Using Alternative Cogeneration Plants in Iraqi Petroleum Industry

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ABSTRACT

The present paper describes and analyses three proposed cogeneration plants include back pressure steam-turbine system, gas turbine system, diesel-engine system, and the present Dura refinery plant. Selected actual operating data are employed for analysis. The same amount of electrical and thermal product outputs is considered for all systems to facilitate comparisons. The theoretical analysis was done according to 1st and 2nd law of thermodynamic. The results demonstrate that exergy analysis is a useful tool in performance analysis of cogeneration systems and permits meaningful comparisons of different cogeneration systems based on their merits, also the result showed that the back pressure steam-turbine is more efficient than other proposals. Moreover, the results of the present work indicate that these alternative plants can produce more electric power than that required in the refinery. At present time, the industrial cogeneration plants are recommended in Iraq, especially in petroleum industry sectors, in order to contribute with ministry of electricity to solve the present crisis of electric power generation. Such excess in the power can sold to the main electric network. The economic analysis are proved the feasibility of the proposed cogeneration plants with payback period of four year and six months ,three year and eight months, and ten years for steam cogeneration plant, gas turbine cogeneration plant and diesel engine cogeneration plant respectively.

Key words: cogeneration, power plants, energy, refinery, economic

استخدام محطات التوليد متعددة الاغراض في الصناعة النفطية في العراق

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الخلاصة

يتضمن البحث الحالي وصف وتحليل لثلاث مقترحات من محطات التوليد متعددة الاغراض ومقارنتها بالواقع الحالي المستخدم في مصفى الدورة. المحطات المقترحة تشمل الوحدات الغازية ووحدات الديزل ووحدات بخارية بتوربين ذو ضغط خلفي. تم التحليل والمقارنة استناداً الى قانوني الثرموديناملك الاول و الثاني وباختيار معطيات عمل حقيقية. اظهرت النتائج فائدة استخدام مفهوم الاكسيرجي في تحليل ومقارنة البدائل المقترحة مع الاخذ بنظر الاعتبار الاستفادة من مميزات التوربين ذو الضغط الخلفي و ادخاله في محطات التوليد متعددة الاغراض بانه افضل من بقية البدائل من حيث الاداء اضافة الى امكانية توليد طاقة كهربائية تفوق احتياج المصفى وهذه الطاقة تدعم وتساهم في حل ازمة الكهرباء وعلى هذا الاساس نوصي باستخدام هذه البدائل في الصناعة النفطية .اثبت التحليل الاقتصادي ان فترة استرداد راس المال المستثمر في منظومة التوربين البخاري ذو الضغط الخلفي تساوي اربع سنوات ونصف تقريبا بينما للوحدة الغازية ووحدة الديزل تساوي حوالي ثلاث سنوات وثمانية اشهر وعشرة سنوات على التوالي .

1. INTRODUCTION

Cogeneration is the production of electricity and heat energy for process simultaneously from the same energy source. Cogeneration plants capture wasted thermal energy. The main advantage of these systems is their ability to improve the thermal efficiency of the fuel used in the production more than one useful form of energy. Also cogeneration lead to significant environment advantages, that is the increase in efficiency and corresponding decrease in fuel used by a cogeneration system compared to other conventional processes for thermal and electrical energy production, normally yield large reductions in greenhouse gas emissions. Cogeneration systems utilizing internal combustion engines and gas-turbines in open cycle are the most utilized technologies worldwide. Heavy fuel-fired diesel power plants run on relatively inexpensive diesel fuel, a low-grade product of oil refineries such power plants can be set up quickly, normally in less than twelve months to generate hundreds of megawatts of energy. Large diesel engine-cogeneration systems are particularly well suited to applications requiring a relatively high proportion of electrical power compared to thermal products **Benelmir, and Feidet, 1998**. Many energy and exergy analyses of cogeneration systems have been reported and pointed out their advantages. **Ertesva, 2007** presented an exergetic comparison of efficiency indicators for cogeneration and he concluded that exergetic improvements were only captured to a limited degree by the various energy-based efficiency indicators. **Ust, et al., 2007** optimized a gas-turbine regeneration system by an exergetic performance criterion and indicated the advantageous of this method. **Khaliq, and Khan, 2007,** analyzed a gas-turbine heat and power system using the first and second law of thermodynamics. . **Kathem, 2007,** proposed using a back-pressure turbine instead of the present plant used in the Dura refinery in Baghdad. The result showed a substantial increase in efficiency (6-13%) as well as the achievement of (24%) saving in fuel. Moreover, the results of his work indicate that these alternative plants can produce more electric power than that required in the refinery. Such excess in the power can sold to the main electric network. **Isam Aljundi, 2009,** analyzed the system components of Al-Hussein power plant in Jordan using exergy and energy concept he concluded that there is no drastic change was noticed in the performance of major components and the main conclusion remained the same; the boiler is the major source of irreversibility in the power plant, chemical reaction is the most significant source of exergy destruction in a boiler system which can be reduced by preheating the combustion air and reducing the air–fuel ratio. **Godoy, et al., 2010,** presented optimization designs of a combined gas turbine (CCGT) power plant by second law efficiency, technical relationships are used to systematize optimal values of design and operative variables of a CCGT power plant into optimal solution sets named as optimal solution families. **Godoy, et al., 2011,** optimized combined cycle gas turbine power plants characterized by minimum specific annual cost values are determined for wide ranges of market conditions as given by the relative weights of capital investment and operative costs, by means of a non-linear mathematical programming model. A strategy for simplifying the resolution of the rigorous economic optimization problem of power plants is proposed based on the economic optima distinctive characteristics which describe the behavior of the decision variables of the power plant on its optima. **Abdolsaeid, et al., 2012,zaaaaa** presented comprehensive thermodynamic modeling of a dual pressure combined cycle power plant using exergy concept , results are compared with an actual data taken from one of the Iranian power plant to ensure the developed code, then they made optimization for number of decision variables to have a better understanding and optimal design of the system, The results show that gas turbine temperature, compressor pressure ratio and pinch point temperatures are significant design parameters. In this paper thermal analysis and economic analysis of various refinery cogeneration plants is conducted through energy and exergy efficiencies, four plants are considered one of them is currently serves the Dura refinery, Baghdad and the others are proposed.

2. MATHEMATICAL MODEL

2.1. First and second laws analysis and thermodynamics relations

i. The general energy and exergy efficiencies, these are given as: **Hameed, 1990**.

$$\eta_{cog} = \frac{E+H}{Qin} \tag{1}$$

$$\eta_{th} = \frac{H}{Qin} \tag{2}$$

$$\eta_{ele.} = \frac{E}{Qin} \tag{3}$$

This relation is referred to as the utilization efficiency to differentiate it from the thermal efficiency, which is commonly used for a power plant with single output power.

It is normally inappropriate to compare commodities that are different. Although work and heat have the same units, they are fundamentally different, with work being more valuable. The efficiency in Eq. (1) treats the electrical and thermal products equally. We can overcome this deficiency by defining the efficiency of a cogeneration plant based on the second law of thermodynamics using the concept of exergy (i.e., exergy efficiency or second-law efficiency), as the ratio of total exergy output to exergy input:

$$\eta_{cog,ex} = \frac{E+Ex_p}{Ex_f} \tag{4}$$

$$Ex_f = \dot{m}_f \, ex_f \tag{5}$$

Where ex_f is the specific exergy of the fuel. The exergy of a fuel may be obtained by writing the complete combustion reaction of the fuel and calculating the reversible work obtainable assuming all products are at the state of surroundings. The exergy of the fuel is equal to the reversible work. For fuels which yield water as a combustion product, the exergy of the fuel differs depending on the phase of water (vapor or liquid). **Szargut, et al., 1988,** list the exergies of various fuels based on vapor phase of water in combustion gases.

ii. Power to heat ratio (PHR)

It is the ratio of the electric energy produced to the heat process, it is given by:

$$PHR = \frac{E}{H} \tag{6}$$

iii. Net heat rate (NHR)

It is the ratio of fuel convertible-to-power to net electricity generated. The fuel convertible-to-power is the fuel energy input rate less the amount that would be necessary to produce the useful thermal energy only by conventional means.it is determined by:

$$NHR = \frac{(Q_f - H/\eta_b)}{E} \tag{7}$$

iv. Consumed fuel rate

The relationship between the overall efficiency, generated power, consumed fuel rate and low heating calorific value is given by:

$$\eta_{overall} = \frac{E}{m_f \ C.V} \tag{8}$$

We can estimate the consumed fuel rate per MW of power for different type of fuel, the result are tabulated in Table 4 and used to estimate the rate of consumed fuel.

v. Fuel saving rate (FSR)

It is given by:

$$FSR = \frac{m_f)_{present} - m_f)_{proposed}}{m_f)_{present}} \tag{9}$$

Where m_f is fuel consumed for the same output (heat + electric) from both plants. Considering the lack of electric power (generated in the present plant) are supplied from another condensing plant with $\eta = 0.35$ (estimated from Table 4)

2.2 Economic analysis

The economic evaluation of the cogeneration plants depends on the payback period, the short period is desired. The payback period calculated from: **Mehervan, 2002**.

$$N = \frac{Ct}{R_{ef}} \tag{10}$$

The total cost (Ct) is the sum of the annual fixed cost and running cost, the annual fixed cost is the sum of annual payment and maintenance cost, the annual payment is the investment times capital recovery factor (CR) , the capital recovery factor is given by:

$$CR = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{11}$$

The total annual income (R_{ef}) is the sum of the incomes from electricity and heat energy sealing. The maintenance cost and the other cost are taken as a percent of the investment, the running cost mainly annual fuel cost, all the required data for economic analysis are taken from **Meherwan, 2002**.

3. DESCRIPTION OF THE PRESENT AND PROPOSED COGENERATION PLANTS

i. Present plant

Dura refinery was established in the middle of the last century and Iraq nowadays is interested in reconstruct his old refineries and inspired to build a new refineries. Therefore several researchers found that it is necessary to analyze the heat cycle of the present Dura refinery and propose a new design for cogeneration plants **Kathem, 2007** and **Hameed, 1990**.

The present plant shown in Fig.1 supplies the whole refinery with 21.6 ton/h process steam at 18 bars, 260 ^{o}C as well as about 4.5MW electric power **Hassan, 1988**. An additional 11 MW of electricity is purchased from the main electric network. **Fig. 1** shows the unit, while **Table 1** shows the quantitative details for the unit.

ii. Back pressure steam turbine cogeneration plant

The back-pressure non-condensing turbine of type R-50-127-13 were suggested, where the first number refers to power (MW), the middle one refers to inlet turbine pressure (bar) and the last number refers to turbine exit pressure (bar) **Kathem, 2007**. The back-pressure turbine can generate maximum electricity at approximately the same time as the system heat at its peak demands. Furthermore, it is simple in design and has high reliability and it also has a very low heat rate which permits the achievements of high fuel savings. Also, its equipment cost and space requirements for back-pressure (non-condensing) units are very much less than for condensing units. In this cogeneration system boiler was selected according to operation condition of **Kathem, 2007.** To supply the heat demand of unit turbine must be operated continuously at a partial load with exit pressure 18bar. The temperature of steam from turbine exhaust is around 316^{o}C, so most of superheat being removed by water injection. **Fig. 2** represents a simple layout for this unit and the quantitative details are listed in **Table 2** and **Table 3**. This plant can cover the process heat as well as, produce 34.5MW surplus electric powers which can be sold at a profit to the grid.

iii. Gas turbine based cogeneration plant

The refinery gas turbine cogeneration plant produces electricity and 21.6 ton/h of steam at 18bar and 260^{o}C from the waste heat recovery boiler. A cogeneration gas-turbine power plant considered in this study of a net power output of 20 MW and maximum and minimum pressures of 1200 and 100 kPa in the system, respectively. The fuel is natural gas, the turbine inlet temperature is 700^{o}C and the isentropic efficiencies of both the turbine and compressor are 85%. Under these operating conditions, exhaust gases leave the turbine at 303^{o}C. All steam and the required electrical energy are used in the refinery, while the surplus electric power can be sold at a profit to the grid. The gas turbine is operated continuously at full or part load by natural gas with lower heating value of 50050 kJ/kg. The general plant flow diagram is shown in **Fig. 3, Hameed, 1990** and **Hassan, 1988.**

iv. Diesel-engine based cogeneration plant

A diesel-engine powered cogeneration plant is considered where the outputs are electrical power and heat, which is transferred from the hot exhaust gases to water in an unfired waste heat recovery boiler, The general plant flow diagram is shown in **Fig. 4**. Some of the values to be used in this grid are from an actual diesel-engine power plant **Kanoglu, 2005**. The same rate of heat transfer as in the steam and gas-turbine cogeneration is assumed. The net power output from the plant is 20 MW when the rate of fuel consumption is 1.25 kg/s and the air–fuel ratio is 40.4. This corresponds to an exhaust flow rate of 51.75 kg/s. The exhaust gases enter the waste heat recovery boiler at 400^{o}C, extra fuel needed to produce the required steam with 85% assumed boiler efficiency and flue gas inlet temperature of 150^{o}C. The plant uses heavy diesel fuel with a lower heating value of 39300 kJ/kg. Note that the exergy of heavy diesel fuel with an unknown composition is taken as 1.065 times the lower heating value of the fuel following the approach by **Brzustowski and Brena, 1986.**

4. RESULTS AND DISCUSSION

The aim of the present study includes a brief description of the present Dura refinery plant and the suggested alternative cogeneration plants in which back-pressure non-condensing turbine, gas turbine and diesel engine are examined, the analysis in this work gives a good agreement for currently Dura refinery plant and back pressure turbine plant alternative with, **Kathem, 2007.** In order to describe the performance of a cogeneration plants various thermodynamic parameters were determined, a summary of results are given in **Table 5** ,to facilitate comparisons of the plants the same heat requirement for the refinery is considered (145 MW) with different electric power output and depending on **Table 4** which help to estimate the rate of fuel consumed. The results show that the presently plant have the smallest efficiency compared with other alternative plants this because of its dependence on the bottoming cycle which leads to waste energy without power producing. The present plant consumes 6.1 kg/s of fuel **Hameed, 1990**. for both electric power and refinery heat requirement the fuel consumed rate and net heat rate decreased in all alternatives so there are a saving in the fuel consumed rate about 28.59% for back pressure turbine, 20.787% for gas turbine cogeneration plant and 12.787% for diesel engine cogeneration plant. This advantage is due to the thermal recovery from the flue gas by the heat recovery steam boiler and because of increase plant heat rate .This means new advantage that the alternatives can produced surplus electric power which can supports and solve the present crisis national electric power generation i.e. back pressure turbine plant can added 34.5MW to the national electric network. The back pressure turbine cogeneration plant is the best alternatives (high efficiency, low NHR, high fuel saving and surplus power produced). The payback period given in Table 6 indicate that the gas turbine unit payback period is shorter than other alternatives this due to the price of natural gas is cheaper than gas oil fuel used in both back pressure turbine cogeneration plant and diesel engine plant.

5. CONCLUSIONS

1- According to 1st and 2nd thermodynamics law, the proposed plants can improve thermal efficiency.
2- The back pressure turbine cogeneration plant is the most suitable for cogeneration. Although the application this type leads to increase initial cost, but at the same time leads to increase PHR by 222% and FSR by 28.6%.
3- The price of electric and heat power from cogeneration plants is depending on the method of estimation specific fuel consumption. Therefore this estimation method should be chosen so that it can be promote to build new cogeneration plants in Iraq.
4- The payback period of gas turbine unit is shorter than other alternatives.
5- Due to its high efficiency, the cogeneration plants are recommended in Iraq, especially in petroleum industry sectors, in order to contribute with ministry of electricity to solve the present crisis of electric power generation.

Table 1. Specifications data of steam circuit for Dura's refinery **, Kathem, 2007.**

State	P (bar)	t (°C)	m (kg/s)	Pt.	P (bar)	T (°C)	m (kg/s)
0	18.93	260	75.6	19	1.36	108.4	6.433
1	18.24	260	3.143	20	18.39	209.6	9.639
2	18.24	260	4.187	21	1.36	108.4	7.796
3	18.24	260	57.182	22	1.36	108.4	1.843
4	18.24	260	11.088	23	22.37	86.7	85.239
5	0.1	45.8	11.088	24	18.24	248.9	0.547
6	0.1	46.1	11.088	25	1.7	115.2	0.512
7	17.55	248.9	1.462	26	3.01	34	66.125
8	17.48	96.5	1.462	27	1.01	33.9	66.125
9	18.24	260	2.725				
10	1.7	115.2	2.725				
11	0.1	46.1	11.088				
12	1.01	71.1	11.494				
13	1.01	26.1	54.631				
14	1.01	93.3	76.627				
15	2.01	39.9	78.675				
16	18.24	260	0.887				
17	1.36	108.4	0.756				
18	1.8	86	85.239				

Table 2. Specifications data of steam circuit for Dura's refinery with the turbine type R 50-127-13**, Kathem, 2007.**

State	P (bar)	t (°C)	m (kg/s)	Pt.	P (bar)	t (°C)	m (kg/s)
0	130	565	83.337	17	1.01	93	51.115
1	34	389.7	3.571	18	1.01	27	48.232
2	23.61	343.3	2.232	19	1.01	38.94	58.695
3	18.24	316.18	77.534	20	6	38.96	58.695
4	18.24	316.18	7.232	21	18.24	260	1.216
5	18.24	316.18	70.302	22	6	158.8	83.337
6	18.24	316.18	11.607	23	130	160.3	83.337
7	18.24	316.18	58.695	24	130	204.5	83.337
8	1.01	27	2.871	25	130	218.2	83.337
9	18.24	260	61.566	26	130	238.1	83.337
10	17.55	258.9	1.216	27	34	240.9	3.571
11	18.24	260	60.35	28	23.61	221	3.571
12	1.01	27	0.012	29	23.61	221	5.803
13	17.55	248	1.228	30	18.24	207.8	5.803
14	1.01	93	60.35	31	18.24	207.8	13.035
15	1.01	93	9.235	32	6	158.9	13.035
16	17.48	96	1.228				

Table 3. Operation design conditions for turbine type R50-127-13 **, Kathem, 2007.**

P MW	p_{in} (bar)	t_{in} (°C)	$m_{max.}$ (kg/s)	m_o (kg/s)	$m_{1st,b}$ (kg/s)	$m_{2nd.b}$ (kg/s)	$m_{3rd.b}$ (kg/s)	$p_{c.s.}$ (bar)	$p_{1st.b}$ (bar)	$p_{2nd.b}$ (bar)	$p_{s.4}$ (bar)	p_{exit} (bar)
50	127	565	136	102	5.5	6	9.58	95	37	22	65	13

Table 4. Consumed fuel rate (kg/s)/MW_p for different efficiency and different fuel low heating value.

Heating value Overall efficiency	30	32	34	36	38	40	42	44	46	48	50	52
0.14	0.238	0.223	0.210	0.198	0.188	0.179	0.170	0.162	0.155	0.149	0.143	0.137
0.16	0.208	0.195	0.184	0.174	0.164	0.156	0.149	0.142	0.136	0.130	0.125	0.120
0.18	0.185	0.174	0.163	0.154	0.146	0.139	0.132	0.126	0.121	0.116	0.111	0.107
0.2	0.167	0.156	0.147	0.139	0.132	0.125	0.119	0.114	0.109	0.104	0.100	0.096
0.22	0.152	0.142	0.134	0.126	0.120	0.114	0.108	0.103	0.099	0.095	0.091	0.087
0.24	0.139	0.130	0.123	0.116	0.110	0.104	0.099	0.095	0.091	0.087	0.083	0.080
0.26	0.128	0.244	0.113	0.107	0.101	0.096	0.092	0.087	0.084	0.080	0.077	0.074
0.28	0.119	0.112	0.105	0.099	0.094	0.089	0.085	0.081	0.078	0.074	0.071	0.069
0.3	0.111	0.104	0.098	0.093	0.088	0.083	0.079	0.076	0.072	0.069	0.067	0.064
0.32	0.104	0.098	0.092	0.087	0.082	0.078	0.074	0.071	0.068	0.065	0.063	0.060
0.34	0.098	0.092	0.087	0.082	0.077	0.074	0.070	0.067	0.064	0.061	0.059	0.057
0.36	0.093	0.087	0.082	0.077	0.073	0.069	0.066	0.063	0.060	0.058	0.056	0.053
0.38	0.088	0.082	0.077	0.073	0.069	0.066	0.063	0.060	0.057	0.055	0.053	0.051
0.4	0.083	0.078	0.074	0.069	0.066	0.063	0.060	0.057	0.054	0.052	0.050	0.048

Table 5. Energy and exergy analysis results for different cogeneration systems.

Parameter	Present plant	Back pressure turbine cogeneration	Gas-turbine cogeneration	Diesel engine cogeneration
Energy eff. %	58.3	76.89	68.22	70.3
Exergy eff. %	21.8	31.67	32.52	43.7
Ele. Power (E)(MW)	4.5	50	20	20
Surplus power(MW)	-11	+34.5	+4.5	+4.5
Heat requirement(H)(MW)	145	145	145	145
PHR	0.107	0.345	0.138	0.138
NHR	22.7	2.32	9.43	11.3
FSR %	-	28.59	20.787	12.787

Table 6. The economic analysis summary.

Item	Back pressure turbine cogeneration	Gas-turbine cogeneration	Diesel engine cogeneration
Investment (million $)	50	25	22
Interested (i)	15	15	15
Operation period (years)	25	20	15
Capital recovery factor (CR)	0.155	0.16	0.171
Annual payment(million $)	7.75	4	3.762
Operation & maintenance cost($/MWh)	0.6	0.4	0.6
Annual fixed cost(million $)	8.77	4.58	4.5
Annual variable cost(million $)	49.45	20.4	60.4
Total annual cost (Ct) (million $)	58.22	24.98	64.9
Annual income from electricity (million $)	10.512	4.205	4.205
Annual income from heat energy (million $)	2.27	2.27	2.27
Total incomes (R_{ef}) (million $)	12.782	6.475	6.475
The payback period(years)	4.55	3.858	10.02

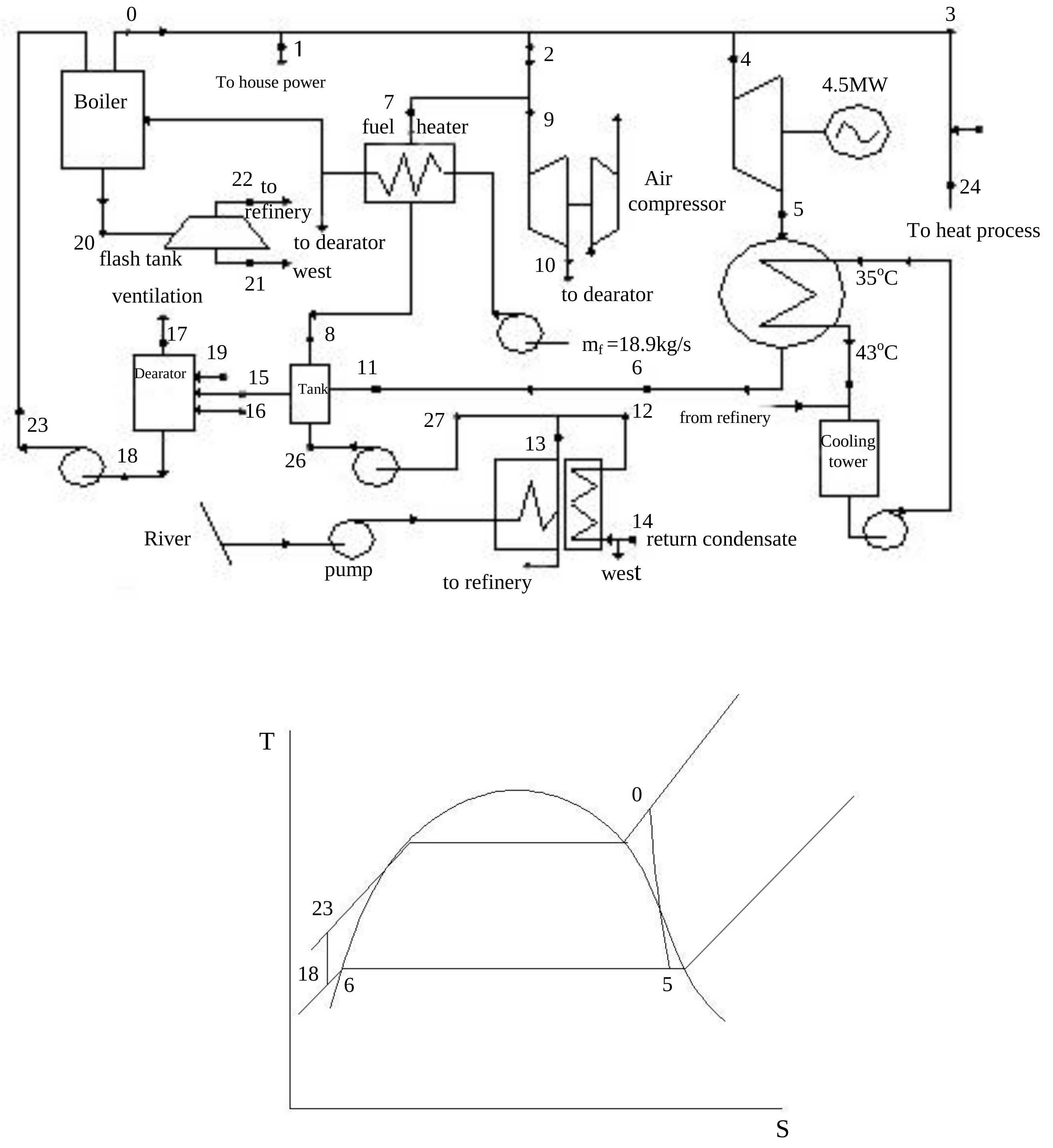

Figure 1. Present Dura refinery plant and T-S diagram.

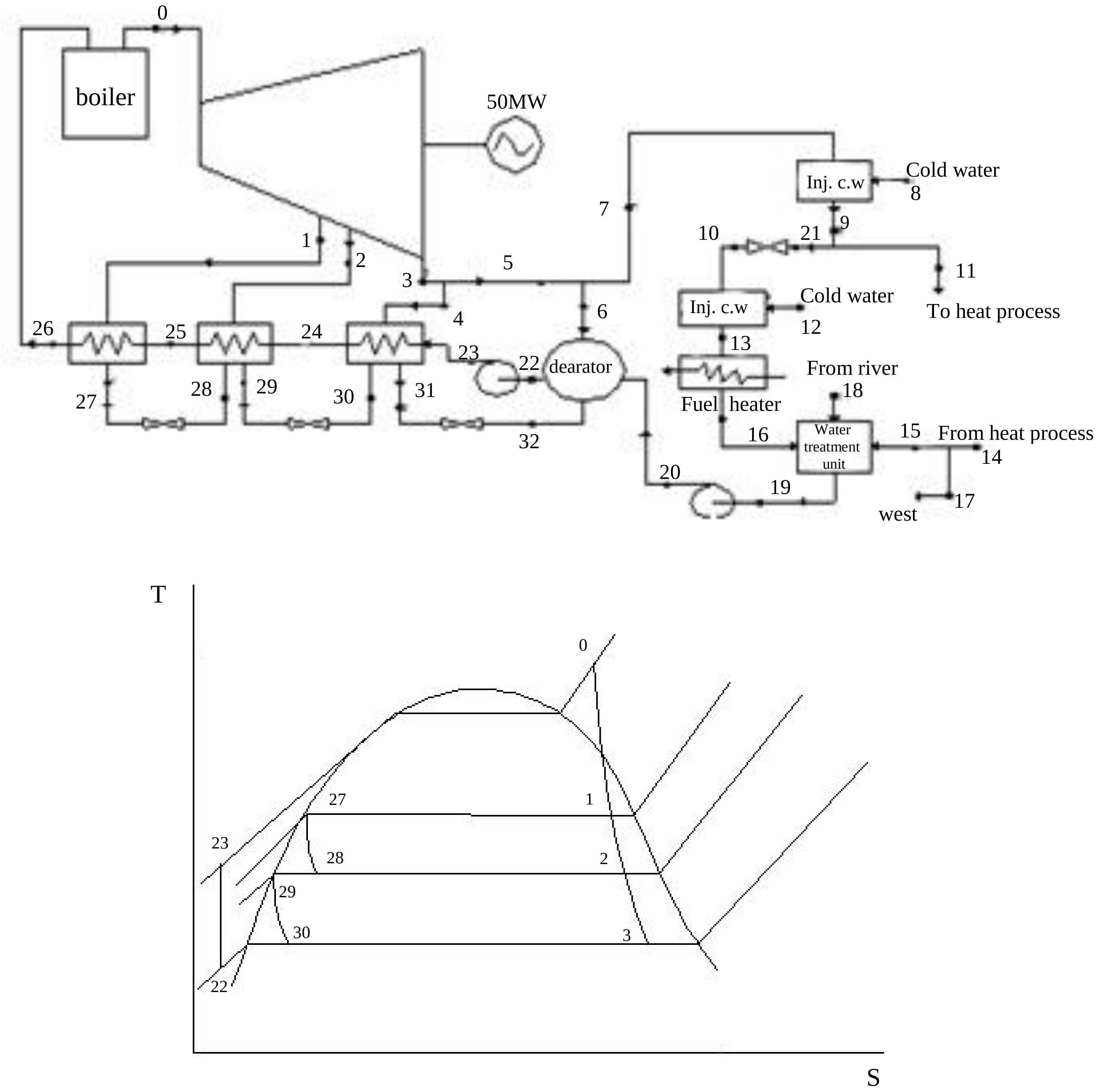

Figure 2. The back pressure cogeneration plant and T-S diagram.

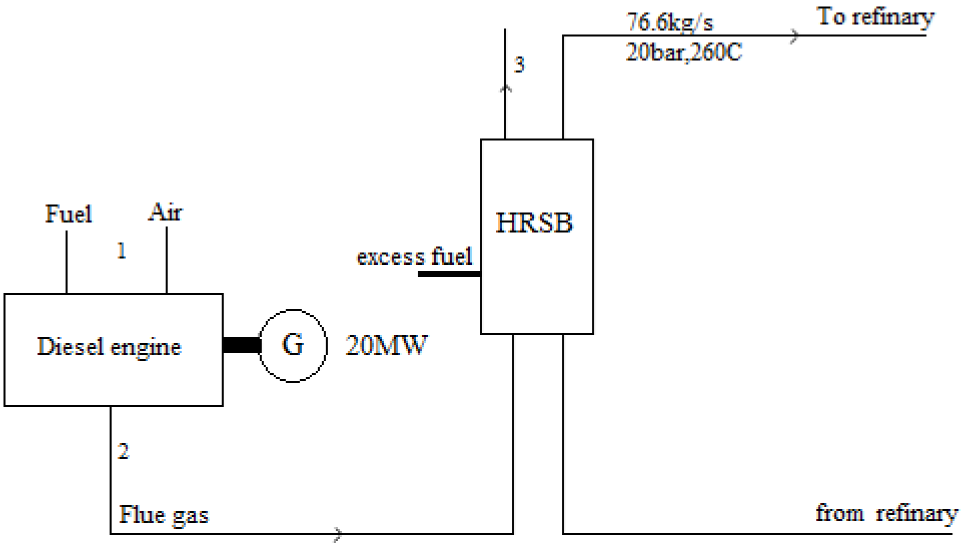

Figure 3. A cogeneration diesel engine plant plant.

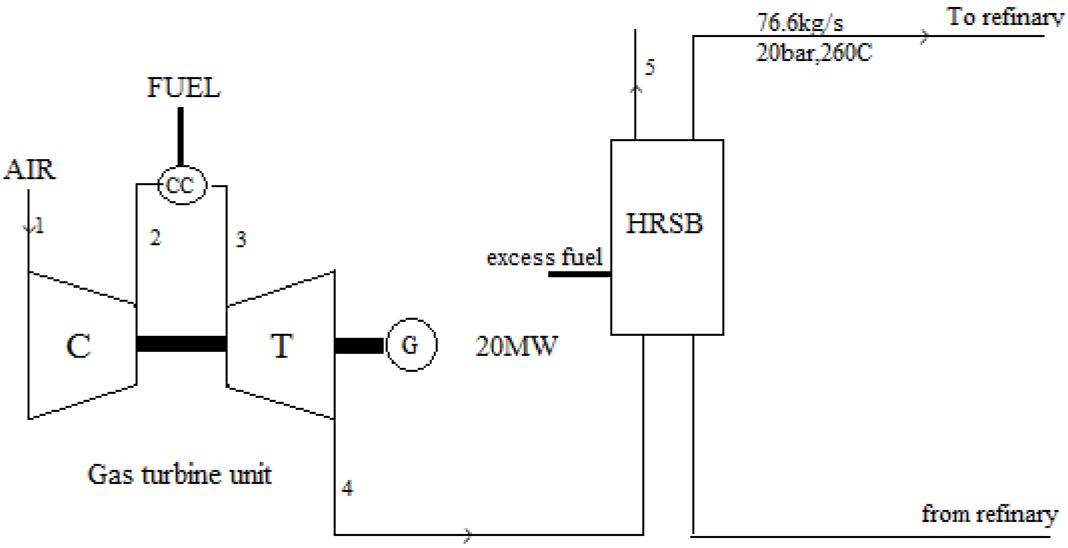

Figure 4. The gas turbine cogeneration power plant.

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Nomenclature

Latin

Ct = total annual cost ($)
CR = investment recovery factor
$H.V$ = fuel heating value (kJ/kg)
E = electric energy produced (MW)
H = heat requirement (MW)
m = mass flow rate (kg/s)
N = payback period (year)
Q = total heat (kJ)
R_{ef} = total annual income ($)

Greek letters

η : Efficiency

Subscript

add : added
b : boiler
ele.: electric
f : fuel
g : generated
h : heat
i : interest
in : inlet
n : number of years

Abbreviations

FSR**:** Fuel Saving Rate
HRSB: Heat Recovery Steam Boiler
NHR: Net Heat Rate
PHR: Power to Heat Ratio