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An exergy–cost–energy–mass analysis of a hybrid copper–chlorine thermochemical cycle for hydrogen production

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ABSTRACT

An exergoeconomic assessment using exergy–cost–energy–mass (EXCEM) analysis is reported of a copper–chlorine (Cu–Cl) thermochemical water splitting cycle for hydrogen production. The quantitative relation is identified between capital costs and thermodynamic losses for devices in the cycle. A correlation detected in previous assessments, suggesting that devices in energy systems are configured so as to achieve an overall optimal design by appropriately balancing thermodynamic (exergy-based) and economic characteristics of the overall system and its components, is observed to apply for the Cu–Cl cycle. Exergetic cost allocations and various exergoeconomic performance parameters are determined for the overall cycle and its components. The results are expected to assist ongoing efforts to increase the economic viability and to reduce product costs of potential commercial versions of this process. The impacts of these results are anticipated to be significant since thermochemical water splitting with a copper–chlorine cycle is a promising process that could be linked with nuclear reactors to produce hydrogen with no greenhouse gases emissions, and thereby help mitigate numerous energy and environment concerns.

1. Introduction

The rapid growth in worldwide population, technology advancement and demand for energy resources, combined with increasing greenhouse gas emissions and diminishing fossil fuel reserves, has increased the need to improve the efficiency of energy utilization and to develop environmentally benign energy resources. One of the more promising alternative energy carriers for the transportation energy sector is hydrogen, which has the potential to reduce CO_2 and other greenhouse gases emissions and the dependence on fossil fuels, and to prepare society for diminishing oil reserves. Nuclear energy is a candidate to supply the energy needed for extracting the hydrogen from water or other molecules while avoiding concerns related to greenhouse gas emissions.

Thermochemical water splitting with a copper–chlorine (Cu–Cl) cycle is a promising process that could be linked with nuclear reactors to decompose water into its constituents, oxygen and hydrogen, through intermediate copper and chlorine compounds. The cycle consists of five main steps, in each of which a reaction takes place. Heat is transferred between various endothermic and exothermic reactions in the Cu–Cl cycle, through heat exchangers that supply or recover heat from individual processes.

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Although technical studies of the Cu–Cl cycle have been reported, there is a need to understand the potential economics of the cycle, to facilitate eventual commercialisation. But such economic assessments are lacking, especially utilizing advanced tools like exergy.

Exergy is defined as the maximum work that can be produced by a stream or system in a specified environment. Exergy is a quantitative measure of the ''quality'' or ''usefulness'' of an amount of energy. When energy quality decreases, exergy is destroyed. From the viewpoint of exergy, maximum efficiency is attained for a process in which exergy is conserved. Efficiencies determined using ratios of exergy provide a measure of ''an approach to an ideal.'' Efficiencies determined using energy are often misleading because, in general, they are not measures of an approach to an ideal. Exergy analysis accounts for energy quality and irreversibilities, and provides more meaningful and useful information than energy analysis about efficiency and losses. Exergy destruction can be used as the basis for the formulation of a theory of ''cost'' because it clearly relates the idea that to produce any output, some resources have to be ''consumed.'' Exergy is the ''part'' of energy that is useful to society and has economic value.

In this paper, an exergoeconomic assessment of the copper–chlorine cycle using EXCEM (exergy, cost, energy and mass) analysis is described. Exergoeconomic analysis combines thermodynamic analysis based on the first and second laws with principles of economics, mostly cost accounting. The objective is to reduce product costs and to increase the economic viability of the process. In the study, the relations between exergy loss and capital cost and those between exergy and environmental impact are investigated. The relation between exergy and cost is demonstrated using plots of exergy loss as a function of cost generation. The applicability of a previously identified correlation, which suggests devices in energy systems are configured so as to achieve an overall optimal design, by appropriately balancing the thermodynamic (exergy-based) and economic characteristics of the overall system and its components, is investigated for the Cu–Cl cycle. Exergetic cost allocations and various exergoeconomic performance parameters are determined for the overall cycle and its components.

2. Exergy-based economics

A design engineer often strives for high efficiency and low cost under prevailing conditions (technological, economic, legal, ethical, environmental, social, etc.). The merit of a system or process has conventionally been based on parameters like performance, efficiency, economics and safety. Concerns like environmental impact and resource scarcity have recently made the evaluation of merit more complex. Designing efficient and cost effective systems, which also meet environmental requirements, is a significant challenge for engineers. Given the world's finite natural resources and growing energy demands, it is increasingly important to understand energy and resource degradation and to improve systems while reducing environmental impact.

The selection of energy sources for industrial and other uses is primarily governed by prices. Sometimes energy conversion systems are shown to be uneconomic over the long term and prices become inadequate for planning. For example, problems can occur when prices are set based on near-term political assessments or insufficient knowledge of the resource and the consequences of its use. It is therefore important to set prices using appropriate methods, and enhanced approaches have been sought.

One alternative method, ''thermoeconomics,'' combines economic and thermodynamic methods. In this approach, efficiencies are calculated via exergy analysis, and ''non-energetic expenditures'' (financial, labour and environmental remediation) are explicitly related to the technical and thermodynamic parameters of the process under consideration. Corresponding optimization activities determine the final design point and operating schedule that minimize the overall monetary costs under a proper set of financial, environmental, technical and other constraints.

A comprehensive methodology for the analysis of systems and processes was developed by Rosen et al. [1]. The methodology is based on the quantities exergy, cost, energy and mass, and is referred to as EXCEM analysis. Excluding the zeroth and third laws of thermodynamics, thermodynamics can be defined from a broad perspective as the science of energy and exergy. These terms involve a number of concepts such as temperature, pressure, enthalpy, heat, work, energy and entropy. The first law of thermodynamics embodies energy analysis, which identifies only external energy wastes and losses. Potential improvements for the effective use of resources are not consistently evaluated with energy, e.g. for an adiabatic throttling process. However, the second law of thermodynamics, which can be formulated in terms of exergy, takes entropy into consideration and accounts for irreversibilities.

Although exergy has received the least attention of the EXCEM components, it is often considered the most important. In combination with economics (both macro and micro), exergy provides a powerful tool for the systematic study and optimization of systems. Exergy is a useful tool for engineers and offers unique insights into the nature, cause and location of losses and possible improvements. Exergy has also been linked with environmental tools. For instance, exergy-based life cycle analysis has been proposed as more advantageous than conventional methods for improving environmental conditions. Exergy is also useful in economics. Exergy offers a means in macroeconomics to reduce resource depletion and environmental destruction, e.g. via an exergy tax. In microeconomics, exergy has been combined beneficially with cost-benefit analysis to improve designs. By minimizing life cycle costs, the most beneficial system under given prevailing economic conditions is obtained by reducing exergy losses and environmental effects.

Exergy is thus applicable not only to efficiency studies but also to cost accounting and economic assessments. Exergy provides a rational basis for evaluating fuels and resources, efficiencies, dissipations, value and costs. Costs should reflect value. Since value is not generally associated with energy but with exergy, costing based on energy can be inappropriate, often leading to difficulties. Exergy-based cost accounting can