



# Development and use of exergy efficiency for complex cryogenic processes

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## ABSTRACT

In this paper, exergy efficiencies, which are effective performance parameters for cryogenic processes, are categorized based on their exergy decomposition levels. However, the existing efficiencies are not standardized for a variety of unit operations. Thus, the extension of the exergy transfer effectiveness (*ETE*) has been suggested with a general mathematical expression. The extended *ETE* is defined by decomposing both thermo-mechanical and chemical exergy to the chemical component level. A case study with a complex natural gas liquefaction process and its optimization has also been performed. The results indicate that the extended *ETE* brings consistent and accurate results for all types of units, also properly reflecting the changes in process performance after optimization. Other efficiencies, however, struggle to measure the performance improvement for some equipment, even showing decreases in their efficiency values.

## 1. Introduction

With the current focus on global warming and use of fossil fuels, energy efficiency is an important performance measure in industrial plants. As a post-design tool, energy efficiency has been applied to various energy systems in order to evaluate and compare them, thus finding opportunities to improve the processes. Such definitions of energy efficiency are case-dependent based on the characteristics of a process, which means a general mathematical expression for energy efficiency does not exist [1]. This may bring misinterpretations into the definitions of energy efficiency and produce inconsistent results even for the same system. Thus, there is a need for an objective performance parameter for energy conversion efficiency. Another limitation of using energy efficiency is that it does not take energy quality into account when measuring process performance. Different energy forms have different qualities, for example, the value of heat cannot be directly compared with the value of power because the energy quality of the heat will vary, depending on the temperature level. In the case of refrigeration processes where work is transformed into a cooling duty, there is no proper definition for energy efficiency [2]. Instead, a coefficient of performance is used, which unfortunately gives equal values to heat and power.

Unlike energy analysis, exergy accounts for both quantity and quality of various energy forms, which is why exergy has been recommended as a measure of system performance [3]. Due to the characteristics of entropy generation below ambient temperature, exergy efficiency is a good performance indicator, especially for low

temperature processes in a post-design phase. Regarding liquefied natural gas (LNG), specific power consumption per produced amount of LNG is widely used to evaluate the performance of liquefiers, since there is no proper energy efficiency definition for such processes. However, this value does not consider the cold energy of the produced LNG. The LNG generally contains a significant amount of cold exergy (around 1000 kJ/kg), and this exergy is utilized in many LNG terminals [4]. Thus, the cold energy of the produced LNG has to be included when measuring the performance of the liquefaction process. In addition, the specific power consumption will depend on local environmental conditions (i.e. climate). An LNG plant located in a warm climate region will always show a larger power consumption than one in cold climate, even when they have exactly the same processing system. In contrast, exergy can represent various energy forms in one standard (i.e. heat, work and power), while considering the effect of the environment conditions, particularly temperature and pressure. Therefore, exergy efficiency would be a good candidate to measure the performance of processes in order to have an objective and consistent analysis.

Such an exergy efficiency can be formulated in various ways, but tends to fall into two main categories [1]. One is the input-output efficiency, which is the ratio between the exergy leaving and entering the system. The input-output efficiency is defined by a simple formulation and applicable to any types of processes, thus widely used [5]. Yet, this efficiency definition may not be ideal for process evaluation and comparison [5–9]. The input-output efficiency may show only a marginal difference with changes in process performance, since it is not focusing on the task of a process. Thus, there have been various suggestions for

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Nomenclature		$\eta$	exergy efficiency [%]
<i>Roman letters</i>		<i>Subscripts and superscripts</i>	
ASU	air separation unit	0	ambient conditions
CBC	component by component exergy efficiency [%]	Ch	chemical exergy
CEE	coefficient of exergy efficiency [%]	Chem	standard chemical exergy
CMR	cold mixed refrigerant	Conc	concentrational exergy
DMR	dual mixed refrigerant	cons	consumed
$\dot{E}$	exergy rate [kW]	Consumed-produced	consumed-produced type exergy efficiency
$\bar{e}$	molar exergy [kJ/kmol]	D	exergy destruction
ETE	exergy transfer effectiveness [%]	i	chemical component
EX	set of exergy components	in	inlet
$\dot{H}$	enthalpy rate [kW]	in-out	input-output exergy efficiency
I	set of inlet streams	j	inlet stream
L	liquid stream	k	outlet stream
LMTD	log mean temperature difference [K]	l	chemical component
LNG	liquefied natural gas	m	exergy component
M	two-phase stream	mixture	multi-component stream
$\dot{n}$	molar flow rate [kmol/s]	net	net work
O	set of outlet streams	out	outlet
$p$	pressure [bar]	p	pressure based exergy
$\dot{Q}$	Heat rate [kW]	prod	produced
R	universal gas constant [8.314 kJ/kmol K]	pure	pure component
SQP	sequential quadratic programming	Q	exergy of heat
$\dot{S}$	entropy rate [kW/K]	Reac	reactional exergy
$T$	temperature [K]	T	temperature based exergy
V	vapor stream	TM	thermo-mechanical exergy
WMR	warm mixed refrigerant	Total	total exergy of a stream
$x$	mole fraction [-]	tr	transit exergy
Z	set of chemical components	W	work exergy
<i>Greek letters</i>			
$\Delta p$	pressure drop [bar]		

exergy efficiency, considering the purpose of a system [8,10–13]. These are called the consumed-produced or task efficiencies, which is the second category of exergy efficiency. The consumed-produced efficiency describes what is consumed to deliver a specific or targeted product from a process.

Nevertheless, it is difficult to determine which efficiency definition is the right one to use due to their inconsistent results for a typical process. Several definitions of the consumed-produced efficiency suggested in the literature do not contain general mathematical expressions, thus causing room for different interpretations [14]. This has resulted in different definitions of exergy efficiency for the same system, from small units to large systems such as Joule Thomson valves, gas expanders, air separation units (ASUs), LNG processes and processes for offshore platforms [2,5,15–22]. Thus, there have been attempts to develop more generalized task efficiencies by removing so-called transit exergy from consideration, which is defined as the amount of exergy that is preserved across a system [13]. However, this definition requires a high calculation effort. Zanchini also formulated an exergy efficiency that can generalize some of the task efficiencies, while being applicable for both flowing and non-flowing systems [17]. Nguyen et al. suggested an efficiency for offshore platforms, which can cover various processes with decomposition of exergy to the chemical component level [9]. None of the efficiencies mentioned above have explicit definitions for cases where processes operate across or below ambient temperature.

Thus, a new general exergy efficiency, the Exergetic Transfer Effectiveness (ETE) was developed to handle all operating conditions with less computational effort by defining exergy sources and sinks as consumed and produced exergy [23]. The ETE also allows

encapsulating the actual transfer of exergy in a process, indicating the purpose of the system. Such careful definition is achieved by focusing on the effect of temperature and pressure changes, and by decomposing exergy into different forms.

However, the use of the ETE has so far been limited to processes without chemical reactions or compositional changes, simply because the decomposition of exergy forms to identify sources and sinks had not been developed to include chemical exergy. Thus, this paper extends the ETE by including chemical exergy to cover all types of processes at all operating conditions with a general mathematical expression. The extended ETE and other consumed-produced efficiencies are then thoroughly classified and compared, indicating the characteristics of the efficiency definitions. This paper also compares the ETE with the input-output efficiency and selected task efficiencies, where generalized formulas have been suggested. The comparison is conducted by applying them to a natural gas liquefaction process referred to as the dual mixed refrigerant (DMR) process. The DMR process is a good candidate to study the capability of exergy efficiencies to manage changes in temperature, pressure and chemical composition. This comparison of exergy efficiencies will provide guidance about a proper choice of exergy efficiency based on their characteristics (classification). The mathematical optimization of the DMR process is also performed to evaluate exergy efficiencies for the optimal operating conditions. Although exergy efficiency is a post design tool to measure the improvement of systems, the comparison of the efficiency values for the initial and the optimal operating conditions have not been made in previous literature. Thus, this paper conducts the comparison in order to evaluate the performance of exergy efficiencies whether they

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