Modern Environmental Science and Engineering (ISSN 2333-2581)
August 2016, Volume 2, No. 8, pp. 507-513
Doi: 10.15341/mese(2333-2581)/08.02.2016/001
Academic Star Publishing Company, 2016
www.academicstar.us

Thermoeconomic Approach to the Diagnosis of A DHW Microcogeneration Plant

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Abstract: Application of Thermoeconomic in the diagnosis of power plants allows the localization and quantification of an abnormal operation, which can cause significant increase in consumption or even unacceptable shutdowns. Accordingly, the early detection of these anomalies may prevent possible failures and make savings in both maintenance and energy consumption.

Thermoeconomics has not been widely used in the field of thermal installations in buildings, even less its diagnosis application. This communication contains the results of the implementation of Thermoeconomics diagnosis in a micro-cogeneration facility for DHW, consisting of a microcogeneration engine, a condensing boiler and an accumulation tank.

To assess the malfunctions and dysfunctions in a facility in which demand varies over time, virtual testing analysis path has been chosen. This is done through a dynamic simulation software of buildings (Trnsys). For this purpose, a common reference state and various operating conditions have been defined. These operation modes include different types of disturbances; first anomalies are introduced one by one and then several of them are analyzed simultaneously.

Once the productive structure of the system has been determined in its FPR representation, a thermoeconomic study for a specific situation has been performed. This analysis enables the obtainment, among other results, of the exergetic unit cost of the fuel, waste and product of each subgroup. Regarding the reference installation as the comparative base, the endogenous and exogenous effects a malfunction creates along the entire energy chain have been investigated. For the anomaly case, an analysis of the results has been elaborated and conclusions have been obtained.

Key words: Thermoeconomic diagnosis, FPR representation, malfunction and dysfunction

1. Introduction

The aim of diagnosis is to analyse anomalies causing reduction of system efficiency in order to provide specific recommendations to change operating strategies, maintenance actions and component replacements. The cost effect generated by an anomaly is analysed and the economic impact evaluated. In such way, the decision to replace or repair the faulty equipment can be taken.

Thermoeconomic diagnosis has its foundation on exergy analysis, as energy is not the right magnitude to account for losses in an energy system but exergy.

In this paper the bases and the methodology for diagnosis are briefly explained. The theory has been applied to a microgeneration and condensing boiler facility for DHW production The rules of the productive structure in the FPR (Fuel–Product–Residue) representation is defined the exergetic unit cost of fuels, products and residues for each component are hereafter obtained in the reference condition and, finally, the diagnosis is applied to the free operating condition to a study case.

2. Productive Structure: FPR Representation

For an appropriate Thermoeconomic analysis, besides the physical structure of the system a

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productive structure should be defined. The productive structure is the means to understand flows costs making.

For this, purpose is the key concept. The incoming and outgoing exergy flows of a given component can be classified in fuel, product or residue. Fuel refers to the resources that a component requires to carry out the production; product corresponds to the flows that are the production objective and residues are related to the flows extracted outside, which have some exergy load but no functional value as, for example, exhaust gases [1].

Therefore, each component will contain a fuel and an output product that may be further divided into useful final product (B_{io}), or fuel to other component ($\sum_{j=1}^{n} B_{ij}$) or residue ($\sum_{j=1}^{n} R_{ij}$). Thus, a generic i outlet is defined as:

$$P_i = B_{i0} + \sum_{j=1}^{n} B_{ij} + \sum_{j=1}^{n} R_{ij} \qquad (1)$$

The cost treatment follows another structure. In this case, the cost of the residue, and the auxiliary costs for its extinction, must be attributed to the production component that has generated it.

Symbolic analysis is based on the rules of cost formation with residues [2].

3. Case Study

The facility under study has a 5.5 kW electric power and 12.5 kW thermal power Dachs model microcogeneration engine and a 28kW thermal power BIOS/28F model condensing boiler.

The generating circuit converges in a hydraulic compensator, and in turn, the compensator transfers heat to the distribution circuit until it reaches the heat exchanger. The heat exchanger secondary circuit goes to the storage tank in order to accumulate the thermal energy to be extracted by the DHW demand profile. DHW demand is defined by an open circuit which includes both cold water and DHW flow that enters and goes out from the tank. See Fig. 1, where the numbering of the units and the exergy of the flows appear.

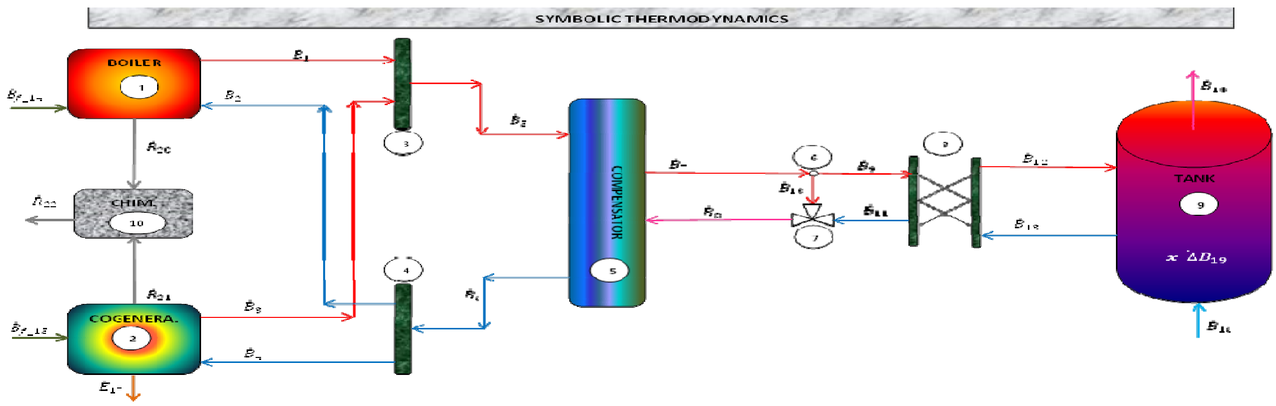

Fig. 1 Installation diagram: Respective components and fluxes used for the analysis.

The DHW profile is obtained based on statistical data, following the document which appeared in the Annex model in the part of the Acceptance conditions of Alternative Computer Programs published by IDAE [3], see Fig. 2.

To begin with the simulation, all components involved in the facility must be modelled in Trnsys. In this way, the simulated system would represent as closely as possible the nominal behaviour of the plant. This state is known as reference condition.

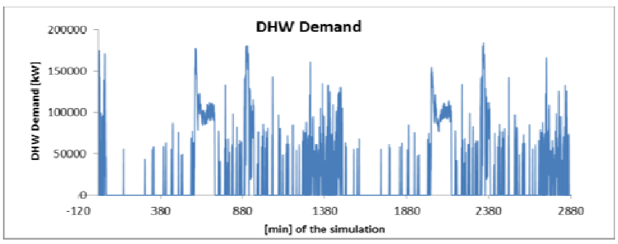

Fig. 2 DHW Profile [kW] during two days of simulation [2880 min].

Using the reference models of each of the units the plant has been simulated for a two-day DHW demand through Trnsys v 17 software [4].

The control of the plant is such that the units are activated and deactivated depending mainly on the tank temperature (T_{19}). If the tank temperature is below 62°C, the cogeneration unit is activated until the temperature reaches 67°C; if the tank temperature is below 58°C, the boiler is activated simultaneously until the temperature reaches 60°C. When the temperature difference between the heat exchanger primary and the tank temperature is higher than 5°C, DHW production will exist; when this increase is less than 2°C, the three-way valve acts so that the heat flow bypasses back through the compensator.

Following the necessary guidelines [4, 5], the matrices <KP> and <KR> are obtained as a result. These matrixes contain $\kappa_{ij}, \vartheta_{ij}$ exergetic unit consumption respectively where

κ_{ij} provides the amount of resources required from *i* for a creation of a unit product of *j*; and ϑ_{ij} provides the amount of residues generated per unit product of *j*.

4. Unit Exergetic Cost Analysis

The objective of this development is to get the values of the unit exergetic costs related to fuels, products and residuals. We must bear in mind that in the exergetic cost of a product not only the cost caused by the irreversibility of the equipment is involved,P_i^{e*}, but also the cost due to the creation and removal of residues,P_i^{r*}. Then, the cost of a generic product, and its corresponding unit exergetic cost, k_P^* are divided into two components [6]:

$$P_i^* = P_i^{e*} + P_i^{r*}, \qquad \mathbf{k_P}^* = \mathbf{k_P}^{e*} + \mathbf{k_P}^{r*} \qquad (2)$$

Once the unit cost of the product is obtained, the exergetic unit cost of fuel, can be calculated,k_F^*.

The following Table 2 shows the results of the exergetic unit costs of the plant components for the reference operation.

It can be checked how as the heat transmission chain moves from the generating devices, 1 and 2, through distribution until the last component 9, the unit exergetic costs are increasing. This is due to the definition of cost, which implies the amount of exergy needed to create a product and then the exergy cost contains both the exergy of the product, and all the irreversibilities generated in the process required to obtain it.

That is the reason why $k_{P1}^* > k_{P2}^*$, as there is proportionately greater exergy destruction in the boiler than in the cogeneration.

5. Diagnosis Theory

For multiple reasons, a system will be operating in a mode different to the reference one, due to external causes or components internal deterioration. The diagnosis is used to locate and quantify these misguided behaviours and in order to do that, the plant in real conditions has to be compared with that same plant in design conditions, the *reference*.

Table 1 Corresponds to the accumulated exergy of the flows at the end of the two-day period (kW).

[kJ] B1	[kJ] B2	[kJ] B3	[kJ] B4	[kJ] B5	
94652	35253	187744	91869	282230	
[kJ] B6	[kJ] B7	[kJ] B8	[kJ] B9	[kJ] B10	
127155	459261	319720	394247	65014	
[kJ] B12	[kJ] B13	[kJ] B14	[kJ] B15	[kJ] B16	
308091	191944	509069	1082536	0	
[kJ] B17	[kJ] B18	[kJ] ΔB19	[kJ] R20	[kJ] R21	[kJ] R22
281043	76222	2752	3564	5752	9316

Table 2 Unit exergetic cost of fuels, products and residuals.

	REFERENCE $\left[\frac{kW_{ex} required}{kW_{ex_i} obtained}\right]$			
	k^*_F [-]	k^*_P [-]	$k^{*,e}_P$ [-]	$k^{*,r}_P$ [-]
1.Boiler	1	8.56	8.09	0.48
2.Cogeneration	1	2.87	2.83	0.04
3.Imp.Collector	5.05	5.06	4.85	0.21
4.Return Collec.	5.06	5.06	4.85	0.21
5.Compensator	5.06	5.62	5.39	0.23
6.Node	5.62	5.62	5.39	0.23
7.Bypas	5.62	5.63	5.39	0.23
8.Heat Exchang	5.62	6.75	6.47	0.28
9.Tank	6.62	10.32	9.90	0.43
10.Chimney	5.05	5.05	4.84	0.21

The main parameter which quantifies the anomalies is the *fuel impact* which measures the increase in total exergy consumption the real plant has with respect to the reference. Provided that the total production is the same, a positive variation in the fuel impact will suppose a decrease in the overall plant efficiency.

The irreversibility caused by the increased of the unit exergy consumption in a component is known as *malfunction* and the effect it induces in the other components is known as *dysfunction*. The malfunction only affects the behaviour of the component device itself, it is an endogenous irreversibility, whereas the dysfunction is an exogenous irreversibility induced by other components malfunctions [7].

Incorporating the effect of residues is a rather difficult task. When residual flows are considered within the analysis two types of outlets exist in the system: those that are final products and those which correspond to residual exits.

$$\Delta \mathbf{P_S} = \Delta \mathbf{P_S}^{\mathbf{e}} + \Delta \mathbf{P_S}^{\mathbf{r}} \tag{3}$$

The theory of diagnosis mentioned above, enables us to quantify the impact on fuel when the total output remains constant. However, when a malfunction takes place, this can increase the residual outflows. Because of this reason, the useful external outputs should be distinguished from the residual outputs, as these will be analysed as internal effects that will be added inside the term of dysfunction [5, 8].

6. Control System Intervention Effect

The control system is generally based on set-points referred to variables of specific components. An anomaly can cause fluctuations in these variables that provoke the intervention of the control system, and this fact can alter the nominal operating mode

To compare a real operation mode with its reference, this control effect should be filtered so that both cases have an equivalent behaviour. The goal is to create an artificial working condition, known as *free condition*, which is characterized by the same regulation as the reference condition, and should be virtually determined [9]. This working condition is clearly unacceptable, since the plant does not follow the programmed operating instructions. However, it allows making a more accurate diagnosis.

The procedure to define this free condition is made through an imposed control simulation. Once the reference installation and its control strategy are simulated the following results are obtained: first, required thermodynamic values are tabulated, and afterwards, a list of control system intervention is obtained. So, the precise moments where engines are activated or are disconnected is printed out. This phenomenon is powered by the start-up and shutdown of the appropriate circuit pump.

The faulty installation simulation is based on the timeline that pumps must follow. For this, instead of incorporating the real control strategy, the new facility will include an imposed control, so each pump is forced to follow the same frequency as that in the reference installation.

The following Fig. 3 contains the Trnsys failure installation scheme together with a brief explanation of the free condition methodology.

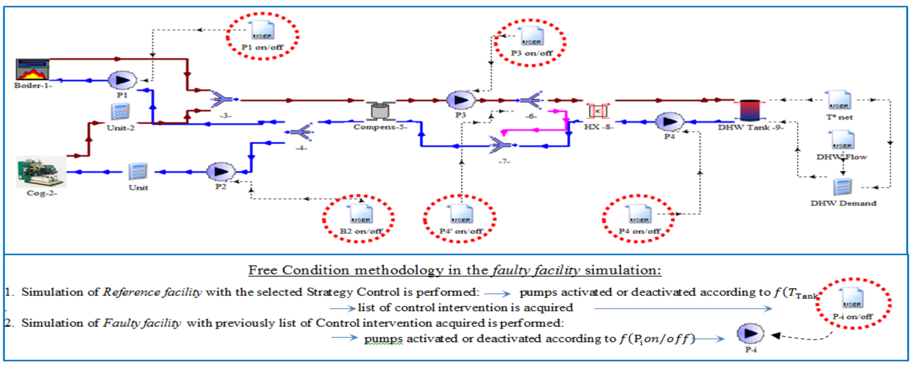

Fig. 3 Free condition simulation scheme.

7. Total Production Effect

Another important aspect to be considered for diagnosis is the increase of the final product, as the theory of diagnosis is fulfilled as long as the total output remains the same.

Considering that the free condition of the installation with anomalies follows the same behaviour as the reference, variations in the output products will occur. One might think that, given the existence of an anomaly, the DHW exergy output will decrease compared with that in the reference, since the storage tank temperature goes down. And by contrast, due to an increment of the natural gas consumption encouraged by this anomaly, the electrical generation will be greater than that in the reference.

The production variation which influences more the diagnosis is DHW demand. To filter this effect, each exergy flow will be multiplied by a α factor that provokes $\Delta P_{S,ACS} = 0$, defined as follows:

$$\alpha = \frac{Q_c(\bar{x}_{ref})}{Q_c(\bar{x}_{fault})} \cong \frac{P_{s_{ref}}}{P_{s_{fault}}} = \frac{(B_{18}-B_{16})_{ref}}{(B_{18}-B_{16})_{fault}} \tag{4}$$

8. Diagnosis Case Study

The case to be examined contains a deliberately fault associated with a characteristic component in the chain of energy production, in this case the compensator.

The α value achieved with the incorporation of the anomaly is $\alpha = 1.15$.

This defect is represented by the enhancement of the component loss coefficient, thus achieving a decrease in the component unit exergy consumption of 11%.

9. Diagnosis Implementation

The next step is to make a diagnosis of the faulty installation with respect to the reference. The summary of the results is shown in Table 3. The box at the bottom displays the representative formulas for fuel impact (ΔF_T), for the calculation of malfunctions (MF) and its costs (MF*) and for the determination of the useful and residual production increment cost ($\Delta P_{s,i}{}^{*,e}$, $\Delta P_{s,i}{}^{*,r}$).

The F_{ref} and F_{fault} values correspond to the net total consumption the plant has in the reference and the faulty condition respectively. The difference between these two values coincides with the value of the fuel impact.

Much attention should be given to the following (five) main points:

(1) MF vector performance. Malfunction affects specially the units located upstream of the anomaly. In other words, the components which are most affected are above the compensator. These types of malfunctions are identified as *induced malfunctions*, as those modules do not incorporate the anomaly itself.

The emergence of this value is due to the new thermodynamic values in the situation with anomaly. The engines have the same energy yield compared to the reference facility but, nevertheless, as the exergy depends logarithmically on the instantaneous environmental conditions (the dead state), the exergy yields are different.

Table 3 Diagnosis result in the study case.

FAULTY FACILITY $[kJ_{ex}]$				
	MF	MF^*	$\Delta P_s^{*,r}$	$\Delta P_e^{*,e}$
1	20834	20834	0	0
2	18645	18645	0	136719
3	0	6564	0	0
4	0	0	0	0
5	19753	99527	0	0
6	0	0	0	0
7	0	0	0	0
8	1410	8922	0	0
9	357	-20324	0	0
10	0	394	5080	0
			F_{ref}	1594357
	ΔF_T	276361	F_{fault}	1870718

$$\Delta F_T = F_T - F_{T_0} \quad [kJ_{ex}]$$

$$\Delta F_T = \sum_{i=1}^{n} \left(MF_i^* + \Delta P_{S_i}{}^{*,e} + \Delta P_{S_i}{}^{*,r} \right) \quad [kJ_{ex}]$$

$$\checkmark\, MF = \Delta K_D \cdot P^0 \quad [kJ_{ex}]$$

$$\checkmark\, MF^* = \left(\Delta k_e{}^t + k_P^{*,eT} \cdot \langle \Delta KP \rangle \right) \cdot P^0 \quad [kJ_{ex}]$$

$$\checkmark\, \Delta P_{s,i}^{*,r} = k_{P,i}^{*,e} \cdot \Delta P_{s,i}^{*,r} \quad [kJ_{ex}]$$

$$\checkmark\, \Delta P_{s,i}^{*,e} = k_{P,i}^{*,e} \cdot \Delta P_{s,i}^{*,e} \quad [kJ_{ex}]$$

(2) Tank malfunction cost is negative. It can be said that, from a global point of view, there is an improvement in the component where this occurs. While locally, the tank has a positive malfunction, its cost decreases due to the $\Delta k_{8,9} < 0$ term.

This parameter refers to the extra amount of resources the tank requires from the heat exchanger to create a unit DHW production respect to the reference situation.

As $\Delta k_{8,9} < \Delta k_{0,9}$ is so pronounced, the cost of malfunction is negative.

(3) $\Delta P_{s,i}^{*,r}$ existence. This point highlights the Eq. (3) where both residual and useful outputs appear. Then an increase in consumption of combustion engines causes a proportional increase in residual gases.

(4) $\Delta P_{s,i}^{*,e}$ existence. This fact justifies paragraph 7 where the insertion of the α parameter is warranted. As there are two useful outputs, only one of those effects can be neutralized.

The increase in electricity production does not directly affect any term of cost, except for the cogeneration malfunction cost, because it has no more element located upstream.

(5) The terms $\Delta P_{s,i}^{*,r}$ and $\Delta P_{s,i}^{*,e}$ are added to the subsequent calculation of the fuel impact.

10. Representative Index

Thermoeconomic diagnosis analyzes the effect on cost of an anomaly and evaluates the economic impact it generates. Hence the term of *malfunction cost*, MF*, is key to the analysis.

A ψ index has been calculated for every unit, to assess the effect of the malfunction cost of each component ($\psi_{\square MF}$), the effect of the growth of residue cost (ψ_{res}) and the effect of the rise in electric generation cost concerning the whole fuel impact ($\psi_{\Delta elec}$). See Table 4.

If the attention is paid to the first column ($\psi_{\square MF}$): the $\psi_{\square MF}$, index contains the highest value just in the component including the anomaly: the compensator.

Table 4 Diagnosis index.

FAULTY FACILITY	$\psi_{\exists MF}$	$\psi_{\Delta res}$	$\psi_{\Delta elec}$
1.Boiler	8%	-	-
2.Cogeneration	7%	-	49%
3.Imp.Collector	2%	-	-
4.Return Collec.	-	-	-
5.Compensator	37%	-	-
6.Node	-	-	-
7.Bypas	-	-	-
8.Heat Exchang	3%	-	-
9.Tank	-7%	-	-
10.Chimney	-	1%	-

✓ $\psi_{\exists MF} = \frac{MF^*}{\Delta F_T} [\%]$ ✓ $\psi_{\Delta res} = \frac{\Delta P_s^{*,r}}{\Delta F_T} [\%]$

✓ $\psi_{\Delta elec} = \frac{\Delta P_s^{*,e}}{\Delta F_T} \cdot 100 \ [\%]$

Because of the explanation given in point 1 of induced malfunctions, the other engines participating in the facility have also a $\psi_{\square MF}$, index different to zero but negligible compared to the compensators one.

Although the aim of diagnosis is to show which component influences more in the global fuel impact, the extra fuel consumption assumed by cogeneration that creates more electric output cannot be ignored: almost the half of the fuel impact is dedicated to increase the electricity production.

11. Conclusions

The diagnosis is used with the purpose of detecting an anomaly located in any component that generates additional fuel consumption, and thereby additional costs.

In the case study, an anomaly is imposed in the compensator. This method enabled to quantify the percentage of the extra fuel consumption due to the malfunction itself (37%) and the percentage induced in different components (8% in boiler, 7% in Cogeneration, 2% in collector, 3% in HX and -7% in the tank).

The percentage on the increase of fuel consumption due to overproduction of electricity (49%) associated with the malfunction is also observed.

Once the diagnosis results are obtained, further economic study is needed in order to determine whether the extra costs generated by malfunctions involve higher cost of maintenance and operation than the replacement of the component itself.

Acknowledgment

The author, A Picallo, acknowledges the support provided to her by the Ministry of Education of the Spanish Government through a scholarship granted to complete her PhD degree. The authors also acknowledge the support provided by the Laboratory for the Quality Control in Buildings of the Basque Government.

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