \left(q_{CCET} - q_{CTE}\right) \tag{8}$$

Where:
H_i - net calorific value of fuel used, [kcal / kg];
Q_T - delivered heat [kJ];
η_{CT} - boiler efficiency to separate production [%];
η_C - average boiler efficiency CET [%];
η_R - return the transmission of heat, [%];
Y - index heating [kWh / Gcal];
q_{CTE} - net specific consumption of the boiler, condenser, [kcal / kWh];
q_{TCET} - net specific consumption for energy district heating [kcal / kWh];
q_{CCET} - net specific consumption for energy condensing CET, [kcal / kWh]
E - total energy supplied to the system [kWh];
E_T - electricity district heating [kWh].

9. Relative increase efficiency in electricity production cycle cogeneration power plants compared to the yield and condensing turbine intakes with adjustable heat produced [kcal / kWh];

$$\Delta\eta_{CET} = \frac{\eta_{CET}}{\eta_C} - 1 \tag{9}$$

$$\Delta\eta_{CET} = \frac{1 - \eta_C}{\frac{1}{B} + \eta_C} \tag{10}$$

4. TECHNICAL AND ECONOMICAL EFFICIENCY INDICATORS FOR COGENERATION SYSTEMS WITH HEAT RECOVERY FROM THE OVEN TECHNOLOGY

Cogeneration system groups with condensing turbine with heat recovery from flue gases through furnaces process have found application in the chemical industry, in refineries and large petrochemical plants, which are equipped with independent boilers for steam production. In principle, the three networks of refineries required superheated steam, the pressure corresponding to three domains: a network with low pressure steam p = 3...6 bar, medium pressure steam network p = 12...25 bar and a network with high-pressure steam p = 30... 60 bar.

The achievement of such cogeneration systems for recovering heat through flue gases compared to conventional heat recovery systems is possible only with steam generators.

Even if in a period of time, the consumer demand for steam is low, classic steam system works with a very low economic efficiency, an opportunity to streamline the relaxation of consumer's unsolicited steam turbine which drives electric generators.

To get as much energy as mechanical work by loosening the steam turbine is necessary that the pressure and degree of superheat of steam to be as high as possible.

Heat recovery system it is adapting to a base installation, which is a power plant with steam (Figure 5) working after Clausius-Rankine cycle.

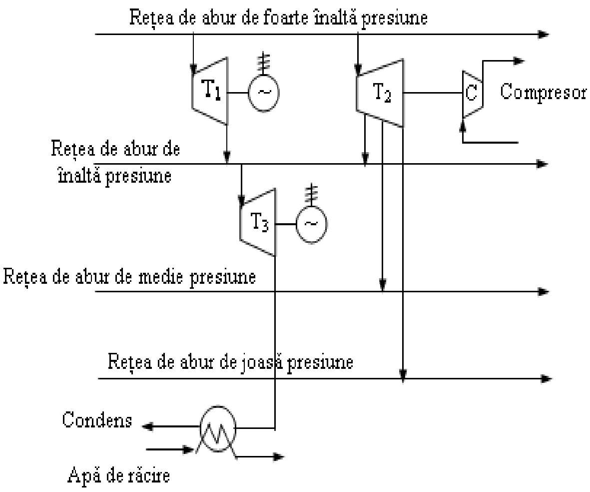

Fig.5. Steam power plant

Base boiler plant produce saturated and superheated steam that partially can supply various consumer and the rest of superheated steam is extends coaxially in a turbine mounted with an electric generator.

For the case of a variable heat demand, the system can work at full capacity, increasing electricity production. From the side intakes and final turbine outlet T_2 all three networks feeds the refinery steam.

Cogeneration system with heat recovery from flue gases (Figure 4) consists of a classic boiler to get steam from the flue gases, which then delivers the appropriate network parameters in the condition of the refinery [1].

Boiler flue gas flows through the action of an exhaustive and are discharged into the atmosphere through a very height chimney.

Part of superheated steam is supplied to the refinery steam network with compatible parameters when there is high demand from consumers, and the other part is relaxed in the turbine (3).

The turbine drives the electric generator (4) which provides electricity on the refinery network. The steam turbine is condensed and relaxed in, recharge through a waste heat boiler circulation pumps.

Technical and economical parameters associated with such a system are forced industrial cogeneration potential recoverable heat from flue gases through the flow and temperature level and the quantity and quality of produced steam is coming [3], [4], [6] [9]:

1. Potential recoverable heat from flue gases, Q_{ga}, [kJ/h]:

$$Q_{ga} = m_{ga} \cdot \left(i_{ga,tg1} - i_{ga,tg2}\right) \tag{11}$$

Where:
m_{ga} - flue gas mass flow [kg/h];
$I_{ga,tg1}$ - enthalpy of combustion gases from the boiler inlet temperature, t_{g1}=550°C;
$I_{ga,tg2}$ - enthalpy of combustion gases from the boiler outlet temperature, t_{g2}=180°C.

2. The flow of steam produced in the boiler, I, [kg/h]:

$$m_a = \frac{Q_{ga}}{i_{ab,tas} - i_{ab,ta1}} \tag{12}$$

Where:
$i_{ab,tas}$ - enthalpy of superheated steam temperature t_{as}=400ºC, entry into turbine, [kJ/kg];
$i_{ab,ta1}$ - enthalpy of liquid water at inlet temperature t_{a1}=20ºC, [kJ/kg].

3. Total area of heat exchange surfaces, $A_{t,sch}$, [m^2]:

$$A_{t,sch} = \frac{Q_{ga}}{k_{ed} \cdot \Delta t_{med}} \tag{13}$$

Where:
k_{ed} – overall heat transfer coefficient [W/(m^2·°C)];
Δt_{med} - logarithmic mean temperature difference [°C].

4. Condensate pump power required, P_{pump},[kW]:

$$P_{pompă} = \frac{m_a \cdot \Delta p}{\rho_a \cdot \eta \cdot 1000} \tag{14}$$

Where:
Δp- difference between pump discharge pressure and suction pressure (pa=2 bar) [bar];
ρ_a - steam density [kg/m3];
η - average pump efficiency.

5. Theoretical power turbine, P_T, [kW]:

$$P_T = m_a \cdot \left(i_{ab,tas} - i_{ab,teT}\right) \tag{15}$$

Where:
$i_{ab,teT}$-enthalpy of superheated steam leaving the turbine (kJ/kg).

6. Turbine condenser water consumption, folders, [t/h]:

$$m_{apă} = \frac{m_a \cdot \left(i_{ab,teT} - i_{cd}\right)}{c_{p,apă} \cdot \Delta t_{apă}} \tag{16}$$

Where:
i_{cd} - condensation enthalpy [kJ / kg];

$c_{p,apă}$ - water - average specific heat of cooling water [kJ/(kg·°C)];
$\Delta t_{apă}$ - cooling water temperature variation.

7. Exergetic efficiency of steam boiler, η_{ex}:

$$\eta_{ex} = \frac{Ex_{2,i}}{Ex_1} \tag{17}$$

Where:
Ex_1 - exergy transferred from the flue gas stream, [kJ/h];
$Ex_{2,i}$ - exergy received water-steam circuit, [kJ/h].
In general, these parameters are not independent variables, which are correlated with the physical properties of the combustion gases and steam.
Technical and economic parameters calculation using constructive-functional parameters (Table 1), which differ for the three variants analyzed.

Table 4.1. Constructive-functional parameter values of a cogeneration system with heat recovery from flue gases for the three variants analyzed [6], [9]

Constructive-functional parameters	Value networks superheated steam		
	j.p. p=5 bar	m.p. p=15 bar	î.p. p=40 bar
1 Flue gas mass flow, [kg/h]	7639	7639	7639
2 Enthalpy of combustion gases from the boiler inlet temperature, t_{g1}=550ºC, [kJ/kg]	3499	3499	3499
3. Enthalpy of combustion gases exit the boiler temperature, t_{g2}=180ºC, [kJ/kg]	1067,89	1067,89	1067,89
4. Enthalpy of superheated steam temperature t_{as}, [kJ/kg]	3272	3254,50	3211
5. Enthalpy of liquid water at inlet temperature t_{a1}, [kJ/kg]	84,2	85,2	87,6
6. The pressure in the pump inlet, p_a, [bar]	2	2	2
7. The difference between the pump discharge pressure and suction pressure (p_a=2 bar), [bar]	3	13	38
8. Water density, ρ_a, [kg/m^3]	915,20	866,60	798,70
9. Average pump efficiency	0,7	0,7	0,7
10. Overall heat transfer coefficient, [W/(m^2·°C)]	45	45	45
11. Logarithmic mean temperature difference, [°C]	178	148	117
12. Enthalpy of steam at the turbine entry, [kJ/kg]	3272	3255	3211
13. Enthalpy of the steam leaving the turbine, [kJ/kg]	3041	3011	2927
14. Enthalpy of condensation, [kJ/kg]	111,86	111,86	111,86
15. Average specific heat for water cooling, [kJ/(kg·°C)]	4,184	4,184	4,184
16. Cooling water temperature variation, [°C]	17	17	17
17. Exergy transferred from the flue gas stream, [kJ/h]	12,48·10^6	12,48·10^6	12,48·10^6
18. Exergy received water-steam circuit, [kJ/h]	5,76·10^6	6,59·10^6	7,31·10^6

Relations based on computing 11...17 and the constructive-functional parameters in Table 1, for the three pressure levels were obtained the following values of technical efficiency indicators - economic industrial cogeneration systems with heat recovery steam the technological ovens (table 2).

Table 2. The main technical and economic indicators of a cogeneration system with heat recovery from flue gases [6], [9].

Technical and economic indicators	Value networks superheated steam		
	j.p. p=5 bar	m.p. p=15 bar	î.p. p=40 bar
1. Potential recoverable heat from flue gases, [kJ/h]	18,571·10^6	18,571·10^6	18,571·10^6
2. The flow of steam produced in the boiler, [kg/h]	5825,65	5859,65	5945,76
3. Total area of heat exchange surfaces, [m^2]	644,02	774,57	979,79
4. Condensate pump power required, [kW]	0,758	3,490	11,232
5. Theoretical power turbine [kW]	373,76	397,23	469,17
6. Turbine condenser water consumption, [t/h]	239,91	238,84	235,32
7. Exergetic efficiency of steam boiler, [%]	46,15	52,80	58,57

5. CONCLUDE

The CHP basics elements can be grouped in thermodynamic and technical order elements - the cycle for combined power and heat, economic elements - determining the effectiveness of its economic and social and hygienic elements in relation to the role of cogeneration in improving working and living conditions [7].
Energy use for technical purposes involves a number of processes that are usually used in intermediate forms of energy that temporarily appear to shift from one form to another gained. Forms of energy that can totally transform are more valuable than unprocessed or only partially convertible, find a wide range of technical use [7].
Promoting cogeneration new solutions, but also evaluating existing ones, the question of economic quantification is the environmental effects of each of the proposed solutions. When comparing different cogeneration systems for selecting the optimal solution, the final decision has economic factor, which is higher conclusively when embedded and ecological effect.
Environmental analysis based on determining indicators, can be "impact with impact", but overall, given the share of different types of impact on the overall effect.
Conclusions drawn from such an analysis are not directly measurable economic. It is therefore necessary to find a methodology for incorporating environmental effects into the cost (or price) of the two forms of energy products, electricity and heat.
Nowadays, as separate systems performance and thermal power generation has improved considerably, the required performance installations for combined production of electricity and heat, to be preferred, must be very high.
Energy analysis of the performance achieved energy systems for combined production of electricity and heat based on diagrams illustrating some basic parameters, needed for comparing the separate production technologies.
Most experts consider that the scheme for combined production of electricity and heat leads to a primary energy savings of 30% for yields values: η_E=32%, η_Q=53%, η_{CE}=38%, η_{CQ}=80%.
In practice, yields production systems combined electricity and heat are strongly influenced by specific

applications of these types of facilities that can be achieved meaningful analysis on ways to save energy.

Analyzing economic indicators values obtained by calculation (Table 2) we can draw the following conclusions [6], [9]:

- With increasing mass flow steam, the pressure steam produced relatively small increase, about 2% for a pressure increase from 5 to 40 bar;
- Consumed recycled water flow to the condenser steam turbine relaxed in decreases with increasing steam pressure generated;
- Compression power required condensate pump about 14 times while increasing the pressure from 40 bar to 5 bar pressure, absolute consumption level is insignificant;
- Increased theoretical power turbine shaft is directly proportional to the pressure superheated increase steam turbine relaxed;
- Increased pressure steam produced in the boiler from 5 to 40 bar leads to an increase of 25,53% theoretical power and exergetic efficiency increased from 46,15% to 58,57%;
- Disadvantage of increasing pressure steam produced is increasing investment, on the one hand due to the necessary heat exchange surface higher (up to 52,14% of surface coils at a pressure of 40 bar to 5 bar), on the other hand due to increased pipe wall thickness;
- If they would not use the relaxation system in turbine cogeneration with electricity production, the advantage is producing low pressure steam, and if the system is applied cogeneration, steam generation is very advantageous pressure as high as possible.

Acknowledgment

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