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On Thermoeconomic Diagnosis of a Fouled Direct Expansion Coil: Effects of Induced Malfunctions on Quantitative Performance of the Diagnostic Technique

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ABSTRACT

Thermoeconomic diagnosis represents a promising technique for the detection of common faults in refrigeration systems, which are responsible of degradation in their energetic performance. Recently, the authors have carried out a sensitivity analysis of the performance of this method to the thermodynamic conditions of inlet air and to the geometry of the direct expansion coil, in case of degradation induced by evaporator fouling. The analysis showed that the method is able to detect this fault, but sometimes its quantitative assessments are not satisfactory. In order to understand more in-depth the origin of such results and identify margins for refinement of the technique, this paper is aimed at evaluating at what extent changes in the exergetic performance of faults-free components may negatively influence the model capability to detect the fouled evaporator and quantify the consequent additional exergy consumption. The results suggest that the method is particularly sensitive to the cost of "induced malfunctions" on the compressor and the condenser, especially when low coil depth or high relative humidity of inlet air are considered.

KEYWORDS

Thermoeconomic diagnosis, Evaporator fouling, Direct expansion coil, Exergy, Malfunction cost, Fuel impact, Induced malfunction, Intrinsic malfunction.

INTRODUCTION

In last few decades, thermoeconomic diagnosis has been shown to represent a promising instrument for the detection of malfunctions occurring in energy systems. Most of the works available in literature have been focused on diagnosis in power plants, with a focus on coal fired plants in [1] and [2], cogeneration plants in [3] and combined cycles in [4]; for such applications, the method has been proven to furnish promising results. Only in the last few years the idea to extend its application to refrigeration system has been emerging as a research trend. As shown in several studies [5], large energy

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consumption is related with space cooling in buildings, where the poor maintenance of air conditioning plants frequently induces relevant degradation of their performance [6] and a consequent increase in their energy consumption. Having a reliable tool which informs on any deviation occurring in plant performance and identifies its causes would be very helpful to schedule preventive maintenance program and thus achieve energy savings.

Exergy and cost represent the key concepts of thermoeconomic diagnosis; exergy, is a measure of thermodynamic "quality" of energy flows [7], and it allows to evaluate the rationale of energy conversion process by assessing the exergy destruction occurring at each stage [8]. As regards exergy application in built environment, useful methods were developed in [9] in order to estimate exergy/energy consumption; furthermore, practical design-support instruments have been defined in COST Action C24 in order to facilitate the application of the exergy concept in this sector [10].

As regards HVAC systems, in [11] the authors showed that these components are characterized by very poor exergetic efficiency, since they are supplied with high quality energy, fossil fuel or electricity, in order to produce thermal energy flows at low temperature (i.e. low exergy content) as required by heating and cooling processes. As it was outlined in Annex 37 [12], and in the following developments achieved in Annex 49 [13], exergy analysis suggests that the most rational way to use energy in HVAC systems consists of supplying them with low quality energy sources as process waste heat or renewable sources (solar thermal heat, geothermal heat), thus leading to economic and environmental benefits from substitution of non-renewable energy sources to renewable ones [14]. Some examples of buildings which are already equipped with such systems can be found in [15]. Other promising solutions are presented in [16], where different typologies of solar trigeneration systems for HVAC are proposed, and in [17] where economic assessment for a trigeneration plant for HVAC systems in Italy are presented.

The above analyses were carried out considering systems which operate in design condition: when faults occur in a component [these faults being associated with poor performance of the unit, either in terms of decreased capacity or Coefficient of Performance (COP)], its exergy consumption increases due to higher generation of irreversibility, thus reducing the exergy efficiency. In order to maintain its production rate constant (as usually imposed by the control system), the plant consumes more "fuel" (to be intended as "input resource", either being represented by fossil combustibles, electricity, etc.); thermoeconomic diagnosis aims at disaggregating this additional fuel consumption (caused by the presence of faults) into contributions associated with the malfunctions occurring in each specific component, based on rigorous instruments such as cost balances and appropriate cost allocation rules [18]. As a first step, it is necessary to define for each component the exergy of its consumed resources [i.e. its "fuels" (F)] and its useful outputs [i.e. its "products" (P)]; then, based on an analysis of the interactions between plant components and with the external environment, a "productive structure" of the examined system is developed. Depending on the expertise of the analyst and on the disaggregation level adopted for the thermoeconomic representation of the plant, it is clear that different productive structures of a same energy system can be defined, which could lead to more or less accurate results even when diagnosing a unique faulty operating condition.

In a recent paper [19] the classical thermoeconomic approaches have been tested with a set of multiple faults scenarios in air-cooled direct expansion air conditioning unit: the results indicated that conventional thermoeconomic diagnosis is not a reliable technique when applied to refrigeration systems because: it cannot efficiently deal with "system level" faults, i.e., with faults not associated with any specific component like refrigerant under- or over-charge, and the usually adopted "productive" model for the expansion valve erroneously leads to identify this component as "faulty" even when its operation has no anomalies. In order to overcome these limits, an innovative thermoeconomic model has been proposed in [20], which was proven to be sufficiently reliable when the effects of "system level" faults like refrigerant undercharge are filtered.

More recently the authors of the present paper have investigated the robustness of this innovative diagnostic technique for the detection of evaporator fouling in direct-expansion air-conditioning units [21]. In particular, the sensitivity of the performance of the method to a number of different variables was assessed, focusing the attention on the coil geometry and on the thermodynamic conditions of the inlet air at the evaporator coil, which evidently influence the intensity of its cooling and dehumidification process.

From a qualitative point of view, the method was very efficient in detecting the evaporator as the faulty component in almost all the examined cases; conversely, from a quantitative point of view, the technique was efficient in quantifying the additional energy consumption induced by evaporator fouling only when the inlet air had a low absolute humidity (i.e. not particularly high values of temperature and relative humidity) and when coils with higher depth were concerned (i.e. coil with a high number of rows and a consequently high dehumidifying capacity).

The limited capability of this method to localize anomalies within a system and to quantify their effects mainly derives from the fact that under faulty condition not only the exergetic performance of the malfunctioning component changes, but also variations in the performance of fault-free components occur due to change in their operating conditions (and/or in the thermodynamic states of the working fluids). As a consequence, there is a strong risk that a diagnostic technique erroneously identifies possible malfunctions located in "fault-free" components. If the diagnosis technique is not able to filter all these "induced effects", i.e. effects generated by the faulty components on the other ones, misleading results might be achieved. In the scientific literature several works have already focused on this topic; with reference to a gas turbine-based cogeneration plant, for instance, in [22] a method was proposed to filter the malfunctions induced by the control system and by the specific behaviour of each plant component.

In the present paper, starting from the diagnostic results obtained in [21], the authors focus their attention on those cases where the method did not properly quantify the effects provoked (in terms of additional electricity consumption) by evaporator fouling and, based on in-depth analyses, attempt to identify the causes of these erroneous/misleading results. In particular, the present work attempts to clarify at which extent the induced malfunctions influence the quantitative performance of this diagnosis technique, and under what conditions the thermoeconomic model adopted may be able to reduce their impact.

Although the scope of the study might appear of interest only for expert thermoeconomic analysts, it must be observed that:

- Developing efficient diagnostic techniques for refrigeration and air conditioning systems has been emerging as a challenging but very promising research line, as proven by the dozens of scientific articles published on this topic in the last few years;
- The scope for such significant research efforts is absolutely justified by the high energy saving potential related with the adoption of rational maintenance schedules in air conditioning systems, which have been proven to be often poorly maintained both in the commercial and in the residential sectors.

ON THE METHOD OF THERMOECONOMIC DIAGNOSIS

In this section a brief overview on thermoeconomic diagnosis is given, in order to clarify some main features and criticisms of this technique; a detailed description of the fundamentals of this method is out of the scopes of this paper. The reader may refer to the referenced works [3] and [4] for a comprehensive explanation of this technique.

The first step in any thermoeconomic analysis consists of the definition of the exergy of the "Fuel" F_i consumed, as an input, by each generic i-th plant component, and of its useful output P_i (i.e., its "Product"); both these flows must be evaluated in exergy units. Applying the exergy balance to the generic i-th component, $F_i = P_i + I_i$, the irreversibility I_i generated during its operation may be easily obtained.

Once the fuel(s) and the product(s) are defined for each component, it must be clarified how each component interacts with other components within the system and with the external environment, in terms of exergy flows exchange. The representation (alternative to the physical plant scheme) where all components are interconnected on the basis of their "functional" relation (that means, each i-th component is connected only with the components that supply its fuels or consume its products) is named "productive structure".

In some cases the aforementioned Fuels/Products representation is not sufficient to reflect the operation of the components, since it is not possible to identify a "productive scope" of the components (i.e. a useful product) to be measured in exergy terms. As an example, when we consider the condenser of an air conditioning unit, it evidently dissipates the thermal exergy of the refrigerant to the external cooling air, without producing any useful exergy flow. In order to model such components, the theory of Thermoeconomics defines such exergy flows (dissipated with no apparent scope) as "residues", suggesting to consider them as a sort of "product" of the component where they are physically dissipated, and then to allocate them as additional inputs to the different plant components which had contributed to their formation process [23].

For a generic i-th component an overall unit exergy consumption k_i and an overall unit residue consumption r_i, are defined as follows:

$$k_i = \frac{F_i}{P_i} \tag{1a}$$

$$r_i = \frac{R_i}{P_i} \tag{1b}$$

The overall increase of exergy destruction in a generic i-th component due to presence of faults is determined as sum of additional local exergy destruction due to irreversibility ΔI_i (where $I_i = F_i - P_i$) and additional residue consumption ΔR_i [3], eq. (2):

$$\Delta I_i + \Delta R_i = \Delta\left[\left(k_i - 1\right)P_i\right] + \Delta\left(r_i P_i\right) = \Delta k_i P_i\left(X^0\right) + \left[k_i(X) - 1\right]\Delta P_i + \Delta r_i P_i\left(X^0\right) + r_i(X)\Delta P_i \tag{2}$$

In eq. (2), X and X^0 represent two sets of thermodynamic variables, respectively indicating the system operating under "design" (i.e. fault-free) and "faulty" conditions. Basing on eq. (2), we may distinguish between:

- Malfunction (or endogenous irreversibility), represented by the terms $\Delta k_i P_i\ (X^0)$ and $\Delta r_i P_i\ (X^0)$ in eq. (2) and associated with increases in unit exergy consumptions or unit consumption of residues in the i-th component:

$$MF_i = MF_i^{(\mathrm{k})} + MF_i^{(\mathrm{r})} = \Delta k_i P_i\left(X^0\right) + \Delta r_i P_i\left(X^0\right) \tag{3}$$

- Dysfunction (or exogenous irreversibility), induced in the i-th component by the malfunction of other components that provoke a variation ΔP_i in the production rate of component "i":

$$DF_i = \sum_{i=1}^{N} \left(DF_{ij}^{(\mathrm{k})} + DF_{ij}^{(\mathrm{r})} \right) = \left[k_i(X) - 1 \right] \Delta P_i + r_i(X) \Delta P_i \tag{4}$$

The method aims at distinguishing the additional exergy destruction in each component provoked by faults occurring in the same component and those induced by malfunctions occurring in other components; at this purpose, a malfunction cost MF_i^* is introduced:

$$MF_i^* = MF_i + \sum_{j=1}^{N} \left(DF_{ij}^{(\mathrm{k})} + DF_{ij}^{(\mathrm{r})} \right) \tag{5}$$

where MF_i^* represents the additional fuel consumption provoked by faults occurring in component "i", and is calculated summing up the additional exergy destruction MF_i that these faults induce on the same component "i" [see eq. (3)] and the dysfunctions that these faults generate in other components "j" (for j = 1 to N, with $j \neq i$) [24]. The second term on the right hand side of eq. (5) is synthetically indicated as DI_i [11].

As can be seen from eq. (4), the dysfunctions represent the extra irreversibility occurring in the component when they are forced to vary their product in order to satisfy the increased fuel consumption of the faulty units; since they represent a secondary phenomenon related to the propagation on all the plant components of the malfunction occurring in a specific component, quantification of their cost has no meaning.

The overall fuel impact ΔF_{T} is the additional overall exergy consumption induced by the faults occurring in the N plant components, and it can be finally calculated as:

$$\Delta F_{\mathrm{T}} = \sum_{i=0}^{N} MF_i^* \tag{6}$$

In order to assess whether the method quantifies properly the impact of malfunction on the additional fuel consumption, an appropriate indicator $\Psi^{\mathrm{fault},i}$ is defined:

$$\Psi^{\mathrm{fault},j} = \frac{MF_j^*}{\Delta F_{\mathrm{T}}^{\mathrm{fault},j}} \tag{7}$$

As can be seen from eq. (7), $\Psi^{\mathrm{fault},j}$ is defined as ratio between the malfunction cost (i.e. the additional energy consumption induced by fault j, according to the estimation provided by the diagnostic technique) and the "fuel impact" ΔF_{T}, i.e. the actual additional energy consumption induced by fault j, calculated as difference between the energy consumption evaluated experimentally (or by the use of a simulator, as in the case of the referenced paper [9]) in presence of fault j and that evaluated in absence of fault j.

Obviously, when $\Psi^{\mathrm{fault},j} = 1$, the diagnostic technique exactly quantifies the additional energy consumption provoked by the fault; conversely, when $\Psi^{\mathrm{fault},j} > 1$ or $\Psi^{\mathrm{fault},j} < 1$ the diagnostic procedure respectively over- or under-estimates the additional energy consumption provoked by fault j.

As stated in the previous section, the main reasons for the scarce reliability of the diagnostic technique in detecting the malfunctioning component is related with the fact that in presence of faults the unit exergy consumption increases (or the exergy efficiency decreases) not only in the component where malfunctions are located, but also in the remaining faults-free components, due to the changes induced in their "operating point". As a consequence, according to eq. (3), a malfunction MF_i arises not only in the actually malfunctioning components but also in those components where no anomalies are occurring. It is thus important to distinguish between "intrinsic malfunctions", which are related to the variation of unit exergy consumption occurring in the actual faulty component, and "induced malfunctions", which are related to the variation of unit exergy consumption occurring in faults-free component. It is clear that if a faults-free component was characterized by a constant value of unit exergy consumption (i.e. if induced malfunctions were absent), the extra irreversibility generated in it would be entirely classified as a dysfunction induced by the faults occurring in other components; particularly this increase of irreversibility generation [as quantified by eq. (4)] would only derive from the greater amount of product necessary to satisfy the increasing consumption of the faulty components.

The presence of induced malfunctions is related with the non-flat exergy efficiency curves of components (at different production rates). Induced malfunctions also derive from the intervention of the control system which, aiming at restoring the values of controlled parameters in a plant, further modifies the operating point of each component and consequently its exergy unit consumption [22].

According to eq. (5), the presence of induced malfunction implies that a non-null malfunction cost is obtained for fault-free components; as a consequence, due to the presence of several simultaneous positive malfunction costs, the analyst could not identify the components that are actually experiencing performance degradation due to the presence of local faults. The elimination of these induced effects is complex and requires the use of a thermodynamic model for each component, in order to predict its response to changes in the operating conditions; as an example, in [25] some thermodynamic models were developed in order to predict changes of component exergetic performance when anomalies occur. In [26] it has been shown how the accuracy of a diagnostic procedure improves when filtering respectively the effect of induced malfunctions caused by the control system and by the dependence of component efficiency curves from the operating condition.

ON THE REFERENCE PLANT AND ITS PRODUCTIVE STRUCTURE

In this section only the main features of the reference plant adopted in [21] and serving as a basis for the present analysis are given; a more detailed description can be found in the referenced paper. The plant consists of a 120 kW air-cooled air conditioning rooftop unit, using R407C as refrigerant, equipped with a Thermal Expansion Valve (TXV) which imposes a fixed 6 °C superheating at evaporator outlet, and a thermostatic control to start and switch-off the compressor. In the referenced paper, several scenarios were investigated, each differing from the other for the evaporator geometry (i.e. the coil depth expressed in terms of "number of rows") and for the inlet air conditions at the evaporator. In particular:

- Three different coil depths were analysed, equal to 3-rows, 5-rows and 7-rows respectively;
- Five values of air inlet temperature (i.e. 22 °C, 25 °C, 28 °C, 31 °C and 34 °C) and three values of air inlet relative humidity (i.e. 45%, 60% and 75%) were considered.

The faulty operating condition on the evaporator was implemented by imposing for all the scenarios and coil geometries a "heavy fouling" condition, corresponding to a decrease in the air face velocity to the coil from 2.7 m/s down to 2.1 m/s. Following a well-established approach already adopted in previous papers [19] and [20], accurate 1-D simulations were performed using the tool IMST-ART version 3.60 [27].

In this work, the same productive structure defined and presented in [20] was adopted, as shown in Figure 1; as can be seen from the figure, the physical exergy of refrigerant is split in a thermal fraction (indicated as, ΔB_i^{T} see red continuous lines in the figure) and a mechanical fraction, (indicated as ΔB_i^{M}, see blue lines in the figure), which are respectively related to "thermal" and "mechanical" disequilibrium between the refrigerant state and the reference dead state [28]. Splitting exergy flows in these two fractions allows the analyst to define more accurately the consumed resource and the productive function of each plant component: for instance, as can be seen in Figure 1, it is very intuitive that the only component producing "mechanical exergy" (i.e. increasing the pressure disequilibrium between the refrigerant and the ambient) is the compressor, while all the other components (i.e. evaporator, TXV and condenser) only "consume" mechanical exergy. A complete understanding of the productive structure and all the formulas presented in Figure 1 would require long methodological premises, which are not formulated here for the sake of brevity. In fact, an accurate description of the productive structure can be found in [20]; below only some further elements are given, to clarify some key aspects.

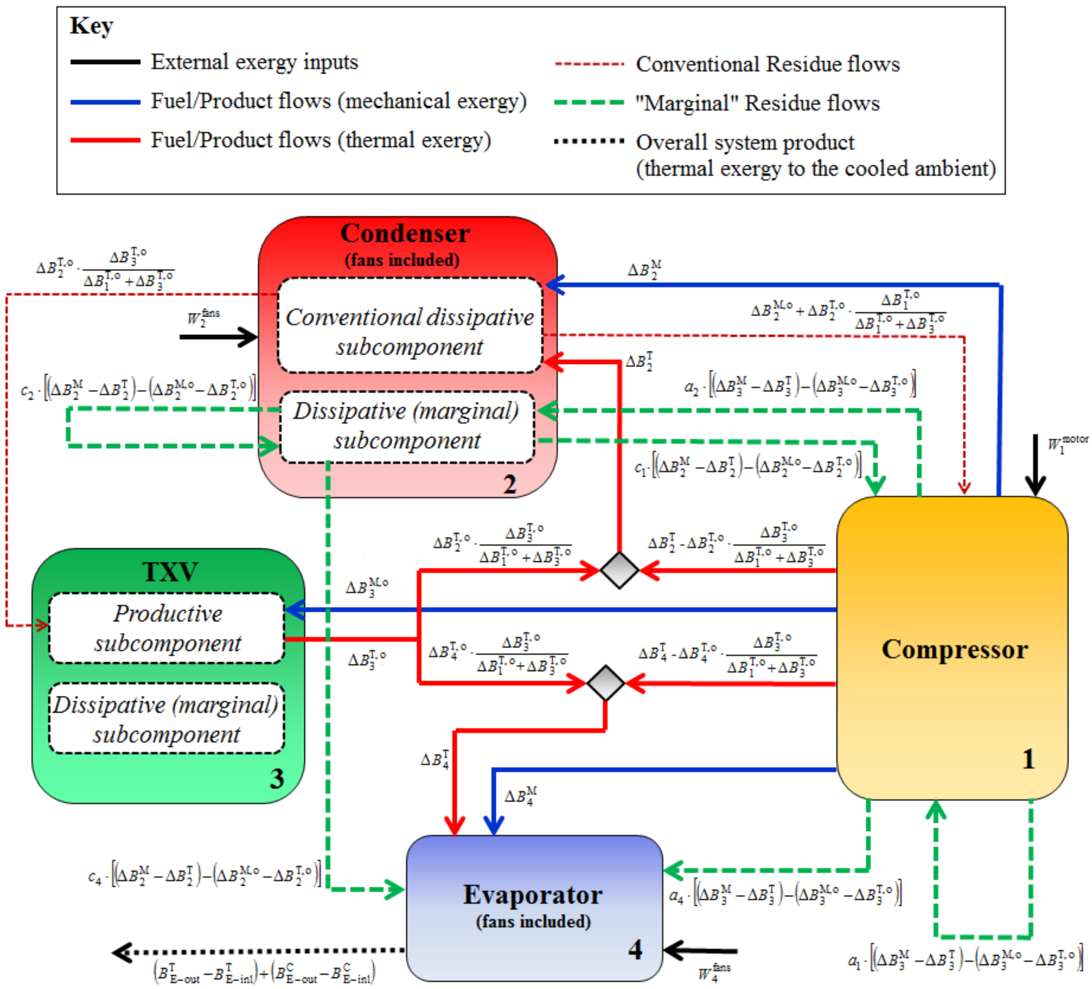

Figure 1. Productive structure of the examined direct expansion refrigeration system

In [20] two kinds of residues have been defined for an air-conditioning system:

- "Conventional residues" (see red dotted lines in Figure 1) refer to the refrigerant exergy dissipated even in case of plant operating in optimal maintenance conditions (i.e., in the absence of faults). As an example, the exergy destroyed at the condenser in the heat exchange with the cooling air at ambient condition represents a conventional residue;

- "Marginal residues" (see green dotted lines in Figure 1) are related to the additional exergy destructions occurring in the TXV and in the condenser when the plant works under faulty conditions. These flows are allocated as additional inputs to the compressor, the condenser and the evaporator, by means of appropriate distribution factors a_1, a_2, a_4 (for the TXV) and c_1, c_2, c_4 (for the condenser). This quite complex approach, discussed in detail in [20], is needed to address the following criticism: when faults occur in components other than the TXV, the high malfunctions induced on the valve do not allow localizing the anomalies taking place in other components, thus leading always to detect the TXV as "faulty", even though it is operating correctly. Modelling the additional exergy destruction at the TXV as a "marginal residue" and reallocating it to the other components allows to overcome this difficulty. The referenced paper provides further details about this approach.

Finally, the product of the whole plant is the exergy variation of the cooled and dehumidified air in the coil; a detailed description on exergy calculations is provided in [21].

In this cited paper, no procedure was adopted to filter the effects induced by intervention of the control system, since a thermostatic control is used to start and shut-off the compressor: then, filtering the effects of the control system is unnecessary because the plant is not "forced" to modify its instantaneous operating conditions, being only the duration of on-cycles adjusted to match the load.

ANALYSIS OF RESULTS

In the paper that inspired the present study [21], it was shown that for all the examined scenarios the method allowed to correctly detect the evaporator as fouled, since its malfunction cost (i.e. MF_4^*) always assumed the highest positive values among the plant components. However, in the same paper the quantitative assessments of the additional exergy consumption provoked by evaporator fouling were not satisfactory, especially when low-depth coils or high values of absolute humidity of inlet air were concerned.

As previously stated, this paper introduces advances with respect to a previous work by the same authors [21]: in the cited work, the authors only presented the results of the thermoeconomic diagnosis of evaporator fouling, in order to highlight the operating conditions (i.e. inlet-air temperature and humidity at the direct expansion coil) for which the diagnostic performance was good from both a quantitative and a qualitative point of view. In the present paper, how the induced malfunctions on the compressor and the condenser influence the poor quantitative performance of the method in the operating conditions when the technique achieved the poorest performance is investigated. To achieve this goal, a detailed zoom on the thermoeconomic quantities (malfunctions, dysfunctions, malfunction costs) is made, so as to understand which components and at which extent are affected by the imposed fault. The proposed analysis thus offers some insights on the thermoeconomic model adopted and suggests eventual solutions for future improvement of the diagnostic technique.

In Figure 2 (a-c), the malfunction costs MF_i^*, the malfunctions MF_i, and the dysfunctions DI_i are presented respectively for the 3-, 5- and 7-rows coils; furthermore, the performance indicator $\Psi^{\text{fault},4}$ is shown inside green or red boxes below in each figure. The two colours distinguish the cases of good and poor diagnostic performance, according to the approach proposed in [21]:

- When the condition "$0.5 < \Psi^{\text{fault},4} < 1.5$" is satisfied, the diagnostic performance is good, since the technique provides a reasonable quantitative estimation of the additional consumption provoked by the fouled evaporator. In such cases green boxes are used;

- Conversely, when the former condition is not fulfilled, the results of the diagnosis are considered unsatisfactory since the diagnostic technique significantly under- or over-estimates the additional consumption provoked by fouling. These cases are identified by the use of red boxes in Figure 2.

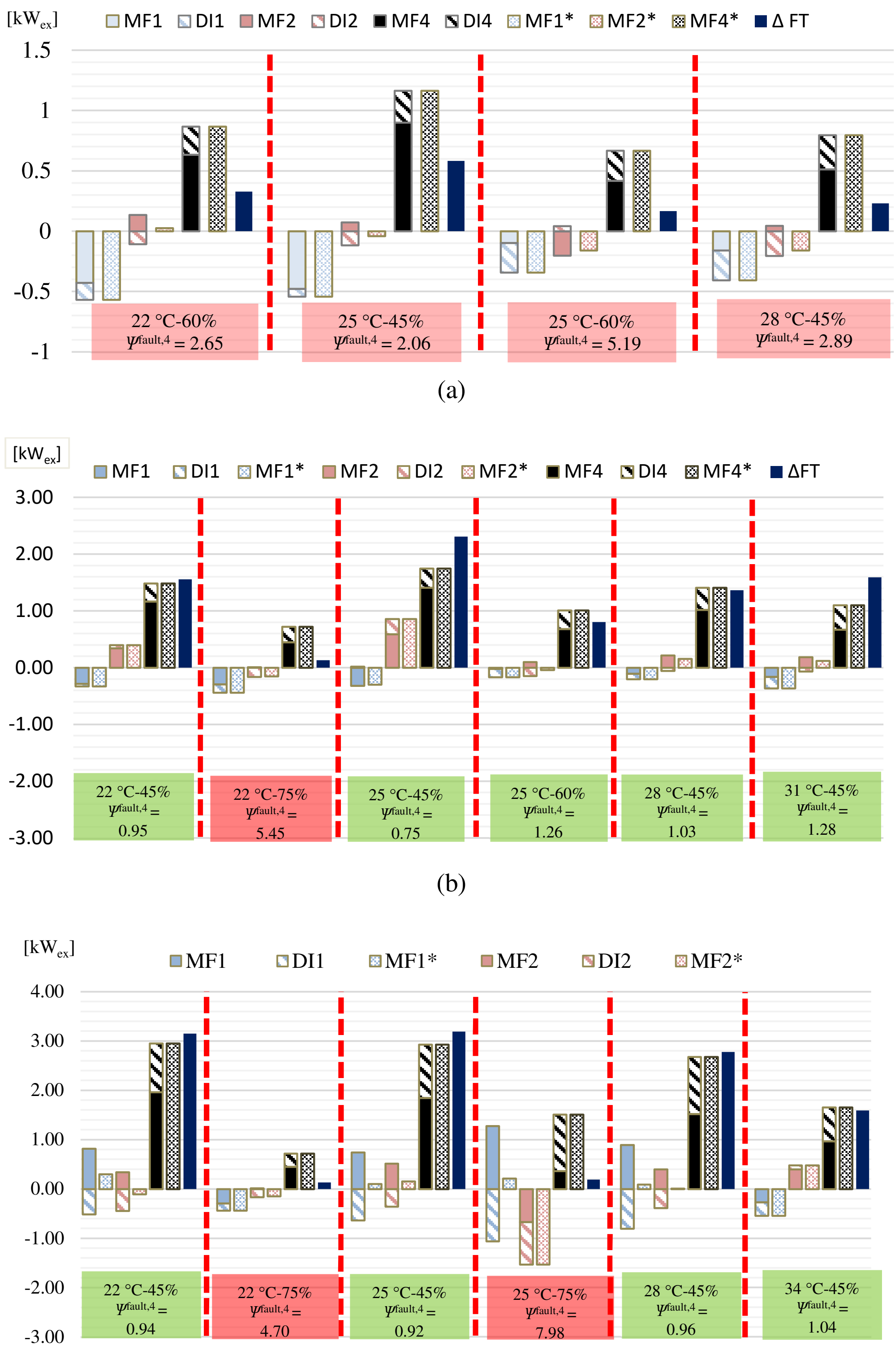

Figure 2. Malfunction cost MF^*, fuel impact ΔF_{T} and performance indicator of the diagnostic technique $\Psi^{\mathrm{fault},4}$, for 3 rows (a); 5 rows (b); 7 rows (c)

For the sake of brevity, in the section below only the most illustrative cases are presented, among the large number of scenarios simulated in [21].

The influence of the induced malfunctions on the performance of the diagnostic procedure is evaluated by examining the magnitude of the related malfunction cost, keeping in mind that:

- The method recognizes as "faulty" the components characterized by the highest positive malfunction cost;
- The malfunction cost for a faults-free component would be null if induced malfunctions were absent: in such conditions the diagnostic technique would achieve a very good performance. Being malfunction costs represented by algebraic values (i.e. they can be either positive or negative), any high "absolute value" (i.e., any high positive or negative value) of the malfunction cost for a fault-free component will significantly affect the reliability of the diagnostic procedure in quantifying the impact of each fault.

The results are shown in Figure 2, and the components have been enumerated as follows: "Compressor = Component 1", "Condenser = Component 2", "TXV = Component 3" and "Evaporator coil = Component 4". In all the subfigures no bars for the thermal expansion valve are shown (i.e. no values for MF_3, DI_3 and MF_3^* are presented), having been the additional exergy destruction at the valve allocated as "marginal residues" to the other three components. It can be observed that:

- For a 3-row coils, see Figure 2a, the method is not able to estimate correctly the additional exergy consumption provoked by the fouled evaporator. As can be seen from the figure, under all the examined scenarios the exergetic efficiency of the compressor increased (i.e. the unit exergy consumption decreased) as an induced effect of the fouled evaporator, as testified by the negative values of MF_1 resulted. The cost of this induced malfunction (i.e. MF_1^*) is not negligible. Conversely, the exergetic efficiency of the condenser is rather sensitive to the air inlet conditions, oscillating between positive and negative values MF_2 values; however, in terms of malfunction costs, in most cases negative values of MF_2^* were obtained, suggesting that also the condenser seems to benefit of the presence of fouling at the evaporator. Drawing some conclusions, the significant over-estimation of the additional consumption provoked by evaporator fouling (see $\Psi^{\text{fault},4} >> 1$!) is due to a simple fact: as an exergy-based diagnostic technique, the thermoeconomic model erroneously propagates the effects of the fouled evaporator on the compressor (primarily) and the condenser (secondarily), detecting a misleading "improvement" in their performance. This effect is particularly evident for this coil geometry, while it will be mitigated when examining deeper coils (with 5 and 7 rows), as clarified below;
- As evident in Figures 2b and 2c, respectively for 5-rows and the 7-rows coils, the performance method here is satisfactory in most of the examined scenarios, but when a very high relative humidity (i.e., 75%) of inlet air is considered: in these last cases, in fact, the cost of the induced malfunction on the compressor (which is the most affected component for the 5-rows coil case) and the condenser (which is the most affected for the 7-rows coil case) is not negligible compared to the evaporator one. Only in these scenarios the method is not able to filter the effect of induced malfunctions on these components, leading to an unsatisfactory performance of the diagnostic technique. An explanation of this trend may be found in reference [21], where a detailed exergy analysis has shown that significant changes in the chemical exergy of dehumidified air may induce distortions in the exergetic representation of the plant. Dehumification is obviously prevalent when the relative humidity of inlet air to the coil is higher; in such scenarios most of the coil tubes operate in "wet conditions". Conversely, when low relative humidity is considered (i.e., values between 45% and 60%, see cases with green boxes in Figures 2b and 2c), the coil

tubes prevalently operate under "dry cooling" condition, and the intensity of dehumidification decreases (thus making the influence of chemical exergy of cooled air negligible). In these last conditions, the diagnostic technique achieves very good performance, providing a reasonable estimation of the additional power consumption provoked by evaporator fouling (as evident from the $\Psi^{\text{fault,4}}$ values, very close to 1). In these cases, although the malfunctions MF_1 and MF_2 induced on both the compressor and the condenser are sometime high, their impact in terms of malfunction costs MF_1^* and MF_2^* is very low, thus allowing for a reliable use of the diagnostic method.

From the discussion above, it can be stated that the method performance is particularly sensitive to the induced malfunction cost when low-depth coils or high humidity of inlet air are considered; in these cases, the costs of induced malfunctions on the compressor and the condenser are not negligible and consequently the quantitative assessments of additional exergy consumption provoked by evaporator fouling are not satisfactory.

It is clear that the sensitiveness of the diagnostic performance to the induced malfunctions limit the potential of this technique at the present time; one possibility to solve these discrepancies can arise from further improvements in the thermoeconomic model. Some possible research lines for the future refinements of the technique can be identified:

- More promising results could be obtained by the identification of optimal values of the distribution factors a_i and c_i for each specific coil geometry or operating condition. In the present analysis, in fact, fixed values of these constant were adopted, as derived for the same plant from reference [20]; it may be expected that the performance of the diagnostic technique will benefit from the adoption of case-oriented values of these factors introduced to filter the induced malfunctions;
- Improvements could also be achieved by the preliminary development of appropriate "characteristic equations" of the exergetic performance of each component, to better characterize their behaviour (in terms of variation in the unit exergy consumption) when deviations from the design working conditions occur and thus filter the induced malfunctions more efficiently.

CONCLUSION

In this paper a critical analysis of the performance of thermoeconomic diagnosis for an air conditioning unit with a fouled evaporator was carried out. Based on the results obtained by the same authors in a previous work, a zoomed analysis on the induced malfunctions on compressor and condenser was performed, in order to understand the origin of the unsatisfactory diagnostic performance occurred in some of the examined scenarios. It was shown that when high coil depths or low inlet air relative humidities are considered, the costs of the induced malfunctions on fault-free components do not influence the quantitative assessments of the thermoeconomic diagnosis, suggesting that the thermoeconomic model is capable to reduce the impact of these malfunctions even when no filtering techniques are applied. This is no more valid when low depth coils or high relative humidities of inlet air are considered: in such cases, the method is very sensitive to the induced malfunctions and relevant overestimation of the additional exergy consumption provoked by evaporator fouling is obtained. Future studies will be focused on the possible improvements of the thermoeconomic model of the examined system in order to address criticisms that eventually lead to misleading results, thus limiting the applicability of this technique and the current potential for industrial implementation of thermoeconomics-based diagnostic systems.

NOMENCLATURE

a_i	distribution ratio on component "*i*" of valve's additional exergy destruction	[-]
c_i	distribution ratio on component "*i*" of condenser's additional exergy destruction	[-]
DF_i	dysfunction generated in *i*-th component	[kW_{ex}]
DI_i	dysfunction generated by malfunction occurring in *i*-th component	[kW_{ex}]
F_i	fuel of component "*i*"	[kW_{ex}]
ΔF_T	fuel impact	[kW_{ex}]
k_i	overall unit exergy consumption of component "*i*" (dimensionless)	
I_i	exergy destruction in component "*i*" due to irreversibility	[kW_{ex}]
MF	malfunction	[kW_{ex}]
MF^*	malfunction cost	[kW_{ex}]
N	numbers of component	[-]
P_i	product of component "*i*"	[kW_{ex}]
R	"residue" exergy flow	[kW_{ex}]
r_i	overall unit residue generation of component "*i*" (dimensionless)	
T	temperature	[°C or K]

Vectors and matrices

X set of thermodynamic variables that identify an operating condition

Greek letters

Δ indicates variation of the preceded term
Ψ performance indicator of the diagnosis technique

Superscripts

0 referring to the design/no faults condition
M referring to "mechanical exergy" (the fraction related to pressure)
T referring to "thermal exergy" (the fraction related to temperature)
(k) referring to exergy destruction in the generation of "products"
(r) referring to exergy destruction in generation of "residues"

Abbreviations

COP Coefficient Of Performance
TXV Thermostatic Expansion Valve

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