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Olexan: A Tool for Online Exergy Analysis

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Abstract

Exergy analysis is important and has been widely used to evaluate the thermodynamic efficiency of a variety of processes. Therefore, there is a need to develop a tool for monitoring exergy of a process in real-time and for studying the effects of various feed, equipment, process and environmental changes. The ultimate aim of this work is to develop a tool to enable dynamic and online exergy analysis in an interactive manner at various levels of equipment, process, and plant. However, in this paper, we develop methods for the online analysis of exergy in various units of a base-load liquefied natural gas (LNG) process.

Keywords: exergy, monitoring, LNG, energy efficiency

1. Introduction

Energy is an issue of ever-increasing concern globally due to the rising costs of fossil fuels and their adverse impact on the environment. Processes that conserve energy are of key consideration today and will be more so in future. Most chemical plants are energy-intensive, as they need various forms and significant amounts of energy. This is especially true for a plant that liquefies natural gas to produce LNG, because it requires refrigeration and thus compression, which is highly energy-intensive.

A process analysis based on mass and energy balances alone only shows the energy flows and does not give insight into how the quality of energy degrades through the process (lost work). This loss in energy quality is considered in the second law of thermodynamics or entropy balance. As we know, entropy is not conserved; an entropy balance can involve an entropy-generation term that arises from the irreversibilities in a process.

Although entropy-generation term is a fundamental quantity, it is of limited practical use because of the difficulty in interpreting the significance of its magnitude. Since the entropy-generation term is unable to describe comprehensively the degradation of energy quality, a more suitable measure is the lost work due to irreversibility, which can be obtained by multiplying the entropy-generation term by T_0. In other words, more practical surrogates of entropy balance and entropy-generation term are exergy analysis and exergy respectively. This is analogous to using a substitute property (e.g. fugacity) instead of a fundamental thermodynamic quantity (e.g. chemical potential) [1].

The thermodynamic measure of energy quality is the availability. The term *exergy* (from the Greek ex = out and erg = work), coined by Rant (1956), is also used for availability. Although exergy analysis is useful in evaluating chemical processes, even the most widely used commercial process simulators such as Aspen-Plus or HYSYS do not do exergy analyses. While exergy (or availability) function itself is a standard stream property in Aspen-Plus, performing exergy analysis of a process at various equipment and process levels is not direct or straightforward.

In this work, we present a general tool "On-Line EXregy Analysis (Olexan)" for performing exergy analysis at various levels of a given process using online or offline data. It computes and displays various thermodynamic measures of energy effectiveness of the process such as second law efficiency, exergy effectiveness, exergy improvement potentials, irreversibilities (exergy losses), etc. While our focus is on monitoring and energy analysis of an existing LNG plant, the tool is designed to be applicable to and useful for any chemical process. We selected LNG process, because the available work [2] on the exergy analysis of an LNG plant is largely based on off-line simulations or limited to small-scale plants [3]. To our knowledge, an exergy analysis of large-scale existing LNG plants is unaddressed. Energy accounts for about 40% of the total operating cost of LNG production. The expected theoretical thermodynamic efficiency of liquefaction cycles in such plants is reported to be 42-45% [2, 4].

2. Background

A typical LNG plant (Fig. 1) has several sections: acid gas removal and dehydration/ Mercaptan removal for pretreatment; precooling and liquefaction, fractionation for removal of heavy hydrocarbons such as C_2, C_3, C_4, and nitrogen rejection. The pre-cooling and liquefaction part commonly uses two refrigeration cycles, namely the propane pre-cooled cycle (PPC) and the mixed refrigerant cycle (MRC). Evaporation and cooling occur in the main heat exchanger which is the key element of the MRC. PPC provides chilling for the feed, the MR system, and the fractionation unit. In addition, an LNG plant typically uses distillation columns, compressors, coolers, condensers, expanders or valves, separation drums, evaporators, pumps, etc. [5].

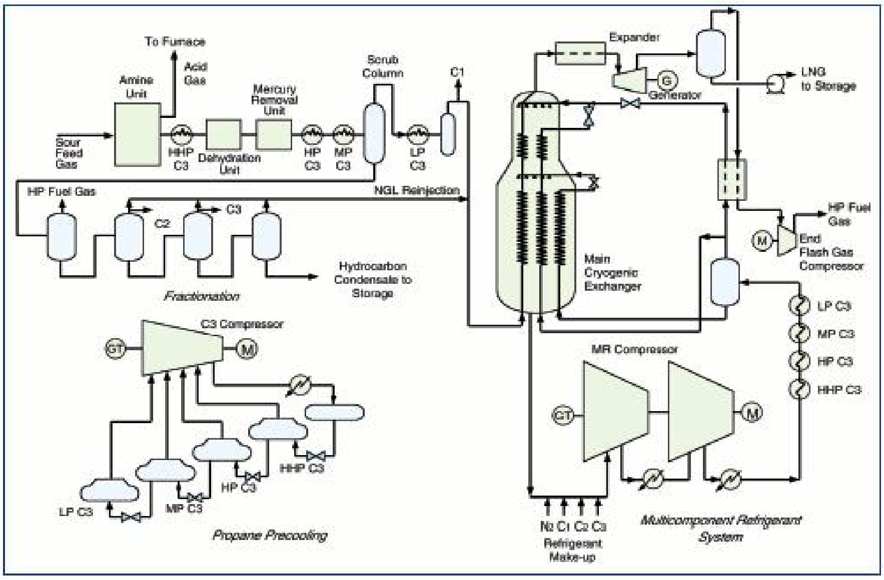

Fig. 1. A typical APCI propane precooled mixed refrigerant process (Source: LNG Technology Selection. Hydrocarbon Engineering Feb 2004 edition)

2.1 Exergy and Its Measures

The availability is a measure of the maximum amount of useful energy that can be extracted, when a matter is brought to equilibrium with its surroundings. It can be of four types: kinetic, potential, physical, and chemical. However, the first two types are usually neglected and chemical exergy is zero in the absence of reactions. Therefore, the most widely used form is physical exergy, which can be computed in terms of:

$$A(T,P) = B(T,P) - B(T_0,P_0) \tag{1a}$$

$$B(T,P) = H(T,P) - T_0 S(T,P) \tag{1b}$$

where, A is availability or exergy, B is availability or exergy function, T and P refer to process stream, and (T_0, P_0) refer to the surrounding. The availability balance derived from the first and second laws of thermodynamics gives us the lost work due to irreversibility for a steady-state flow process as follows:

$$LW = T_0\,(\text{Entropy-generation}) = \sum (mB)_{in} - \sum (mB)_{out} + \sum W_{in} - \sum W_{out} + \sum [Q(1-\frac{T_0}{T})]_{in} - \sum [Q(1-\frac{T_0}{T})]_{out} \tag{2}$$

where, B is the exergy function, T is the uniform temperature at the control surface, Q and W are the heat and work flows. Note that an average temperature is used whenever T is not constant. Work is pure energy and thus its exergy flows are the same as energy flows. The last two terms in eq. 2 are called thermal exergy (*EXQ*).

Several energy/exergy efficiencies are used in practice to analyze the thermodynamic performance of a system or unit. Exergy effectiveness is defined as the capacity of a unit/system to produce the desired effect (power or cooling for example). It is defined as follows:

$$\varepsilon = \frac{Ex_{np}}{Ex_{ns}} = 1 - \frac{LW}{Ex_{ns}} \tag{3}$$

where, Ex_{np} and Ex_{ns} respectively are the net exergy produced and supplied. An exergy analysis would be incomplete, if we do not compute the potential for improving the efficiency or effectiveness of a process. This potential can be obtained by the following expression:

$$Pot = LW(1-\varepsilon) \tag{4}$$

3. Methodology

From eq. 2, we see that lost work can be computed from either entropy balance or exergy balance. In our methodology, we use the latter. We now simplify eq. 2 for different categories of equipment in the LNG plant as follows.

Generally for heat exchangers, evaporators, and condensers we are dealing with temperature distributed heat loads. Therefore, it is not easy to calculate Q and T and the thermal exergies consequently. We can avoid calculating distributed heat loads, if we consider both cooling and heating streams (inputs and outputs) and calculate exergy paid and exergy gained and the difference is loss. Thus, the lost work for this category of equipment is given by:

$$LW = \sum (mB)_{in} - \sum (mB)_{out} \tag{5}$$

Considering the hot stream as the source of availability, eq. 3 becomes:

$$\varepsilon = \frac{m_c\,(B_{out} - B_{in})_c}{m_h\,(B_{in} - B_{out})_h} \tag{6}$$

For compressors and turbines, work can be obtained from energy balance (or enthalpy balance for adiabatic cases). If the process is not adiabatic, we would define the system to include the equipment and its surrounding air that are at a different temperature than T_0, so that the system boundary passes through the atmosphere at T_0 , then EXQ = 0 because $T = T_0$ at the boundary point crossed by Q_0. The lost work is given by:

$$LW = \sum (mB)_{in} - \sum (mB)_{out} + \sum W_{in} - \sum W_{out} \tag{7}$$

and the exergy effectiveness is given by:

$$\varepsilon_C = \frac{m(B_{in} - B_{out})}{W_{in}} \;\; \& \;\; \varepsilon_T = \frac{W_{out}}{m(B_{in} - B_{out})} \tag{8a,b}$$

For separation drums and throttle valves, we have stream-carried exergies only and eq. 2 simplifies to:

$$LW = \sum (mB)_{in} - \sum (mB)_{out} \tag{9}$$

For throttle valves, since $H_{in} = H_{out}$, eq. 2 reduces to:

$$LW = mT_0(S_{out} - S_{in}) \tag{10}$$

Throttle valves typically serve other units, hence we include them as integral parts of other units for exergy analysis.

4. Overview of Olexan

Olexan is written using Visual Basic Application (VBA). It allows the user to develop a process flow diagram (PFD) of his/her process interactively by means of an object palette of common processing equipment. It can interface with the plant online data system to gather the required stream data. When such data are missing, it allows the user to specify data. In many cases, it can also interface with a process simulator to compute the missing data based on the available data. Once the required stream conditions are known, the tool interfaces with a process simulator to get properties such as enthalpy, entropy, etc. and computes exergy function for a given T_0. Based on these computations, it can then perform exregy and efficiency analyses for various parts of the process and display the results (e.g. irreversibility) in forms of charts, tables, and numbers.

Olexan uses panel windows to display information such as exergy function, lost work, exergy efficiency, energy efficiency, and relevant properties for streams and equipment.

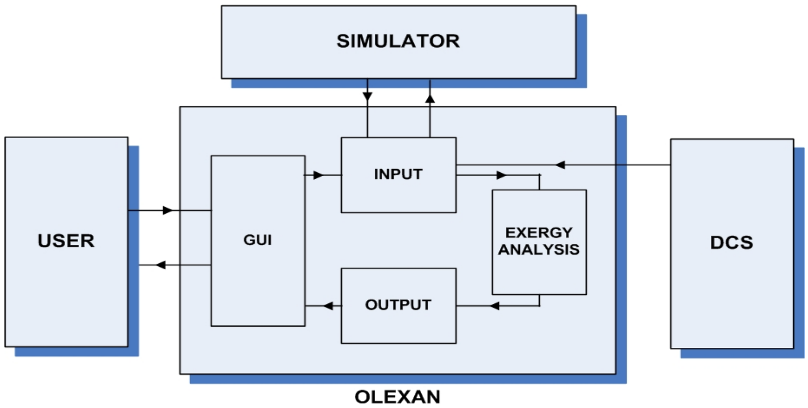

Fig. 2. Schematic of Olexan

5. Future work

A framework for online exergy analysis and interactive interpretation and visualization of the analysis results has been presented. The tool is still under development and implementation. We plan to test this tool to evaluate an existing LNG process, using both online and offline data. This tool can be used for what-if studies as well. One can also use it to evaluate the plant performance at different operating conditions by varying the process parameters such as ambient temperature, feed gas pressure and composition, refrigerant composition, process disruptions, refrigerant cycle compression pressures, flowrates, etc.

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