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PERFORMANCE ENHANCEMENT OF A COGENERATION INSTALLATION IN INDUSTRY

Mota, O. D. S.1, Afonso, C. F. A.2

1[Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial](https://sigarra.up.pt/feup/pt/uni_geral.unidade_view?pv_unidade=150), University of Porto, Porto, Portugal

2[Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial](https://sigarra.up.pt/feup/pt/uni_geral.unidade_view?pv_unidade=150), University of Porto, Porto, Portugal

**ABSTRACT**

The CHP (Combined Heat and Power) is a wide spread technology, which uses one form of energy to obtain two different forms of energy: work (electricity) and heat. For that purpose it uses a thermal engine, or a combination of different types of thermal engines. With this technology the global efficiency of the whole system is increased meeting the sustainability of the primary form or energy.

In this work it was analysed a CHP running simultaneously with an internal combustion engine and a steam turbine used in one factory located in Portugal. After performance enhancement the results obtained shows that there is a 40% profit increase from electricity production by internal combustion engines operating on natural gas. The equivalent electrical efficiency is 67%. On the other hand, steam turbine “upgrade” will expand practically all the vapour produced in the boiler, working on fuel oil. The equivalent electrical efficiency increased from 28% to 55%. The payback period is 4 years.

So this technology is a growing one, and can be used in buildings and small villages.

***Keywords:*** CHP, sustainable energy, thermal efficiency, equivalent electric efficiency.

**INTRODUCTION**

Energy is an indispensable factor for any human activity. Transport, industrial production, trade, communications, etc. depend on the energy availability. Traditionally, consumers meet their energy demand by buying separately electricity and fuel to the distribution companies. With regard to electric energy generation acquired by consumers, a good portion is produced in conventional thermoelectric power plants. In modern ones, the total losses in energy can go up to 52.5% without any kind of recovery. Thermal energy from the fuel purchased by consumers is done in burning systems with a maximum average efficiency, at best, about 90% (10% lost). Faced with this problem arises the need to increase the efficiency of electricity production processes and heat generation in order to reduce the financial and environmental costs. Thus, as an alternative to large conventional power plants, decentralized production of electricity arises, and, in particular cogeneration, in order to take advantage of the inherent limitations of the conversion of heat into work (Afonso, 2012). CHP (Combined Heat and Power) is a combined process of production and exploitation of thermal energy and electricity, in an integrated system, from the same primary source (Çengel, 2001; COGEN, 2013). In spite of not being a new technology its applications are mainly used in the industry. These kinds of systems contribute also for a decrease of CO2 emissions to the environment (Afonso, 2016).

THE CHP FACILITY

Fig. 1 shoes a schematic representation of the combined cogeneration installation. There are two cogeneration systems. The first one is composed by two Otto Cycle internal combustion engines running on natural gas, and working in parallel, M1 and M2. Tab. 1 shows their technical data. They produce electricity, water vapor and hot water in the recovery boiler, CR. The second system is a water vapor turbine, T. Tab. 2 shows its technical data. It expands some of the water vapor produced by three fuel oil boilers, C1, C2 and C3. It produces electricity, and the remaining water vapor is utilized in the process. Tab. 3 shows the technical data of the boilers.



**Fig. 1 -**  Schematic representation of the combined cogeneration installation.

For a typical producing year, the monthly operating hours are given in Tab. 4.

During continuous operation, the measured thermodynamic properties of water and steam during the operation are shown in Tab. 5.

All the electricity obtained from M1 and M2 is sold to the electric grid. The electricity needed to the process is produced by T.

From the data analyses, it is obtained the annual energy consumption of the cogeneration installation as displayed in Tab. 6. Included is the electric energy consumed.

A thermal analysis of the process leads to the annual energy production of the cogeneration installation predicted to produce electricity, water vapor and hot water, Tab. 7.

**Tab. 2 -** Technical data of the water vapor turbine, T shown in Fig. 1.

|  |  |
| --- | --- |
| Constructor | Rateau |
| Construction year | 1951 |
| Type | back-pressure |
| Pressure (bar) | 24 |
| Temperature (°C) | 400 |
| Specific consumption (kg Vapor/kWh) | 11,5 |
| Capacity (MW) | 1,5 |
| R.P.M. | 10500 |

**Tab. 1 -** Technical data of the internal combustion engines, M1 and M2 shown in Fig. 1.

|  |  |
| --- | --- |
| Constructor | JES AG |
| Reference | J616GS-C01 |
| Type | 4 Stroke |
| Configuration | V60° |
| Number of cylinders | 16 |
| Fuel | Natural Gas |
| Diameter (mm) | 190 |
| Stroke (mm) | 220 |
| Displacement (l) | 99,8 |
| R.P.M. | 1500 |
| Oil reservoir (l) | 530 |
| Cooling water capacity (l) | 270 |
| Length (mm) | 3950 |
| Width (mm) | 1680 |
| Height (mm) | 2605 |
| Vacant weight (kg) | 10000 |
| Operating weight (kg) | 10700 |
| Engine starter power (k W) | 15 |
| Voltage (V) | 24VDC |

**Tab. 3 -** Technical data of the boilers in, C1, C2 and C3 shown in Fig. 1.

|  |  |  |  |
| --- | --- | --- | --- |
|   | Boiler C1 | Boiler C2 | Boiler C3 |
| Constructor | Fives Cail Babcock | Babcock & Wilcox | Babcock & Wilcox |
| Construction year | 1975 | 1975 | 1967 |
| Type | D | D | D |
| Model | FML 13-3/65 | FML 13/65 | FML 11/43 |
| Pressure (MPa) | 2.9 / 2.4 | 3.2/2.4 | 2.9 / 2.4 |
| Capacity (m3) | 30 | 20 | 8.5 |
| Max. continuous capacity (t/h) | 35 | 35 | 13.6 |
| Max. peek capacity (t/h) | 40 | 40 | 14.3 |
| Outlet vapor temperature (°C) | 400 | 400 | 305 |
| Fuel | Thick Fuel Oil | Thick Fuel Oil | Thick Fuel Oil |
| Efficiency (%) | 89 | 89 | 86 |

**Tab. 4 -** Monthly operating hours of the Cogeneration Installation.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|   | Hours in | Hours in | Hours in | Hours in | Total |
|   | "Vazio Normal" | "Super Vazio" | "Cheio" | "Ponta" | Hours |
| JAN | 69 | 92 | 276 | 115 | 552 |
| FEV | 60 | 80 | 240 | 100 | 480 |
| MAR | 66 | 88 | 264 | 110 | 528 |
| ABR | 66 | 88 | 264 | 110 | 528 |
| MAI | 66 | 88 | 308 | 66 | 528 |
| JUN | 60 | 80 | 280 | 60 | 480 |
| JUL | 69 | 92 | 322 | 69 | 552 |
| AGO | 66 | 88 | 308 | 66 | 528 |
| SET | 63 | 84 | 294 | 63 | 504 |
| OUT | 69 | 92 | 322 | 69 | 552 |
| NOV | 63 | 84 | 252 | 105 | 504 |
| DEZ | 66 | 88 | 264 | 110 | 528 |
| ANNUAL | 783 | 1044 | 3394 | 1043 | 6264 |

**Tab. 5 -** Thermodynamic properties of water and steam corresponding to the states shown in Fig. 1 (Coelho, 2007).

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| State | Description | Pressure (bar) | Temperature (ºC) | Enthalpy (kJ/kg) |
| 0 | Boiler feed water | - | 115 | 481,482 |
| l | Boiler 1 vapor outlet | 24 | 360 | 3146,799 |
| 2 | Boiler 2 vapor outlet | 23,5 | 280 | 2956,781 |
| 3 | Boiler 3 vapor outlet | 24 | 360 | 3146,799 |
| 4 | Turbine vapor inlet | 24 | 350 | 3123,771 |
| 5 | Turbine vapor outlet | 2 | 170 | 2809,971 |
| 6 | Valve outlet | 2 | 120 | 2706,766 |
| 7 | Recovery boiler outlet | 2 | 120 | 2706,766 |
| 8 | Vapor outlet to process | 2 | 120 | 2706,766 |
| 9 | Saturated liquid | 2 | 120 | 502,165 |

Relating the input and output energies from tables 6 and 7 respectively, it can be concluded that, annually, approximately 80% of the input energy is used. Note that this is the energy utilization factor, not the thermal efficiency, which is considerably less.

**Tab. 6** - Annual energy consumption of the cogeneration installation.

LCVnatural gas= 9,5 kWh/m3, LCVfuel oil = 40610 kJ/kg.

|  |  |  |  |
| --- | --- | --- | --- |
|   | Natural Gas (Nm3) | Fuel oil (kg) | Electricity (kWh) |
| JAN | 262122 | 1484650 | 29192 |
| FEV | 226938 | 1149360 | 23593 |
| MAR | 225952 | 1124090 | 24459 |
| ABR | 105784 | 1369830 | 18914 |
| MAI | 194080 | 1042210 | 23808 |
| JUN | 229095 | 893700 | 29657 |
| JUL | 450477 | 1022400 | 45406 |
| AGO | 340847 | 857690 | 38778 |
| SET | 431375 | 966750 | 44411 |
| OUT | 504358 | 1238950 | 46404 |
| NOV | 440580 | 1003490 | 41264 |
| DEZ | 419199 | 900460 | 38880 |
| TOTAL | 3830807 | 13053580 | 404766 |

**Tab. 7** - Annual energy production of the cogeneration installation.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|   | Operating hours | Electricity (kWh) | Vapor (kg) | Hot water (kWh) |
| JAN | 552 | 1159200 | 21178157 | 235860 |
| FEV | 480 | 1008000 | 16117724 | 198863 |
| MAR | 504 | 1058400 | 15632051 | 216568 |
| ABR | 528 | 1108800 | 18453909 | 88173 |
| MAI | 528 | 1108800 | 15092908 | 126737 |
| JUN | 504 | 1058400 | 14056077 | 147750 |
| JUL | 552 | 1159200 | 16836239 | 361196 |
| AGO | 504 | 1058400 | 13171291 | 381627 |
| SET | 528 | 1108800 | 14726340 | 488035 |
| OUT | 552 | 1159200 | 18516471 | 624628 |
| NOV | 480 | 1008000 | 14915081 | 547029 |
| DEZ | 552 | 1159200 | 13310746 | 519324 |
| TOTAL | 6264 | 13154400 | 192006994 | 3935790 |

In a cogeneration plant, commonly two types of energy (work and heat) are produced from one primary energy, so it is not possible to measure the fraction of primary energy necessary to produce a given output.

One approximation is to assume that the thermal energy could be produced separately in a boiler of common efficiency of 90% (see table 3). The primary energy consumed to produce thermal energy, $\dot{Q}\_{fuel, therm.}$, is given by:

 $\dot{Q}\_{fuel, ther.}=\frac{\dot{Q}\_{therm.}}{Ƞ\_{boil.}}$

The remaining primary energy is used to produce work (electricity):

 $\dot{Q}\_{fuel, elect.}=\dot{Q}\_{fuel}-\frac{\dot{Q}\_{therm.}}{Ƞ\_{boil.}}$

For each cogeneration technology, the equivalent electric efficiency, EEE, represents the fraction of the primary energy source consumption (necessary to produce electrical energy) that is actually converted to electricity:

 $EEE=\frac{\dot{W}}{\dot{Q}\_{fuel}-\frac{\dot{Q}\_{therm.}}{Ƞ\_{boil.}}}$

Results obtained show that EEEM1,M2 = 67% (acceptable electric performance) and
EEET = 28% (unacceptable electric performance) The calculated values took in account the Decree Laws in force (Decree -Law nº 538/99; nº 313/2001; Ordinance nº 58/2002).

It is desirable to enhance the steam turbine performance to acceptable EEE values, greater than 50% in the case of fuel oil combustion.

## RESULTS AND CONCLUSIONS

Modifications where suggested to enhance the performance of the cogeneration plant.

Since in the internal combustion engines the equivalent electric efficiency is acceptable, the operating regime of these engines was analyzed. Electricity prices vary according to the daily selling hour.

Comparing the cost of the electric (kWh) to its selling price as seen in Fig. 2, there is an economic profit obtained in peak hours related to the hours in which the electric needs are greater during the normal working hours (in the daytime schedule, peak and off peak hours).

Super empty Empty Off peak hours Peak hours

**Fig. 2** - Comparison of the electric kWh cost (light color) to its sell price (dark color), produced by the internal combustion engines, M1 and M2.

An interesting modification studied was the conversion of the boiler burners so that natural gas could be fired instead of fuel oil (CIB, 2002). It seemed that emission reduction and economic benefit were feasible.

Two burners were considered, the WS65 and P520 models from CIB UNIGAS, and the natural gas consumption and cost are given in Tab. 8. Tab. 9 shows the fuel oil consumption and cost of the existing burners.

It can be seen from these two tables that burning fuel oil is 4% cheaper.

Another limitation considered was due to the process CO2 needs. These are obtained from the fuel oil combustion. The lower emissions of natural gas could put at stake the necessary CO2 quantities necessary.

These two limitations turned the boiler conversion impracticable.

It was urgent to focus on the Rankine cycle due to the low EEE values of the steam turbine. For this technology alone, the energy utilization factor is 80%, so the low EEE values are explained because approximately 50% of the water produced in the boilers is fed directly to the process, refer to figure 1, point 6.

Upgrade of the steam turbine was mandatory.

With the above modifications in mind, the expected turbine energy outputs (electricity and water vapor) to satisfy process needs are indicated in Tab. 10. Five turbines were selected, having the technical characteristics shown in Tab. 11.

All the turbines met the energy requirements, exceeding from 21% to 35% in the electrical productions to guaranty this electrical requirement. The excess energy is to be sold to the grid, Tab. 12. The obtained profit is compared in Fig. 3.

**Tab. 9** - Fuel oil consumption and cost for the existing burners.

|  |  |  |
| --- | --- | --- |
|   | Fuel oil consumption (kg) | Cost (€) |
| JAN | 1540966 | 315898 |
| FEV | 1164699 | 238763 |
| MAR | 1124428 | 230508 |
| ABR | 1336419 | 273966 |
| MAI | 1080079 | 221416 |
| JUN | 1004230 | 205867 |
| JUL | 1209812 | 248011 |
| AGO | 936748 | 192033 |
| SET | 1052121 | 215685 |
| OUT | 1337962 | 274282 |
| NOV | 1072975 | 219960 |
| DEZ | 940925 | 192890 |
| TOTAL | 13801363 | 2829280 |

**Tab. 8** - Natural gas consumption and cost for the natural gas burners (WS65 and P520 models).

|  |  |  |
| --- | --- | --- |
|   | Natural gas consumption (Nm3) | Cost (€) |
| JAN | 1829785 | 327531 |
| FEV | 1382995 | 247556 |
| MAR | 1335176 | 238997 |
| ABR | 1586900 | 284055 |
| MAI | 1282514 | 229570 |
| JUN | 1192449 | 213448 |
| JUL | 1436563 | 257145 |
| AGO | 1112320 | 199105 |
| SET | 1249317 | 223628 |
| OUT | 1588732 | 284383 |
| NOV | 1274079 | 228060 |
| DEZ | 1117280 | 199993 |
| TOTAL | 16388110 | 2933472 |

**Tab. 10** - Expected water vapor turbine energy outputs for process.

|  |  |  |
| --- | --- | --- |
|   | Electricity (kWh) | Vapor (kg) |
| JAN | 1159200 | 20204314 |
| FEV | 1008000 | 15270904 |
| MAR | 1058400 | 14742890 |
| ABR | 1108800 | 17522407 |
| MAI | 1108800 | 14161406 |
| JUN | 1058400 | 13166916 |
| JUL | 1159200 | 15862396 |
| AGO | 1058400 | 12282130 |
| SET | 1108800 | 13794838 |
| OUT | 1159200 | 17542628 |
| NOV | 1008000 | 14068261 |
| DEZ | 1159200 | 12336903 |
| TOTAL | 13154400 | 180955993 |

**Tab. 11** - Comparison of the technical characteristics of five water vapor turbines.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Make | - | KKK | KKK | KKK | NADROWSKI | ELLIOT |
| Model | - | AFA 6 | AFA 44 | CFR55 | B5S-4 | 2DYR3 |
| Generator electric power | kVA | 3565 | 3625 | 3760 | 4860 | 3874 |
| Vapor flowrate | kg/s | 7.54 | 7.55 | 7.65 | 7.69 | 7.6 |
| Inlet vapor pressure | bar | 25 | 25 | 25 | 25 | 25 |
| Inlet vapor temperature | °C | 344 | 344 | 344 | 344 | 344 |
| Pressão vapor saída | bar | 1.95 | 1.95 | 1.95 | 1.95 | 1.95 |
| Outlet vapor temperature | °C | 150,7 | 148.3 | 133.3 | 127 | 140 |
| Isentropico efficiency | % | 64.6 | 65.6 | 71.4 | 73.9 | 68.8 |
| Price | € | 927049 | 984456 | 1101794 | 1042739 | 1066036 |

**Tab. 12** - Excess electric energy to be sold to grid for the five selected water vapor turbines.

|  |
| --- |
| Excess electrical energy (kWh) |
| KKK | KKK | KKK | NADROWSKI | ELLIOT |
| AFA 6 | AFA 44 | CFR55 | B5S-4 | 2DYR3 |
| 2756160 | 2887704 | 4159296 | 4647888 | 4259520 |

**Fig. 3** - Profit (€) due to electric energy to be sold to grid for the five selected steam turbines.

It was proposed the turbine model B5S-4 (Nadrowski) which has the best results.

The gain obtained from the electricity sold by this steam turbine is to pay the investment of this machine. The payback period is 4 years.

With this modification the equivalent electric efficiency raised to EEET=55%.

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