Suitability of exergy analysis for industrial energy efficiency, manufacturing and energy management

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Abstract

The industrial sector consumed approximately 98 Exa Joules (EJ) of energy worldwide accounting for 28 % of world energy consumption in 2008. World energy consumption growth in 2010 reached 5.6 %, the highest rate since 1973. In 2011, the growth in world energy consumption exceeded economic growth, with energy intensity of economic activity increasing for a second consecutive year. Improving industrial energy efficiency therefore offers a potential for massive reductions in greenhouse gas emissions. Exergy analysis, based on the 2nd law of thermodynamics, shows considerable promise in improving industrial energy efficiency. This paper examines positive and negative aspects of exergy analysis, highlighting its various interdisciplinary forms and critically reviewing its theory. It explains common areas of application, and focuses on manufacturing. It is apparent that exergy analysis can simplify energy efficiency comparisons between different manufacturing systems designs compared to energy analysis, with an example of textile industry reinforcing this claim. Finally some comments on the ease of conducting an exergy vs. energy analysis are made and its use for the energy manager is presented.

Introduction

As part of a global attempt to reduce the consumption of finite resources, engineers everywhere have attempted to reduce energy consumption while increasing the value of industrial output. The role of improving the energy efficiency of industrial processes has become even more important in recent years.

This paper's aim is to present a concept suitable for the analysis of energy using industrial processes, but before we can explore reduction of energy consumption, the question arises; can we really reduce energy consumption? Energy, which is based on the first law of thermodynamics can neither be created, nor destroyed. So, how can we then say it is even consumed at all, and for that matter, reducing the energy consumption becomes a perplexing topic.

Whenever a task is performed in the real world, energy is not consumed, but is in fact transformed into a less useful form. The usefulness of energy is called quality and it is related to the potential of energy to be used to perform work. All real, natural processes in the world tend to transform higher quality energy into lower quality forms. Even as we read this text and breathe, we use the chemical energy given to us in food and air, and convert it into heat and CO_2 that maintains our body processes. Energy is not consumed during this process, but converted into a lower quality form. So, if we want to reduce the 'energy consumption' of any process, we have to control the quantity of energy as well as the degradation of energy quality that occurs. Energy analysis based on the first law, unfortunately does not give any indication of 'energy quality degradation'. The solution to measuring this quality degradation lies in a quantity based on the 2nd law of thermodynamics, namely exergy, which quantifies not only the energy transformation quantity but also the quality.

This paper examines the claim that exergy analysis identifies the true value of a resource/energy interaction more accurately than energy analysis, and describes the applicability and theoretical robustness of such analysis. The paper focuses on applying exergy analysis to industrial engineering problems and concludes by commenting on the practical use of exergy analysis to an energy manager. Review papers on exergy have been written previously [1, 2] which have remarked on the history of exergy, its various forms and disciplines, it applicability to various areas and its future use. On the other hand, recent advances in applying this concept to manufacturing settings have not been documented, so it is one of the goals of this paper to present current research into exergy and manufacturing. Finally, exergy analysis is presented as a useful tool for comparing heterogeneous industrial settings, which can be very difficult using energy and concludes with a discussion on the material presented in the paper.

The concept of exergy

The exergy of a thermodynamic system is based on the second law of thermodynamics and is defined as "The maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only." [3]. Exergy is a property of both the system and the environment when both are considered as part of a composite system [4]. The Main difference between energy and exergy is that exergy is a measure of quality and can be consumed [5]. Exergy quantifies losses within irreversible processes. The final exergy embodied with resources after they pass through a process is lesser than the exergy embodied in the delivered work, heat, primary and secondary products and waste; is not equal to the exergy content of the intake resources; this difference is dissipated through irreversible entropy generation and was quantified by Gouy and Stodola as[2]:

$$Ex_{loss} = T_0 S_{gen}$$

Ex_{loss} is the exergy lost due to the irreversibility in the process, T_0 is the temperature of the surrounding and S_{gen} is the entropy generated. The exergy of a system or a resource is usually split into four contributions: potential exergy, kinetic exergy, physical exergy and chemical exergy [6, 3, 4]. The potential and kinetic exergy is equal to the potential and kinetic energy respectively. Physical exergy, Ex_{ph}, is associated with the flow of a stream and is calculated by:

$$Ex_{ph} = (h - T_0 s) - (h_0 - T_0 s_0)$$
$$Or$$
$$Ex_{ph} = (u + P_0 v - T_0 s) - (g_0)$$

Where T_0 and P_0 are the temperature and pressure of the reference environment, 298.15 K and 1 bar respectively, *u*, *v*, *s* are the internal energy, volume and entropy, and g_0 is the Gibbs free energy per unit mass of the stream respectively. The chemical exergy of a substance is the energy that can be extracted from the substance if it is brought into equilibrium with the environment and is calculated by,

$$Ex^0_{ch,i} = \Delta G^0_r + \sum_k v_k Ex^0_{ch,k}$$

Where $Ex^0_{ch,i}$ is the chemical exergy of the compound 'i' (kJ/mol), ΔG^0_r is the standard Gibbs energy[2] of the reference reaction (kJ/mol), v_k are the number of moles of the kth reference species, and $Ex^0_{ch,k}$ is the standard chemical exergy (kJ/mol) of the kth reference species. The suffix '0' denotes that the reference system is assumed to be at standard 'environmental' temperature and pressure, T_0 & P_0 at 298.15 K and 1 bar respectively. An exergy analysis of any "well defined" system can be carried out by writing the mass balance, energy balance and finally the exergy balance equations of the system. For a manufacturing system, this would mean writing the above balances for all the material and energy streams. The benefits as well as the shortcomings that are associated with exergy and exergy analysis are outlined next.

Merits of exergy

Energy efficiency, based on the first law of thermodynamics, is the most common tool currently in use for measuring the 'effectiveness' of a process. Unfortunately, a focus on energy efficiency alone can mislead the analyst and can result in poor design decisions [7]. This can be illustrated when the energy and exergy efficiencies for various electrical devices are calculated and compared. Rosen [7] analysed a coal power plant in which the overall energy efficiency is 37 % and exergy efficiency is 36 %. Energy identifies the steam generators to be 95% efficient whereas the exergy efficiency is 50 %. Physically, this means that although most of the energy is transferred to the preheated water in the steam generator, its 'quality' is badly degraded. This quality degradation here is not captured by energy efficiency. In the condensers, all large amount of energy enters almost all of which is rejected. On the other hand, a small amount of exergy enters, 25 % is rejected and 75 % internally consumed. To improve energy efficiency, conventional energy analysis would then focus on the condensers, whereas the more significant energy 'consumption' is occurring in the steam generators.

Another efficiency analysis tool, based on the second law of thermodynamics, which overcomes the shortcomings of energy analysis, is entropy analysis which quantifies the irreversibilities in a process but is expressed in the rather obscure units of Joules per degree change in temperature. On the other hand exergy analysis, also based on the 2nd law, is expressed in energy units therefore making easier to understand and accept.

Exergy efficiency can pinpoint the inefficiencies in a better way by identifying and quantifying the types, causes and locations of the losses as compared to energy efficiency [8]. There are many examples in literature reinforcing this point; just a few in varied fields of application are in [9–14]. A very simple one is an example of an electric resistance space heater. The energy efficiency of such a device is almost 100 % but the exergy efficiency is less than 10 %. The reason is that very high quality energy, electricity, is used to provide very low quality energy i.e. heat. The same heating could be accomplished by a heat pump which will increase the exergy efficiency of the process by around 300 %. The concept is to use lower quality input energy for processes that are unnecessarily using a higher quality input energy form.

In buildings, exergy management has good potential for optimization purposes and is explored in the Low exergy (LowEx) approach [15] which proposes matching the quality levels of supply and demand for buildings in order to minimize the low-value energy dissipated into the environment.

In manufacturing systems, it has been shown that the indicator of sustainability may be related to the uniformity of a thermodynamic property of the product during material processing [16]. If that property is a quality control measure, then exergy analysis could prove to be a quality control tool in addition to its usual benefits. Following on from this, the controlled atmospheric brazing of aluminium is analyzed and the results show that Exergy analysis can be implemented for sustainability analysis of materials processing for manufacturing with a focus on resource utilization vs. product quality [17].

Exergy is a flexible tool which has been applied to sustainability study, economics, ecology, policy making, ecosystem analysis and societal systems. Details of these are given later in this paper under 'areas of application'. Exergy analysis can be a very good tool for comparisons of efficiencies between heterogeneous industries. Using energy analysis to do this can be cumbersome and inaccurate whereas the ability of exergy analysis to account for the quality and quantity of not only energy forms but of material streams as well makes it a more useful decision making tool. This point is discussed in detail in a later section of this paper.

Demerits of exergy

Exergy is a property of the system and the environment and is defined when both are considered together, therefore the definition of not only the system but the 'exergy environment' is cardinal to the theoretical formulation of the exergy concept. The problems associated with its theoretical robustness have been outlined[18] and are as follows. The derivation of exergy and the selection of the reference environment can be problematic. In the derivation of non-flow exergy, the fundamental requirements necessary to quantify exergy are inherently in conflict. The basic problem lies in the fact that the natural eco-system environment and the exergy reference environment by their basic descriptions have features completely opposing one another, thus assuming one to be an analogue of the other would be wrong.

Exergy is considered to be the measure of resource value on the basis of the departure of the state of a resource from its equilibrium state [19]. On the other hand, since a resource and waste both indicate a variation of a substance from equilibrium state, exergy cannot differentiate between a resource and waste. Rosen has tried to address this issue by characterising resource exergy as restricted and of waste as unrestricted [20] but since sunlight, water and wind are considered resources, they are also unconstrained which questions the suitability of Rosen's classification. Furthermore, exergy does not quantify well the value of non work producing materials, a simple example being of minerals. Valero has compared the theoretical chemical exergy value of a mineral resource to the empirical work required to refine the minerals from a mixture to pure states [18]. The correlation between the theoretical and empirical values was weak and this exposed a gap in the theoretical robustness of exergy for non-work producing substances.

While exergy is a flexible concept being applied to varied disciplines, its application is problematic. Defining exergy efficiency is difficult when applied to manufacturing processes. The various definitions of exergy are compared by applying them to subtractive, additive and mass conserving manufacturing processes [21]. The results suggest that no definition is robust enough to be applied to all three types of manufacturing processes. Additionally, since energy saving is not the main goal of a manufacturing process, an exergy analysis may be considered superfluous to what is necessary. Furthermore, its practical implementation presents some problems as well. In order to carry out an exergy analysis over the production cycle of a manufacturing process, some necessary thermodynamic assumptions need to be made in order to simplify the analysis. A critical one is assuming the process to be a steady state process. If this assumption affects the accuracy of the analysis considerably, then it makes conducting the exergy analysis much complicated and thus it questions the practical utility of such a technique.

The exergy concept has been used to explain the most probable behaviour of complex natural systems, but the theories that have arisen from it are still heavily debated [2]. Valero advocates 'thermoeconomics' for fault diagnosis and quantification in energy intensive settings where the main barriers to implementation are induced malfunctions [22]. Valero introduced the structural theory and malfunction/fuel impact formula [23] which should quantify inefficiencies of individual components accurately, but is highly criticized by [24] in which approaches to splitting the exergy destruction into endogenous and exogenous parts is given. The fuel impact formula was compared with the three other approaches for a simple gas turbine system. The values from the structural approach varied significantly from the other three approaches which suggest erroneous values produced by this approach.

Since, exergy depends on the reference environment as well as the systems; the changing environment can have an effect on the values generated. [25] Conducted exergy analysis for three systems: A regenerative steam injection gas turbine (RSTIG), a simple Linde air liquefaction gas plant (Air-Liq), and air-source heat pump water heater (HPWH).The results showed the impact of considering the variations in temperature and humidity of the reference environment. The impact of the reference environment was critical for HPWH thus proving that changes in the reference environment cannot always be ignored.

Generally, it is felt that that increasing the energy efficiency of industrial systems contributes to sustainability. To explore this statement, an overview of the historical effectiveness of efficiency improvements in reducing mankind's resource consumption has been conducted [26]. Unfortunately history shows a 'rebound effect' in which improvements in resource efficiency have generally not reduced mankind's overall consumption of resources. For this reason although exergy analysis may be a useful tool to increase energy efficiency, it may still be insufficient for the purpose of sustainable development.

Areas of application and manufacturing

Exergy analysis is a concept that has been adapted in several disciplines for the analysis of systems. It has merged with ecosystem analysis, evolution theory, social theory, economics, environmental impact of systems, sustainability, policy and decision making. Its use in economics and environmental science has given birth to exergoeconomic [3, 6, 27] and exergoenvironmental analysis [6, 28] and has been used in life cycle approaches in the form of ExLCA [29, 30, 35]. Further, advanced exergy analysis has been developed making these technique more accurate in localizing the inefficiencies within processes, thus also originating in advanced exergoeconomic and advanced exergoenvironmental analysis.

The adaptability of Exergy analysis is demonstrated in the fact that it is not limited in application only to industrial systems. Emphasis has been placed on applying exergy to sustainability science [1, 2, 6, 8, 31–34] including a study on the investigation of the relationship between exergy and sustainability [33]. Exergy based environmental impact indicators have been developed such as in [36, 37] and Rosen presents a critical review of such indicators [20]. Exergy analysis has enabled scientists to perform resource accounting on a global scale. Sustainability has been defined as maintaining what is called "genuine wealth" which would be the resource base for maintaining sustainability [38]. The world can be modelled as either a closed system, or a combination of open sub-systems exchanging mass and energy flows with one another [34] and consequently an accounting of exergy flows on a global scale has also been carried out.

An extensive review of the history of exergy dating back to its origins until 2004 has been conducted by Scuibba [1]. The common areas of its application are mainly in energy intensive systems such as power generation, thermal systems [6], steel industry [39, 40] and a review of the use of exergy in cement manufacturing in given in [41]. Valero describes the TEDEAS project which pursues exergy based diagnostics of energy systems [42–46].

According to the basis set by Gyftopoulos and Beretta [47], exergy analysis can be applied to any 'well-defined' system in any state. Based on this, 20 different manufacturing processes have been analysed [48–50] ranging from conventional ones such as machining, casting and moulding to advanced processes like semiconductor manufacturing.

GENERAL PROCEDURE OF CONDUCTING AN EXERGY ANALYSIS

Here, a brief description of applying an exergy analysis to a manufacturing setup is given. Initially, one needs to model the manufacturing setting as a thermodynamic system using the control volume approach. Here critical assumptions need to be made which is a compromise between accuracy and simplicity of the analysis. The most critical assumption is of considering the manufacturing process as a steady state system. This requires that material and energy flows remain within a reasonable limit (for e.g. 5 %) of the average value. If data is not provided from the factory, all the material and energy flows needs to be acquired through a data acquisition system. Again, necessary simplification should be made by neglecting the mass and energy flows which influence the analysis insignificantly. Although a unified energy data standards are still under development, energy management and data communication standards such as ISO 5001, MSE 2000 and MTConnect can be used as guides for data acquisition for this purpose. For process level analysis, bottom-up data must be acquired which necessitates the use of instrumentation that would capture all the energy and material flows with high resolution accurately. If steady state assumption cannot be justified, then all the necessary data to conduct the thermodynamic analysis of an unsteady open system should be acquired. This is considerable effort in addition to an energy analysis; therefore the application of an exergy analysis needs to be clearly warranted. To this effect, the exergy needs and wastes of manufacturing systems have to be compared to their energy needs and wastes. This would help us classify which manufacturing processes really need to be analysed with exergy analysis. These processes should then be analysed with regards to the practical difficulties of implementing such an analysis. The result of this work would be a clear view of the various manufacturing processes on which exergy analysis needs to be focused upon. Only some peripheral work exists in the public domain and so it is the aim of this paper to inspire such inquiry into this unexplored territory of sustainable manufacturing and energy efficiency.

Utility of exergy for the comparison of different manufacturing designs

Evaluations and comparisons of the energy intensities of industrial processes have many benefits. To state one, it helps us find out which process/industry needs to be focused upon in order reduce energy usage and decisions can be made on this basis regarding energy efficiency improvements. On the other hand, the multifarious variety of manufacturing processes makes it very cumbersome to compare two processes with very different manufacturing designs based on energy analysis. Towards achieving this goal, the utility of using exergy analysis for comparisons of energy intensities within a heterogeneous industry is given. A claim is made that in industry comparison situations, where evaluating the energy intensities of the processes is required, energy may not provide a suitable result due to the variance in the manufacturing system design; however exergy may simplify the comparison and provide a better basis for evaluations. This is due to the fact that exergy analysis inherently takes into account quality degradation of energy, and also factors in changes in the embodied chemical exergy, non-uniformity of units used and climate effects.

SCOPE OF THIS ANALYSIS

This paper is meant to highlight the fact that exergy analysis is a powerful tool that can be used to analyse the inefficiencies in manufacturing processes accurately but the complexity of the analysis and the benefits that would come through such an analysis are question marks. It was not in the scope of this paper to gather data from the textile industry but a clear view of the benefits that could be achieved by implementing an exergy analysis is given. This paper builds on the work conducted in [51] which compared the energy intensities of 13 textile plants in Iran in which also "explanatory variables" are given that need to be considered if fair and proper comparison/benchmarking is required. It is therefore claimed in the section, that exergy analysis will reduce the number of the "explanatory variables" thus simplifying the benchmarking study.

COMPARISON OF THE ENERGY INTENSITIES WITHIN THE 13 TEXTILE PLANTS

The industry taken as an example is the textile industry, where a study has been carried out on thirteen textile plants [51]. While energy use is one of the main cost factors, due to the textile industry in Iran being dominated by small and medium enterprises, it is a very complicated industry when energy intensity comparison is required. The 13 plants are divided into the following 5 major sub-sectors and the energy intensities within each sub-sector compared.

(1) Spinning

The three spinning plants were A, B and C which produced cotton, polyester and blended yarns. In all plants, the energy use is dominated by electricity (60 %–70 %) and 30 % was steam production for heating purposes. Plant C had the lowest specific electricity consumption possibly because of the processing equipment employed (open-end spinning) which has a higher production rate. Plant B had the lowest specific fuel consumption, possible because it was located in a hotter climate thus having lesser heating requirements.

(2) Weaving

The Two plants, D and E were studies producing cotton, polyester and blended fabrics. Plant E had lower specific electricity consumption as the equipment employed (projectile type) has a higher production rate and lower electricity requirements than the equipment employed in plant D. Furthermore, due to the location of plant E, its local climate requires less heating and thus less fuel consumption than plant D.

(3) Wet-processing

In this sub-sector, three plants F, G and H were studied producing cotton, polyester and blended fabrics. Due to the many high temperature steps involved in wet-processing, the energy use is dominated by fuel consumption. Plant H has the lowest specific fuel consumption but this is misleading as plants F and G have an extra sub-process (printing) as well as their preparation and finishing processes are more exhaustive than in H.

(4) Worsted fabric manufacturing

Three complex plants I, J and K for worsted fabric were studied all containing spinning, weaving, dyeing, and finishing subprocesses producing worsted fabric. The electricity consumption and fuel consumption was mainly affected by the age of the machinery used.

(5) Carpet manufacturing.

Two plants L and M were studied. The energy intensity of plant M was lower than L, but this was partly because plant M does not have the fibre dying process which uses significant amount of steam.

The level at which the study was carried out

This study was at the plant-level but also considering explanatory variables. The explanatory variables are factors that affect textile plant energy intensity and affect comparison/benchmarking studies. Considering all sub-sectors, a total of 15 different explanatory variables were identified. Without considering these influencing factors, the energy intensities alone paint a misleading picture.

THE ROLE OF EXERGY IN SIMPLIFYING PLANT LEVEL ANALYSES BY REDUCING THE NUMBER OF EXPLANATORY VARIABLES

It is suggested here that if an exergy analysis were carried out rather than an energy analysis; then nine out of the fifteen factors would be automatically accounted for. This would not only simplify the comparison, but also make it possible to compare the varied manufacturing designs on a more accurate benchmark. These nine factors out of a total of fifteen are given below with each accompanied by an explanation of how exergy analysis will inherently take them into account thus taking them out of the list of explanatory variables and consequently simplifying the benchmarking effort.

(1) "Climate"

Climate effects have been repeated three times in different sub-sectors suggesting it to be one of the most important comparison factors. It is when the surrounding climate of the plant influences the energy intensity.

To analyse the effect of exergy on this variable, we first refer to the definition of exergy, "The maximum theoretical useful work (shaft work or electrical work) obtainable as the system is brought into complete thermodynamic equilibrium with the thermodynamic environment while the system interacts with this environment only." In implementing the exergy analysis, the natural environment is taken to be the thermodynamic environment, so by definition exergy takes into account the natural environmental temperature and pressure. All energy streams involved in the analysis take into account the temperature of the environment in the quantification of exergy. In our textile example, for the plant level analysis, if the control volume boundary is taken to be the building shell, then an exergy analysis would accurately quantify the effects of changes in the environmental temperature. This should take out one of the most important explanatory variable from this comparison study thus making the comparison more accurate and simpler.

(2) "Type of fibre" and (3) "The preparation process"

The type of fibres used in spinning (cotton, polyester, viscose, or combination of two of them) also influences energy intensity. Cotton usually needs more cleaning; requiring more cleaning sub-processes in the spinning process. The preparation process variable depends on the type of fabric and the specifications of the final products, some fabric may go through a greater number of preparation processes like washing. This directly influences the energy intensity of the final products.

In both these explanatory variables, value is imparted to the final product by removing impurities. In both these cases, the input material specific exergy will be lower than the output material specific exergy. This is because chemical exergy associates value to the useful part of the material stream. Furthermore, higher quality or a material that has more processing steps will have higher output material exergy and thus will be accounted for in the analysis.

To illustrate this point clearly, let us take the example of cotton. Cotton, mostly cellulose and an organic compound has the formula $(C_6H_{12}O_5)_n$, a polysaccharide consisting of a linear chain of several hundred to over ten thousand linked D-glucose units. The chemical composition of unprocessed cotton fibre consists of 95 % cellulose, 1.3 % protein, 1.2 % ash, 0.6 % wax, 0.3 % sugar, and 0.8 % organic acids, and other chemical compounds that make up 3.1 %. After processing and removing all the non cellulose chemicals, the cotton fibre is approximately 99 % cellulose. The standard chemical exergy of D-Glucose compound per mole has been given as 2975.85 (kJ/mol) [52].

In this analysis, if cellulose (pure cotton) is the useful material, the exergy associated with cellulose will only be taken into account. Clearly, the cellulose per unit mass of the input stream will be lower than the output stream. Therefore, higher chemical exergy per unit mass will be associated with the output stream. Furthermore, varying quality of cotton will have varying cellulose units per mole which will translate into varying output exergy. The extra preparation processing steps carried out will influence the quality of cotton and therefore will also be clearly accounted for in the exergy analysis.

Assuming there is a reasonably good correlation between the chemical exergy of these non-work producing materials and the actual work required to refine these materials, then each refined "type of fibre" will have its own associated amount of exergy and therefore will be clearly accounted for in the analysis. Both these variables are related to the chemical composition of the material stream, and an exergy analysis provides a more accurate comparison by assigning value only to the useful chemical composition part of the material stream.

The standard chemical exergy of 138 organic chemical compounds is given in [52] and can be used to quantify the exergy of these compounds used in other manufacturing processes.

(4) "Yarn finishing processes", (5) "Final product", (6) "existence of printing" and (7) "Unit of production used in energy intensity calculation"

"Yarn finishing processes" are additional processes after spinning such as doubling, yarn singeing, mercerizing, dyeing, etc. The "final product" explanatory variable depends on the specifications of the final products; some fabrics may be further processed (finishing) adding value, e.g. waterproofing, fireproofing, coating. The variable "existence of printing" is when some fabric wet-processing plants have both printing and dyeing sub-processes, while some others just have either. These processes will increase the plant's energy use by adding a material to the product and can be viewed as mass addition manufacturing processes.

These mentioned variables are post-processes that can be modelled as open systems adding mass and value to the product. Since exergy analysis considers mass along with the energy streams, and it associates exergetic value to mass and the chemical structure of a material, a metric like "specific exergy" will inherently incorporate all of these four mentioned explanatory variables.

(8) "Yarn Count", (9) "The weight of fabric"

Yarn count represents the fineness of the yarn for e.g. weight per length. A common system is the Tex, which represents the weight in grams per 1 km of yarn. The weight of the fabric (g/m^2) influences the amount of production which in turn influences the energy intensity.

An exergy analysis takes into account material as well as energy streams, thus inherently accounting for both these explanatory variables.

EFFECT OF THE EXERGY ANALYSIS UPON COMPARISON WITHIN SPECIFIC TEXTILE MANUFACTURING SUB-SECTORS

Based on the effect of an exergy analysis on the explanatory variables, the analysis of four out of the five sub-sectors will be simplified and more accurately compared.

(1) Spinning

As mentioned in the energy intensity comparison of the three spinning plants, of A, B and C; plant B has the lowest fuel consumption possibly due to climate effects on the plant. Here exergy analysis will give a clearer picture as the climate effects will be accounted for.

(2) Weaving

In the two plants, D and E energy intensity was affected by the local climate. Again, here exergy analysis will account for the climate variation and will therefore offer a more accurate analysis.

(3) Wet-Processing

In plants F, G and H, H had the lowest specific fuel consumption but this was misleading as plants F and G had extra post-processes In an exergy analysis, the extra processing steps will result in a higher output exergy and will increase the exergy efficiency of plants F and G. Therefore a more accurate idea of energy usage will be provided by exergy when comparing these three plants.

(4) Carpet manufacturing

In the two carpet manufacturing plants L and M, the energy intensity of M was lower than L, was although partly since M does not have the fibre dying process (a heavy user of steam), Here the fibre dying process will impart extra exergy to the output material stream , affecting process efficiency. If plant L purchases pre-dyed fibre, then the exergy of the input material stream will be higher, also reflected in process efficiency. Therefore, an exergy analysis will take into the processes variation and provide a more suitable standard for comparison.

COMMENTS ON THIS SPECIFIC CASE

This example of the textile industry suggests exergy analysis to be a powerful benchmarking tool but but requires practical validation. Exergy may also provide a more accurate localization of inefficiencies in this manufacturing sector, especially in the processes dominated by steam production, i.e. fuel consumption. To apply the steady state assumption, energy and material data needs to be acquired. If the material and energy streams do not remain reasonably "steady" within a practical "measurement window", then the implementation of the exergy analysis needs to be done for an unsteady open system and all requirements fulfilled. Furthermore, the theoretical chemical exergy values of the work required to process raw into finished material may not correlate well with the empirical value of the work needed to refine it. This was done for minerals [18] but needs to be explored for textiles. This extra effort needs to be justified; therefore more research is required to answer these questions.

Comments on the practical utility of exergy in manufacturing and its use for the energy manager

Exergy analysis can account to a certain extent for the complexity in manufacturing processes. It has the ability to account for the variability of the product as well as the process quality. It does not only asses the quantity of energy but also takes into account its quality. This strength may serve well when energy reuse is required. It also accounts for the material flows and associates varying amounts of exergy to the varying amounts of not only the quantity, but also the quality of the material flow.

Although there are benefits in conducting an exergy analysis over an energy analysis, its practical implementation is much more complex. Furthermore, the situations in manufacturing where significant benefits can be achieved have not been clearly characterised and remarked upon. Taking the example of a simple machining process of a metal, in comparison to an energy analysis, the only extra information required to conduct an exergy analysis is the environmental temperature and pressure. If one wants to account for the heat flow from the product between processing steps, the surface temperature is also required. Here, the excess work required to carry out the exergy analysis is reasonable but its benefits are also not significant as an energy analysis will characterise the energy usage profile of the machining centre to a satisfactory level. In processes where the chemical structure of the resource may change during processing, then exergy analysis may provide significant benefits over an energy analysis at the cost of calculating the chemical exergy of the products and reactants. An example of this is its application to the textile industry as mentioned previously. In energy intensive industries such as cement and steel manufacturing, the benefits of exergy analysis will be marked as compared to energy analysis and therefore many exergy analysis studies have been carried out in energy intensive industries.

Energy usage can be measured with portable instruments such as current clamps and flow meters but there are no instruments that can directly measure exergy consumption of a material flow. This provides an extra hurdle for energy managers as exergy consumption cannot be measured through compact instruments on system components.

Exergy analysis should be used for the energy analysis of systems only when its need is required. Generally, when the quality of the input and output energy is not drastically different, the energy and exergy efficiencies will not vary greatly and an exergy analysis will not be required. Further work is required to characterize the energy quality requirements and outputs of manufacturing processes in order to help us better organize and utilize our global resources. In the context of the energy manager, considering the wide variety of manufacturing processes, we still need to specify which processes the energy manager needs to evaluate using exergy instead of energy.

Conclusion

The concept of exergy has been examined from an industrial and manufacturing perspective. Both the strengths and weaknesses of exergy and exergy analysis have been outlined. Its common areas as well as some new areas of application are given. When benchmarking and comparing the energy efficiency is required, it is shown through an example of the textile industry that exergy analysis has good capability of tackling complex system designs but its procedure of application is more complex as compared to an energy analysis which makes it less appealing to the industry. It is concluded that this concept clearly has potential but still more work is required in applying it to non-energy intensive industries for the purpose of better managing our global resources.

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