EXERGY ANALYSIS OF A COGENERATION THERMOELECTRICAL UNITY IN A PETROCHEMICAL COMPLEX

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Abstract. *Rankine cycle can not transform in power all fuel energy that was transfered to water due to the latent heat that remains in the steam after its expansion in the turbine. In order to maximize the power generation by lower exhaust pressure and to recover exhaust mass to feed water to the boiler, the turbine exhaust is condensed by an external cold source that transfers exhaust latent heat to the environment. It corresponds the principal loss of the cycle. Cogeneration reduces this energy loss. The fuel energy is shared foremost in power generation and afterward in heat source that is furnished to another process. It enables an appreciable increase in cycle efficiency. This paper presents an exergy analysis of process irreversibility that could be avoided and can not be detected by a simple energy evaluation. It makes clear that the energy loss of a saturated Rankine cycle might be reduced by small process changes increasing the cycle efficiency. The analyzed unity makes part of the Petrochemical Complex in Camaçari city. A simulator of a real power plant was developed to evaluate the benefits. The simulator was based on EES, Equation Engineering Solver, platform software. It points that energy efficiency might increase from 83,6% to 87,0% and reduces a fuel oil consumption about 36 thousands tons per year (17 millions Reals, Brazilian currency).*

Keywords*: power plant; Rankine cycle; cogeneration; exergy; irreversibility.*

1. Introduction

Oil applications have been widespread in the human life and stand for an indispensable component. It is noticed on food, wares, clothing, among other products, and as energy sources in houses, transports, besides infinity of other utilities and services.

Eletrobrás, (2005) has analized the global oil and energy demand around the world in the last century and verified that both oil and energy consumption rate grew in the last fifty years four times larger than first fifty years. Lora and Nascimento, (2004) carried out a search of fossil fuel reservoires and they estimate that afterward 2010 the growth of global oil production will not keep up with demand growth. It means that we must avoid energy losses anyway.

The thermoelectrical unities are the biggest fossil fuel consumer (SEN/MME, 2004). Basicly, all them develop a Rankine cycle that can not transform in power the fuel energy which was transferred to water in the boiler. The exhaust of condensing turbine retains a large quantity of thermal energy, steam latent heat, that can not be recovered neither transformed in power. On one hand, there is no process stream on Rankine cycle that could recover the exhaust energy by heat transfer. On other hand, the exhaust pressure is so low to be expanded and the exhaust humidity is limited up to 10% to avoid turbine blade erosion (Lora, 2004).

In order to recover the exhaust mass to feed water to the boiler and to maximize turbine power generation by reducing the exaust pressure as low as possible, the turbine exhaust is condensed by an external cold source that transfers the turbine exhaust heat to the environment. It corresponds the principal loss of the cycle.

The regeneration on Rankine cycle where feed water boiler is preheated by extracted steam from turbine rise the Rankine cycle efficiency up to Carnot cycle efficiency (Lora, 2004).

According to Lora and Nascimento (2004), Wylen *et al*. (2003), Moran and Shapiro,(2002), Çengel and Boles (1998), variants applied to Rankine cycle – steam re-heating, regeneration by extraction steam from turbine to pre-heat boiler feed water, increase in boiler steam pressure, boiler steam overheating or even steam generation above its critical pressure – are resources that maximize its energy efficiency. In this way, thermoelectrical unity without cogeneration and combined cycle could raise energy efficiency from 33% to 42%. This case was reported by Singer, (1991) as the best Combustion Engineering project.

Other way that it increases the cycle efficiency may be the cogeneration. The fuel energy that is supplied to water/steam it is shared foremost in power generation and afterwards in heat source which is furnished to another process. It approaches cycle performance to boiler energy efficiency and can reach more than 80%.

This paper evaluates a real cogeneration power plant that takes part of the Petrochemical Complex in Camaçari city. It looks for a way that increases its energy efficiency through an exergy analysis and that reduces process irreversibility which can not be detected by energy analysis. A power plant simulator based on platform software EES, Equation Engineering Solver, was developed to evaluate the process modifications. The simulations show that it is possible to raise the unity energy efficiency from 83.6% to 87.0%. It corresponds a reduction in fuel oil consumption about 36 thousands tons per year, equivalent to 17 millions reals (Brazilian currency).

2. Principles of Thermodynamics

This item shows concepts in energy and exergy analysis developed in this paper.

2.1 Enthalpy and The First Law

For a steam cycle in a thermoelectrical unity, where potential and kinetic energy variations are negligible, the energy and mass balance in stationary regime, Fig. 1, shows that the fluid enthalpy variation corresponds to energy balance between heat flow supplied to a control volume and the power (work) generated from the same, Eq. (1).

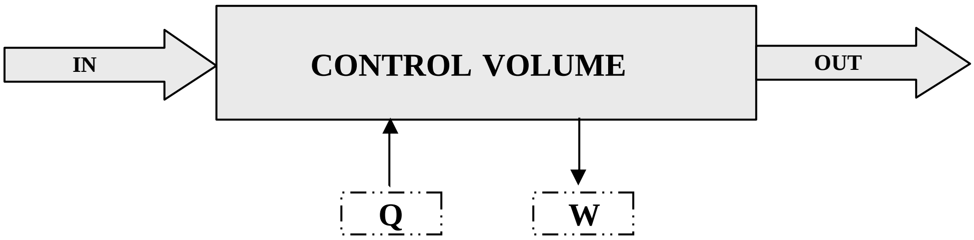

Figure 1 - Balance between de heat and work in a control volume

$$m * (h_{out} - h_{in}) \;=\; Q_{rev} - W \;=\; m * \int_{in}^{out} C_p \, dT \quad (1)$$

The energy efficiency of a equipment or system under this condition is determined by the ratio between useful energy flow and the total energy flow supplied. In a boiler assessment, for example, it can be said that the energy efficiency corresponds to the ratio between energy flow transferred to water/steam, and the energy flow (heat) supplied by the fuel in form of chemical energy, Eq. (2). In no cogeneration power plant, the energy efficiency corresponds to the ratio between power (work) and the fuel energy flow (heat) supplied, Eq. (3).

$$\eta_{energ.} = \frac{m * (h_{out} - h_{in})}{Q_{fuel}} \quad (2)$$

$$\eta_{energ.} = \frac{W}{Q_{fuel}} \quad (3)$$

2.2 Entropy and The Second Law

The second thermodynamic principle is related to energy flow direction and to energy quality. One of the postulates says that the heat flows from the highest to the smallest temperature, and this transference will be none if temperatures are equal.

Clausius inequality, Eq. (4), is a consequence of second thermodynamic principle. It says that in a reversible cyclic process between a hot and a cold sources, the summation of heat flow received from the hot source and heat flow transferred to the cold source, divided by corresponding temperature to each source is zero. In case of irreversibility, this integration is less than zero and the work, which is maximum for the reversible cycle, is smaller.

$$\oint \frac{\delta Q}{T} \leq 0 \quad (4)$$

Entropy, Eq. (5), corresponds to a thermodynamics substance property that allows to identify and quantify irreversibility in state change.

$$m * (s_{out} - s_{in}) = \int_{in}^{out} \frac{\delta Q_{rev}}{T} \quad (5)$$

2.3 Exergy and Irreversibility

In general, exergy corresponds the capacity to do work. Excluding electric, magnetic, nuclear and interfacial effects, a substance exergy can be divided in four components shown in Eq. (6): kinetic, potential, physical and chemical.

$$Ex = Ex_f + Ex_q + Ex_p + Ex_c \quad (6)$$

Among these it will be emphasized thermal exergy corresponding to physical and chemical exergy sum, Eq. (7) that represents the most significant variations in a thermoelectrical unity.

$$Ex_t = Ex_f + Ex_q \quad (7)$$

The potential exergy corresponds to capacity to do work through a field of force, the gravitational case. It will not be approached in this paper once it is negligible in a thermoelectrical steam cycle.

The kinetic exergy corresponds to a maximum capacity to transform a substance momentum in work. The turbine transforms steam physical exergy in kinetic to supply work. It will not be approached because it is an intermediate stage and its final variation is negligible in a thermoelectrical steam cycle.

The chemical exergy in a thermoelectrical unity is related to fuel combustion and corresponds to a maximum substance capacity to do work through thermal interactions and chemical reactions which transform it in its final components under existing environment conditions (temperature and partial pressure). Fuel chemical exergy can be derived in literature tables and represents the maximum heat amount that fuel can supply to the boiler.

Physical exergy corresponds to a maximum substance capacity to do work when it changes its temperature and pressure to environmental, through reversible thermal interactions with the environment. It is expressed by Eq. (8).

$$\varepsilon_f = (h_1 - h_o) - T_o\,(s_1 - s_o) \quad (8)$$

In a stationary process, where a substance enters in a control volume under an initial condition and leave it under a final one, exergy balance is given by Eq. (9) (Torres, 1999, Shukuya and Hammache, 2002).

$$Ex_{in} + Ex^Q = Ex_{out} + W + I \quad (9)$$

This balance shows that substance exergy variation moving through the control volume corresponds to heat received by the system, Eq. (10), plus system power and internal irreversibility.

$$Ex^Q = \Sigma\,[Q_r\,(T_r - T_o) / T_r] \quad (10)$$

According to Kotas (1985), irreversibility in concerned process can be determined by Gouy Stodola expression shown in Eq. (11).

$$I = T_o *[(m_{out} * s_{out} - m_{in} * s_{in}) - \Sigma\,(Q_r / T_r)] \quad (11)$$

This process exergy efficiency can be described by the ratio between system output and input exergy, Eq. (12). This efficiency depicts the thermodynamical perfection in a process, mainly when input exergy is transformed in different exergy components (Shukuya e Hammache, 2002).

$$\eta_{exerg} = \frac{Ex_{saída} + W}{Ex_{entr} + Ex^Q} = 1 - \frac{I}{Ex_{cons}} \quad (12)$$

The exergy or rational efficiency (Kotas, 1985), defined by Eq. (13), is calculated by the ratio between required exergy extracted from the system and the consumed exergy. It needs to know process purpose in order to define it.

$$\Psi = \frac{Ex_{extr}}{Ex_{cons}} \quad (13)$$

3. Petrochemical Industry

Petrochemical industry consist of heat intense consumption unities, providing a great cogeneration potential. It is divided in three groups. The first generation group produces two basic petrochemical products: olefinic and aromatic. The main olenific products, ethylene and propylene, are bound to plastic packing and components production, as a general rule, while butadiene is bound to rubber production. The main aromatic products, benzene, toluene and xylenes, are bound to inks, solvents among other production. It is worth to emphasize paraxylene that is also used in packing (PET bottles) and other plastic components production. The second generation starts from basic petrochemicals to produce polymers, like polyethylene, polypropylene, polyvinyl (PVC), among others. The third generation, also called transformation manufacturer, produces plastic components and final wares, like pipes, packing, films, pieces among others.

In Brazil, the petrochemical industry arose in Capuava Pole, in São Paulo state, in 1971, followed by Camaçari Pole, in Bahia state, in 1978, and Triunfo Pole in Rio Grande do Sul state, in 1982. Thermoplastic consumption has shown since 1990 an average growth rate of 8% per year (ABIQUIM, 2002), bringing about duplication of capacity in these three poles and the establishment of the Rio Polymer Pole, in implementation in Rio de Janeiro.

Camaçari Petrochemical Pole was structured with a Raw Material Station (CMP), and an Utilities Station to supply basic olefinic and aromatic petrochemical products, as well utilities (steam, electrical energy, water, compressed air, etc.) for the second generation companies. The pyrolyse furnaces in CMP were basically specified for naphtha from which about 30% is transformed in streams consumed as fuels for heat generation in petrochemical process and in the thermoelectrical unity.

The Utilities Station holds two operational unities: Thermoelectrical Unity (UTE) and Water Treatment Unity (UTA). It began in productive activities in 1974.

3.1 Thermoelectrical Unity of Petrochemical Complex of Camaçari

Thermal system in UTE operates coupled to CMP, in energy interchange, and holds six steam manometric pressure levels.

- V120 - 120 kgf/cm^2 at 538 ^{o}C;
- V42 - 42 kgf/cm^2 at 385 ^{o}C;
- V15 - 15 kgf/cm^2 at 280 ^{o}C;
- V3.5 - 3.5 kgf/cm^2 at 190 ^{o}C;
- Atmospheric exhaust - 0.0 kgf/cm^2 at 100 ^{o}C (saturated);
- Vacuum exhaust - - 0.85 kgf/cm^2 at 54 ^{o}C (9% humidity).

The figure 2 shows that UTE corresponds to a **regeneration Rankine cycle**, where heating of boiler feed water (BFW) is made by extraction and exhaust steam of backpressure turbines. UTE is also a **combined cycle** characterized by gas turbine and heat recovery steam generator (HRSG) with supplementary fire. Power generation and consumption are identified by "W" and heat source and loss by "Q". The main energy losses are pointed by characteres from (a) to (g).

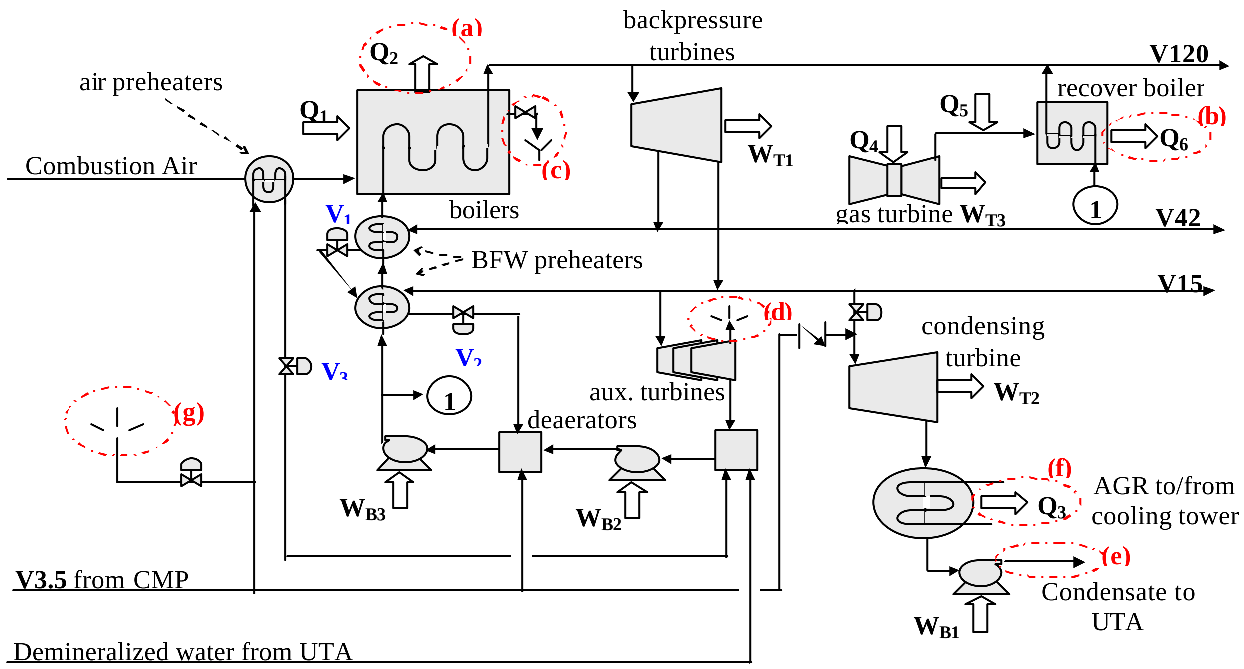

Figure 2 - UTE Thermal Cycle Process Diagram - Unity Energy Loss

The Figure 2 points the energy losses directly send to environment. They are described as folled:
(a) common boilers combustion gaseous;
(b) recovery boilers combustion gaseous;
(c) boilers purge;
(d) auxiliar turbine exhaust that exceeds atmosfere pressure energy balance;
(e) condensate of condensing turbine exhaust;
(f) latent heat of condensing turbine exhaust;
(g) V3.5 steam excess reliefed by control pressure valve;

The highest pressure steam , V120, is produced in five oil/gas boilers and in recovering one, GV-H, coupled to gas turbine, TG-F. This steam feeds the backpressure turbogenerators (extraction to V42 and exhaust to V15) and the Raw Material Station, CMP, for operation of bulky equipments (turbocompressors, etc) in petrochemical plants.

Part of V42 and V15 steam coming from backpressure turbogenerators is supplied to CMP and to companies in Camaçari Petrochemical Complex. Electrical energy generated in these engines arise as by-product, once it is function of steam consumption.

There are two gas turbogenerators : one in UTE, coupled to a recovering boiler with supplementary burning; and other in CMP, coupled to pyrolysis furnaces.

CMP also generates V120 steam through combustion gases residual heat from pyrolysis furnaces. In general balance, CMP is deficient in V120 and V42 steam and plentiful in V15 and V3.5 steam. V3.5 steam is sent to UTE and the V15 steam is distributed to companies in Petrochemical Pole together with V15 steam produced in UTE.

Under normal conditions, V3.5 steam produced in CMP exceeds in over 80 t/h the heating need in UTE. To absorb this surplus, the condensing turbogenerator, TG-E, originally specified to inlet V15 steam, was adapted to double inlet steam and reaches a maximum V3.5 steam consumption of 81 t/h to generate 8.5 MW. For V15 steam, this engine has a capacity to generate 39 MW, under a consumption of 240 t/h.

UTE electrical system operates coupled to the concessionary CHESF, Companhia Hidrelétrica do São Francisco, under a horossazonal contract. In peak hour (HP) from 18:00 to 21:00 , TG-E (condensing turbine) is transferred to V15 steam to increase its generation capacity and to absorb electrical energy demand in horossazonal contract. Out of peak hour (FP) this return to operate with V3.5 steam.

3.2 UTE Simulator

A UTE simulator was developed to evaluate the thermoelectric process. It employs platform software EES, Engineering Equation Solver, which provides a structured language and has some thermodynamic properties and mathematical functions to generate data in case study. It is a static simulator in which the process modifications to optimize UTE was introduced. They can be individually disabled, allowing simulation of current condition and a system assessment step by step. Operational equipments curves were parameterized by data surveyed in field tests.

3.3 UTE Energy Evaluation

Data obtained from field survey and from unity simulations show that boilers produce on the average 1000 t/h V120 steam, which about 70% are exported (30% as V120, 35% as V42, 10% as V15). On the other hand, about 20% of steam returns to UTE as V3.5. Thus, 50% of steam mass produced in boilers is consumed in UTE at many pressure levels. About 10% is sent to condenser turbine which exhaust is condensed by water from cooling tower.

In order to realize difficulty grade to recover loss heat in UTE the Fig. 3 shows symbolicly the simulation results. For exemple, lets analyse the loss corresponding to condensate heat formed at 54 ^{o}C from condensing turbine exhaust, which is sent to UTA and returns to UTE at environment temperature. In order to recover this energy loss, it could simply be not sent to UTA, and be directly pumped to UTE. As UTE steam cycle operates saturated of thermal energy on deaerator pressure level, this heat recovery leads to reduce the V3.5 steam consumption for boiler feed water heating in UTE. As consequence 3 t/h of V3.5 steam are reliefed to environment and the recovery is null.

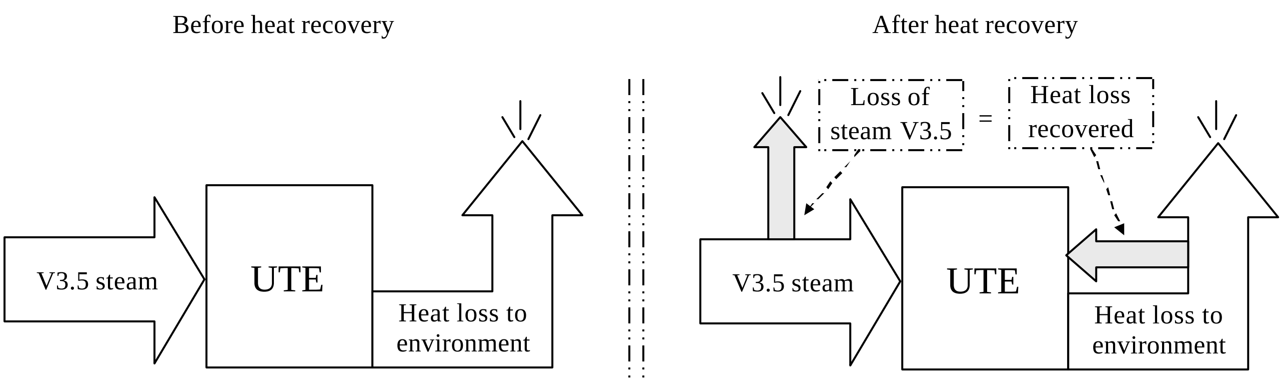

Figure. 3 - V3.5 Steam Loss by Heat Loss Recovery

It is concluded that UTE operates in thermal saturation for temperatures below V3.5 steam. So, any energy recovery for heating cold streams that is heated by low pressure steam, leads to relief V3.5 steam to environment, see Fig. 2. This thermal barrier appeares in all recovery simulations done.

3.4 UTE Exergy Evaluation

UTE thermal cycle, Fig. 2, shows V_1, V_2 and V_3 level control valves, where is found the main recoverable exergy loss in steam cycle, corresponding to saturated condensate expansion to lower pressure. Considering this expansion as adiabatic (there is no heat exchange) and isenthalpic (neither do work, nor generate kinetic and potential energy), it can be seen these exergy loss in Table 1.

Table 1 - Exergy loss by saturated condensate expansion

	P_1	P_2	$h_1 = h_2$	s_1	s_2	e_1	e_2	Exergy loss
	bar	bar	kJ/kg	kJ/kg°C	kJ/kg°C	kJ/kg	kJ/kg	%
Condensate V42	43.0	16.0	1109	2.836	2.871	268	258	3.8
Condensate V15	16.0	4.5	858	2.343	2.379	165	154	6.5
Condensate V3.5	4.5	1.0	623	1.820	1.854	85	75	12.0

To recover those exergy losses, condensate cold be pumped to avoid their expansion in valves. As a consequence, it is not generated low pressure steam, as shown in Table 2. This lessens thermal saturation in UTE, allowing to recover part of energy loss.

Table 2 - Steam generation by saturated condensate expansion

	P_1	P_2	$h_1 = h_2$	h_{1L}	h_{1V}	h_{2L}	h_{2V}	Steam generation
	bar	bar	kJ/kg	kJ/kg	kJ/kg	kJ/kg	kJ/kg	%
Condensate V42	43.0	16.0	1109	1109	2799	858	2793	12.9
Condensate V15	16.0	4.5	858	858	2793	623	2743	11.1
Condensate V3.5	4.5	1.0	623	623	2743	418	2675	9.1

UTE simulator shows that condensate formed on feed water boiler preheaters that uses V15 steam is about 20% of V120 steam generation. Boilers usually generate about 1,000 t/h of V120 steam. So, it corresponds that condensate formed in V15 water preheater is about 200 t/h. Table 2 show us that this condensate expansion generates 11.1% of saturated steam to deaerators, 22.2 t/h, and inhibits consumption of V3.5 steam around 21.6 t/h. Once the V3.5 steam supplyied by petrochemical plants exceeds the UTE consumption, this condensate pumping purposed in Fig.4.will provide a remarkable gain, because will be necessary more V3.5 steam to deaerators.

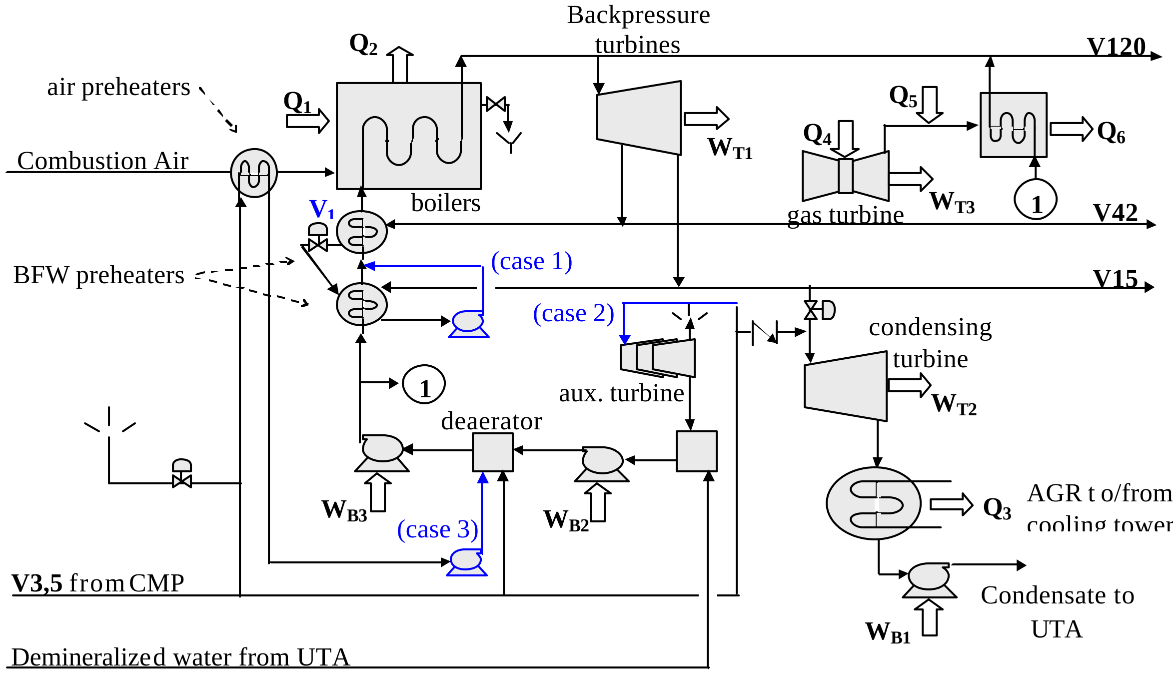

Figure 4 - UTE Thermal Cycle - Exergy Recovery

UTE exergy analysis also shows us that V3.5 steam used to heat water in deaerators has a fair amount of exergy, and can be used as power fluid in turbines of auxiliary equipments, Fig. 4. This would help unity in two aspects : V3.5 steam exergy level would reduce before its heat application and would avoid thermal load coming from V15 steam exhaust of auxiliary turbines which current steam consumption is around 41 t/h. Only part of these turbines could be replaced to inlet V3.5 steam, once demineralized water make up of UTE is not enough to condense them steam exhaust. So, an arrangement of new turbines could be specified to optimize process UTE. Some turbines would operate with exhaust to vacuum that might be condensed by demineralized water supplied by UTA. Others would operate with exhaust to atmospheric pressure that might be condensed by condensate below 60 ^{o}C produced on UTE.

4. Results and Discussions

Several process modifications were figured out to reduce recoverable energy losses presented in Fig. 2. They were applied on EES simulater step by step and showed null benefits as results. In all cases, energy recovery let to relief V3.5 steam in energy equivalence due to UTE deaerators operate in thermal saturation.

The solutions turn up based on the assessment of exergy loss that restricts UTE capacity to recover its energy loss. The three modifications considered important were shown in Fig. 4. They take UTE off a thermal saturation state, and give space for supplementary energy recoveries. Creation of four water temperatures levels was the fundamental feature in this optimization, arising a progressive boiler feed water heating.

In simulations, power consumption in Petrochemical Complex was kept in 240 MW unless variation consumption of UTE. In Table 3 it is shown that purposed modifications leads UTE to reduce its own generation, kept by an increase of 9.7 MW in electrical energy imported from CHESF.

Table 3 - Simulations Results of Cases

Case	Operational Description (see Fig. 4)	Recoverable Loss		Electrical Demand		Operational Cost	
		total	variation	UTE	CHESF	total	variation
		GJ / h	GJ / h	MW	MW	k R$ / ano	k R$ / ano
	Actual	208.2	-	125.3	113.7	473,281	-
01	Boiler water preheater condensate pump	173.8	34.6	120.3	116.1	466,869	6,412
02	V3.5 steam turbines to auxiliary equip.	110.3	63.5	111.0	126.0	456,293	10,576
03	Air preheater condensate pump	110.3	0	111.0	126.0	456,293	-
total		**-**	**97.1**	**-**	**-**	**-**	**16,988**

Results from employed simulations shows that purposed modifications generated an increase in UTE energy and exergy efficiency in 3.4% and 3.8%, respectively, and a reduction of fuel oil OCA1 about **36,000 tons per year**, as well a financial gain estimated in **R$ 17 millions**, considering taxes in october/2004 for OCA1 oil and for horossazonal electrical energy.

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