Exergy Concept and its Characteristic

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***Abstract*– In this paper about the concept of exergy, application of exergy in various fields and its characteristic has been discussed and different forms of exergy have been derived. Also a brief comparison between energy and exergy analysis has been done.**

***Keyword* –** Exergy, Application, Analysis and Characteristic

I. INTRODUCTION

The term Exergy was used for the first time by Rant in 1956, and refers to the Greek words ex (external) and ergos (work). Another term describing the same is Available Energy or simply Availability. The term Exergy also relates to Ideal Work as will be explained later, and Exergy Losses relate to Lost Work. One of the challenges in Thermodynamics compared to Mechanics is the introduction of somewhat abstract entities (or properties) describing pVT systems, such as Internal Energy, Entropy and Exergy. In addition, there are special energy functions such as Enthalpy, Helmholtz energy and Gibbs (free) energy that are important in thermodynamic analysis but can be difficult to fully comprehend. While Enthalpy is important for flow processes (open systems) in Mechanical Engineering Thermodynamics, Helmholtz energy (to define equations of state) and Gibbs free energy (for physical and chemical equilibrium) are important in Chemical Engineering Thermodynamics [1]. Summaries of the evolution of exergy analysis are provided at [2-10].

II. EXERGY CONCEPT

The concept of exergy is stated as the maximum work that can be obtained from an energy flow or produced by a system. The fraction of exergy content expresses the quality of an energy source or flow. This concept can be used to combine and compare all flows of energy according to their quantity and quality. Unlike energy, exergy is always destroyed during conversions because of the irreversible nature of energy conversion process. The exergy concept enables people to articulate what is consumed by all working systems (e.g. man-made systems like thermo-chemical engines and heat pumps, or biological systems including the human body) when energy and/or materials are transformed for human use. Exergy analysis can give insight into the extent to which the quality levels of energy supply (e.g. high-temperature combustion) and energy demand (e.g. low temperature heat) are matched. High-valued energy such as electricity and mechanical work consists of pure exergy. Energy which has a very limited convertible potential, such as heat close to room air temperature, is low-valued energy. Low exergy heating and cooling systems therefore allow the use of low valued energy, which can be delivered by sustainable energy sources, as well.

However, in most cases, the low-valued energy demand is met with high quality sources, such as fossil fuels or using electricity. Many researchers and practicing engineers refer to exergy methods as powerful tools for developing and optimizing systems and processes. Exergy losses clearly pinpoint the locations, causes and sources of deviations from ideal circumstances in a system. Exergy efficiencies are measures of the approach to ideal. Nevertheless, exergy analysis is only used by a small group of people, because the analysis method might seem cumbersome or complex (e.g. choosing a suitable reference environment) to some people and the results might seem difficult to interpret and understand. In building profession, the exergy concept has been applied to the built environment. Some researchers have also used the exergy concept in a context of sustainable development. In the last few years, a working group of the International Energy Agency has been formed within the Energy Conservation in Buildings and Community Systems programmer: “Low Exergy Systems for Heating and Cooling of Buildings; IEA Annex 37”. The overall objective of the IEA Annex 37 was to promote the rational use of energy by means of low-valued and environmentally sustainable energy sources.

This PhD research has been carried out in close collaboration with the international Low Ex Net network of exergy researchers, which is a follow-up of the annex. During the course of the PhD research, the COST exergy project (COST Action 24) and the EOS-LT project (entirely financed by SenterNovem) were initiated and have been running. In addition, research outputs of the PhD research have served as inputs to the formulation of the annex on low exergy systems for high-performance buildings and communities (IEA Annex 49). The objective of this PhD research is to develop knowledge into the applicable domains and potential added values of exergy analysis in the built environment, by 134 studying under what conditions exergy could function as a useful concept for the built environment. The research is carried out in the levels of HVAC components and systems and of building systems, and provides metrics that can be used to quantify and express exergy values in buildings and HVAC systems. Firstly, the influences of possible definitions of the standard state of environmental air are critically analyzed in order to determine the exergy of air in buildings. The exergy value of air entails three contributions, a thermal one related to the air temperature, a mechanical one related to the air pressure, and a chemical one related to the humidity ratio of the air. The possibility to calculate the exergy of air in buildings, based on only one or two of these contributions, for example expressed by a characteristic air temperature and/or air as dry air, is explored for three different locations on earth. These values are compared to those calculated using hourly statistical climate data during one year. The results show that it is acceptable in some climates to consider a static reference environment only, instead of a dynamic reference environment, for calculating the exergy value of air in buildings for a year. In a cold climate, the exergy value of the air strongly depends on its thermal contribution.

Accordingly, the outdoor air temperature might be sufficient as a reference environment for the exergy calculation. This is not acceptable for the exergy calculation in a hot and humid (or temperate sea) climate, where the chemical contribution to exergy due to moisture can be substantial. Secondly, exergy analysis is carried out for HVAC components and systems. In the level of HVAC components, critical analyses of exergy efficiency definitions are carried out for air-to-air sensible heat exchangers and vapor compression heat pumps. The exergy efficiency definitions that were studied in the work are: the universal ones in which gross exergy inputs and outputs are considered, and the functional ones in which net exergy flows are considered respectively. A dimensionless temperature is defined and used to illustrate the analysis results. The dimensionless temperature expresses a distance between the hot (or cold) inlet air temperature and the environmental air temperature, relative to the inlet air temperature difference. These analyses resulted in a better understanding of exergy values and of the sensitivity of exergy efficiency definitions applied to this equipment operating at near environmental temperatures.

The functional exergy efficiency in combination with the dimensionless temperature can be used as a guide for selecting temperatures to operate heat exchangers near environmental temperature in an exergy efficient way. The functional exergy efficiency shows that not only heat exchanger performance (expressed in terms of exchanger heat exchanger effectiveness), but also the relationship between temperatures (in the heat exchanger and of the environment) is important to operate the heat exchanger efficiently. The analysis for the air-to-air sensible heat exchangers can be useful when designing a heat exchange system, for example when deciding between using a heat exchanger of higher exchanger heat transfer effectiveness and pre-heating the outside air (e.g. by using a sunspace or the underground). The functional exergy efficiency is also recommended to be used as a performance criterion for the heat pump for space cooling application, especially when the 135 temperature of the environmental air is between the inlet temperatures of the hot and cold air streams and also close to the inlet temperature of the hot air stream. In the level of HVAC systems, energy and exergy analyses for dwelling ventilation with and without air-to-air heat recovery, in winter conditions in the Netherlands, are presented.

The analyses are carried out on an instantaneous and a daily basis. The analysis results show that, from the viewpoint of total exergy consumption (which is the summation of thermal exergy by a ventilation airflow and electricity exergy by a ventilation unit) at room level, it could make sense to use heat recovery only when the environmental air temperature is low enough to compensate the additional need for electricity, when the temperature of the environmental air is not too low let ventilation air bypass the heat recovery unit, or if possible by operating the heat recovery unit at low ventilation airflow rate. Nevertheless, the ventilation airflow rate must be qualified to guarantee the indoor occupancy conditions. Lastly, a method for energy and exergy analysis of a building and building services is proposed. The analysis is based on a build-up model from the energy demand of the building side to the energy supply side. This method is intended to enable building designers (and building engineers) to compare, in terms of exergy, the impact of improvements in the building envelope and in building services. In addition, some examples of the energy and exergy analysis of the building and its building services with some changes of their parametric values are studied by using the building simulation tool TRNSYS.

The analysis results show that, in terms of exergy, solar exergy gains in a cold day create the main exergy losses when cooling is needed. These solar exergy gains should be minimized, or better captured to be useful somewhere else e.g. for domestic hot water production or electricity generation. Exergy losses in the building services depend on a temperature level of the thermal energy supply and (electric) auxiliary energy required by the building services, and this is applicable for both heating and cooling cases. This research provides knowledge that is essential to future development of design instruments and guidelines for exergy efficient building and building services design. Yet, the exergy analyses for the HVAC components and systems and for the building systems are carried out only with outdoor conditions of a cold climate. The exergy analyses for other climates are excluded from this study, since the standard states of environmental air in different climates for the analyses are not similar and should be carefully defined in a proper way. In addition, buildings in different climates are mostly designed in different ways. Exergy in buildings and building services, where they have other different and more complex types, is an interesting topic to study in the near future, and at the same time the knowledge obtained from the research should be disseminated to students and practitioners in a field related to building and HVAC system design.

III. BRIEF COMPARSION OF ENERGY AND EXERGY ANALYSIS

The energy balance is the basic method of process investigation. It makes the energy analysis possible, points at the needs to improve the process, is the key to optimization and is also the basis to developing the exergy balance. Analysis of the energy balance results would disclose the efficiency of energy utilization in particular parts of the process and allow comparing the efficiency and the process parameters with the currently achievable values in the most modern installations. They will establish also the priority of the processes requiring consideration, either because of their excessive energy consumption or because of their particularly low efficiency. Energy analysis is a basic and traditional approach to estimating various energy conversion processes. The analysis is using the concept of energy and its conservation. The forms of energy can be expressed as enthalpy, internal energy, chemical energy, work, heat, electricity, etc. However, the energy approach has some deficiencies. The energy analysis is not able to recognize different quality of energy, (e.g., 1 MW of heat equals 1 MW of electricity). Accordingly, the energy analysis does not recognize the heat quality, which however depends on the heat source temperature, e.g., a 100 kJ of heat at 1000 C is dramatically more valuable than the 100 kJ of heat at the 50 C level. The energy analysis is blind for the process direction, and, e.g., will not indicate any error considering a 100 kJ of heat at 5 C conducted through a partition to an environment at 100 C. For these reasons the modern approach to the process analysis uses the exergy analysis, which provides a more realistic view of the process. The exergy analysis is the modern thermodynamic method used as an advanced tool for engineering process evaluation. Whereas the energy analysis is based on the First Law of Thermodynamics, the exergy analysis is based on both the First and the Second Laws of Thermodynamics. Both analyses utilize also the material balance for the considered system. Analysis and optimization of any physical or chemical process, using the energy and exergy concepts, can provide the two different views of the considered process. The exergy concept was introduced to overcome limitations of the energy analysis. The exergy expresses the practical value of any substance (or any field matter, e.g., a heat radiation), and is defined as a maximum ability of this substance to perform work relative to human environment. In the background of the exergy concept it is assumed that all the common human environment components, available for free in the unlimited amounts, are practically worthless and their exergy is zero. However, any matter at parameters (e.g., pressure, temperature, composition) being not in equilibrium with the environment, has a certain practical value, which can be measured as its potential to work and is expressed as the exergy. This nature of the exergy concept relating to the environment suggests a potential of successful involving exergy into some quantitative consideration of economy and ecology problems. The exergy of a substance is the function of its temperature, pressure and composition, as well as of the temperature, pressure and chemical form of this substance when in physical and chemical equilibrium with human environment. Exergy can be also the function of the substance location and velocity. Therefore, the exergy can consist of the following components:

Physical exergy resulting from the temperature and pressure of the substance measured with respect to the temperature and pressure of the environment. The physical exergy is used for analysis of physical processes, in which the kind of the considered substance is unchanged; ***chemical exergy*** resulting from the difference in the substance composition with respect to the common components of this substance in the environment. The chemical exergy is used for analysis of chemical processes, in which unchanged are the chemical elements. The chemical exergy corresponds to the substance calorific value; ***kinetic exergy*** of the substance, which results from its velocity relative to the environment; ***potential exergy*** of the substance resulting from the substance location above the ground level. Most often, in the practical engineering considerations, only the ***thermal exergy***, which is the sum of the physical and chemical exergy, is taken into account. The chemical exergy is important particularly for fuels. The physical exergy is possessed by any substance, whose temperature and/or pressure deviate from the environmental conditions. Exergy was introduced as the function of any matter which could be either a substance, which has a rest mass larger than zero, or a field matter, for which the rest mass is zero; e.g. the matter of radiation field (photon gas), a field of surface tension, magnetic field, acoustic field or gravitational field.

Exergy analysis was already applied to many different processes [11], [12], [13]; however, still some processes were not analyzed based on the exergy. Examples of application of exergy to the thermal radiation problems are presented in [14] and [15]. Concluding, an energy analysis of the conversion process of energy, which conserves itself totally regardless of its quality, serves rather well for design calculations, whereas the exergy analysis, which takes into consideration the quality of energy and does not conserve itself, serves mostly for practical estimation and analysis of the process.

IV. CHARACTERISTIC OF EXERGY

Some important characteristics of exergy are described and illustrated:

• A system in complete equilibrium with its environment does not have any exergy. No difference appears in temperature, pressure, concentration, etc. so there is no driving force for any process.

• The exergy of a system increases the more it deviates from the environment. For instance, a specified quantity of hot water has higher exergy content during the winter than on a hot summer day. A block of ice carries little exergy in winter while it can have significant exergy in summer.

• When energy loses its quality, exergy is destroyed. Exergy is the part of energy which is useful and therefore has economic value and is worth managing carefully.

• Exergy by definition depends not just on the state of a system or flow, but also on the state of the environment.

• Exergy efficiencies are a measure of approach to ideality (or reversibility). This is not necessarily true for energy efficiencies, which are often misleading.

• Exergy can generally be considered a valuable resource. There are both energy or non-energy resources and exergy is observed to be a measure of value for both:

• Energy forms with high exergy contents are typically more valued and useful than energy forms with low exergy Fossil fuels, for instance, have high energy and energy contents. Waste heat at a near environmental condition, on the other hand, has little exergy, even though it may contain much energy, and thus is of limited value. Solar energy, which is thermal radiation emitted at the temperature of the sun (approximately 5800 K), contains much energy and exergy.

• A concentrated mineral deposit ‘contrasts’ with the environment and thus has exergy. This contrast and exergy increase with the concentration of the mineral. When the mineral is mined the exergy content of the mineral is retained, and if it is enriched or purified the exergy content increases. A poor quality mineral deposit contains less exergy and can accordingly be utilized only through a larger input of external exergy. Today this substitution of exergy often comes from exergy forms such as coal and oil. When a concentrated mineral is dispersed the exergy content is decreased [16].

V. DEAD STATE, SURRONDINGS, IMMEDIATE SURRONDING, ENVIROMENT

In an exergy analysis, the initial state is specified, and thus it is not a variable. The work output is maximized when the process between two specified states is executed in a reversible manner. Therefore, all the irreversibilities are disregarded in determining the work potential. Finally, the system must be in the dead state at the end of the process to maximize the work output. A system is said to be in the dead state when it is in thermodynamic equilibrium with the environment. At the dead state, a system is at the temperature and pressure of its environment (in thermal and mechanical equilibrium); it has no kinetic or potential energy relative to the environment (zero velocity and zero elevation above a reference level); and it does not react with the environment (chemically inert).

Also, there are no unbalanced magnetic, electrical, and surface tension effects between the system and its surroundings, if these are relevant to the situation at hand. The properties of a system at the dead state are denoted by subscript zero, for example, P0, T0, h0, u0, and s0. Unless specified otherwise, the dead-state temperature and Pressure are taken to be *T*0 _ 25°C (77°F) and *P*0 =1 atm (101.325 kPa or 14.7 psia). A system has zero exergy at the dead state. Distinction should be made between the surroundings, immediate surroundings, and the environment. By definition, surroundings are everything outside the system boundaries. The immediate surroundings refer to the portion of the surroundings that is affected by the process, and environment refers to the region beyond the immediate surroundings whose properties are not affected by the process at any point. Therefore, any irreversibility during a process occurs within the system and its immediate surroundings, and the environment is free of any irreversibilities. When analyzing the cooling of a hot baked potato in a room at 25°C, for example, the warm air that surrounds the potato is the immediate surroundings, and the remaining part of the room air at 25°C is the environment. Note that the temperature of the immediate surroundings changes from the temperature of the potato at the boundary to the environment temperature of 25°C [17].

VI. DIFFERENT FORMS OF EXERGY

A. Work Exergy

Because exergy is defined as the maximum work potential, the work transfer rate, $\dot{W}$ equivalent to the exergy transfer rate, $\dot{E}_{x,w}$, in every respect.

$$\dot{E}_{x,\,w} = \dot{W} - P_0 \frac{dv}{dt} \tag{1}$$

B. Heat Transfer Exergy

Assuming a uniform temperature distribution in a thermal energy reservoir, the exergy transfer rate, $\dot{E}_x$ connected with the heat transfer rate, *Q*, can be calculated by the following formula:

$$\dot{E}_{x,Q} = \dot{Q}\,(1 - \frac{T_0}{T}) \tag{2}$$

Where T_0 is the ambient temperature, which is set to 298 K (Szargut et al, 1988) and T is the heat source temperature.

C. Stream Flow in Steady State Exergy

Exergy transfer rate associated with material streams can be calculated with the following formula [18]:

$$E_x = E_x^{tm} + E_x^{ch} \tag{3}$$

$$\dot{E}_x^{tm} = \dot{E}_x^{ke} + \dot{E}_x^{p} + \dot{E}_x^{pe} \tag{4}$$

Where:

$\dot{E}_x^{ke} = \frac{1}{2} m V_0^2$ represents the kinetic exergy rate, where V_0 is the speed of the stream. Flow relative to the earth surface. $\dot{E}_x^{p} = \dot{m} g Z_0$ presents the potential exergy rate, where *g* is the earth gravity and Z_0 he stream altitude above the sea level. $\dot{E}_x^{pe}$ represents the thermo mechanical exergy based on the temperature and the pressure of the stream.

$\dot{E}_x^{ch}$ represents the chemical exergy based on the chemical potentials of the components in the stream. The specific exergy is written as:

$$e_x = e_x^k + e_x^p + e_x^{pe} + e^{ch} \tag{5}$$

Where $e_x = \dfrac{\dot{E}_x}{\dot{m}}$ (6)

$\dot{m}$ is the mass flow rate of the stream.

D. Physical Exergy

Physical exergy, known also as thermo mechanical exergy, is the work obtainable by taking the substance through reversible process from its initial state (T, P) to the state of the environment (T0, P0). The specific physical exergy is written as:

$$e_x = h - h_0 - T_0 (s - s_0) \tag{7}$$

For a perfect gas with a constant c_p

$$e_{x,flow,g} = C_p T_0 (\frac{T_1}{T_0} - 1 - \ln\frac{T_1}{T_0}) + R T_0 \ln\frac{P_1}{P_0} \tag{8}$$

For solids and liquids when assuming a constant specific heat c:

$$e_x^{ph} = c\left[\left(T - T_0\right) - T_0 \ln\left(\frac{T}{T_0}\right)\right] - \upsilon_m (p - p_0) \tag{9}$$

Where υ_m is the specific volume, determined at temperature T_0.

E. Chemical Exergy

Chemical exergy is equal to the maximum amount of work obtainable when the' substance under consideration is brought from the environmental state (T0, P0) to the dead state ($T0,\ P0, \mu_{i0}$) by processes involving heat transfer and exchange of substances only with the environment The specific chemical exergy e_x^{ch} at P0 can be calculated by bringing the pure component in chemical equilibrium with the environment. For pure reference components, which also exist in the environment, the chemical exergy consist of the exergy, which can be obtained by diffusing the components to their reference concentration P00. The specific molar chemical exergy of a reference component i is:

$$\dot{E}_x^{ch} = \sum n_i(\mu_{io} - \mu_i^e) \tag{10}$$

When a substance does not exist in the reference environment, it must first react to reference substances in order to get in equilibrium with the environment. The reaction exergy at reference conditions equals the standard Gibbs energy change. So the overall specific chemical exergy term becomes:[19]

$$\mu_{i0} = \bar{g}_i(T_0, p_0) + \bar{R}T_0 \ln y_{i\,j} \tag{11}$$

$$\mu_i^e = \bar{g}_i(T_0, p_0) + \bar{R}T_0 \ln y_i^e \tag{12}$$

The chemical exergy of a gaseous mixture or a mixture of ideal liquids is given by:

$$\bar{e}_x^{ch} = \bar{R}T_0 \sum_{i=1}^{j} y_i \ln \frac{y_i}{y_i^e} \tag{13}$$

The chemical exergy of real solutions can be computed from:

$$\bar{e}_x^{ch} = \sum_{i=1}^{j} y_i \bar{e}_i^{ch} + \bar{R}T_0 \sum_{i=1}^{j} y_i \ln y_{i\ I} \tag{14}$$

The chemical exergies of gaseous fuels are computed from the stoichiometric combustion chemical reactions. The standard chemical exergies of various fuels are published in the [20].

For many fuels, the chemical exergy can be estimated on the basis of the Lower Heating value LHV. The relation between the LHV and the chemical exergy is where can be calculated with formulas C_aH_b based on the atomic composition.

When C_aH_b is gas

$$\frac{\bar{e}_x^{ch}}{LHV} \cong 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \tag{15}$$

When C_aH_b is liquid

$$\frac{\bar{e}_x^{ch}}{LHV} \cong 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \tag{16}$$

TABLE 1: LOWER HEATING VALUE (LHV), HIGHERT HEATING VALUE (HHV), GIBS ENERGY DIFFRENCE AND CHIMICAL EXERGY FUELS AT (T_0=25 ^{0}C, P0=1atm) [19]

Fuel (Phase)	**LHV** (KJ/mol)	**HHV** (KJ/mol)	$(-\Delta G)$ (KJ/mol)	$\bar{e}_x^{ch}$ (K J/mol)
Hydrogen (g)	241.8	285.9	237.2	235.2
Carbon (s)	393.5	393.5	394.4	410.5
Paraffin Family, C_nH_{2n+2}				
Methane (g)	802.3	890.4	818	830.2
Ethane (g)	1427.9	1559.9	1467.5	1493.9
Propane (g)	2044	2220	2108.4	2149
Butane (g)	2658.5	2878.5	2747.8	2802.5
Pentane (g)	3272.1	3536.1	3386.9	3455.8
Pentane (l)	3245.5	3509.5	3385.8	3454.8
Hextane (g)	3886.7	4194.8	4026.8	4110
Hextane (l)	3855.1	4163.1	4022.8	4106
Heptane (g)	4501.4	4858.5	4667	4764.3
Heptane (l)	4464.9	4816.9	4660	4757.3
Octane (g)	5116.2	5512.2	5307.1	5418.6
Octane (l)	5074.6	5470.7	5297.2	5408.7
Olefin Family, C_nH_{2n}				
Ethalene (g)	1323	14.11	1331.3	1359.6
Propylene (g)	1926.5	2058.5	1957.3	1999.9
Butene (g)	2542.6	2718.6	2598.3	2655.1
Pentene (g)	3155.8	3375.9	3236.5	3307.4
Naphthene Family, C_nH_{2n}				
Cyclopentane (g)	3099.5	3319.5	3196.5	3267.4
Cyclopentane (l)	3053.6	3273.6	3189.6	3260.5
Cycloxehtane (g)	3688.9	3953	3821.2	3906.3
Cycloxehtane (l)	3655.9	3919.9	3816.2	3909.9
Aromatic Family, C_nH_{2n-6}				
Benzene (g)	3169.5	3301.6	3207.5	3298.5
Toluene (g)	3772	3948	3831.7	3936.9
Toluene (l)	3771	3947	3834	3939.2
Ethylbenzene (g)	4387.1	4607.1	4471.6	4591

VII. CONCLUSION

In this paper the concept of exergy and its characteristic and application in various fields has been discussed. And different forms of exergy have been derived. Also a brief comparison between energy and exergy analysis has been done. The search shows that Exergy get us better understanding of energy availability for doing work. Exergy is a useful concept that could use for analysis different kind of industry. For optimization and improvement industries efficiency exergy analysis has more effort than energy analysis.

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