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Diagnosis of an alternative ammonia process technology to reduce exergy losses

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ABSTRACT

Ammonia production through more efficient technologies can be achieved using exergy analysis. Ammonia production is one of the most important but also one of most energy consuming processes in the chemical industry. Based on a panel of solutions previously developed, this study helps to identify potential areas of improvement using an exergy analysis that covers all aspects of conventional ammonia synthesis and separation. The total internal and external exergy losses are calculated as 3,152 and 6,364 kJ/kg, respectively. The process is then divided into five main functional blocks based on their exergy losses. The reforming block contains the largest exergy loss (3,098 kJ/kg) and thus the largest potential for improvement including preheating cold feed through an economizer, developing technology towards isobaric mixing, and pressure drop reduction in the secondary reformer as the main contributors to the irreversibility (1,302 kJ/kg) in this block. The second largest exergy loss resides in the ammonia synthesis block (3,075 kJ/kg) where solutions such as reduced temperature rise across the compressor, proper compressor isolation, reducing undesired components such as argon in the reactor feed, and using lower temperatures for reactor outlet streams, are proposed to decrease the exergy losses. Throttling process in the syngas separator is the key contributing mechanism for the irreversibility (1,635 kJ/kg exergy losses) in the gas upgrading block. The exergy losses in the residual ammonia removal block (833 kJ/kg exergy losses) are mainly due to the stripper and the absorber column where a modified column design might be helpful. The highest exergy loss in the preheating block belongs to the compressors (518 kJ/kg exergy losses) where a lower inlet temperature and better system isolation could help to reduce losses.

1. Introduction

Conventional ammonia production process was reported as one of the lowest exergy-efficient processes in the list published by the Department of Energy's (DOE's) Industrial Technologies Program (ITP) "Chemical Bandwidth Study" [1]. As a result, the final report prepared for the DOE suggested to retrofit the ammonia production flowsheet to enhance the process efficiency [2]. However, even the revamped process flowsheet displays relatively high exergy losses. Thus, this paper presents a further study on the revamped process flowsheet in order to identify possible further process improvements and eventually to pave the way for sustainable production of ammonia.

As the demand for more sustainable processes increases, improving the energy efficiency of existing processes is considered more frequently. One of the main tools that helps to identify if a process is sustainable enough or further improvements are required is the exergy analysis and this has been already used for some chemical processes. These include petroleum separation processes used in offshore platforms [3], methanol production from the sewage sludge process [4], the conventional textile washing process [5], a sulfide-pulp preparation process in the pulp and paper industry [6], jatropha curcas oil extraction processes [7], chemical looping with oxygen uncoupling process [8], the hybrid molten carbonate fuel cell power plant, and a carbon dioxide capturing process [9]. Through all these examples, exergy analysis was shown to be an efficient tool to evaluate the sustainability of a process [10].

Unlike energy, exergy is not subject to a conservation law except for reversible processes. Rather, exergy is consumed or destroyed due to irreversibilities in any real process. Therefore, the higher the exergy losses the more is the irreversibility of the process. The exergy consumption during a process is proportional to the entropy created. Exergy measures both the quality and quantity of the energy involved in transformations within a

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system. Thus, exergy analysis, also called "*lost work analysis*" [11] can be a helpful tool in the evaluation of the energy efficiency of a process. With exergy analysis, it is possible to quantify the exergy losses in each process step, to identify units that can be improved and, and finally to compare different process configurations from an efficiency point of view. Exergy analysis could also be used in an early stage in the development of new processes [12] to make sure that the process is inherently efficient.

As shown in the literature, one needs to deal with all types of exergy and to calculate the exergy of all the material, heat and work streams in a process and utilities [21] before coming up with an exergy balance. To facilitate this step of exergy analysis, some tools have been integrated within the process simulators [22–26]; which were then applied in a number of case studies such as water–gas-shift reactors [27] and coal power plant [28]. Although such computer-aided calculations make the analysis more accessible, exergy analysis within the process simulators is not still straightforward [21]. Most of these case studies do not follow a systematic methodology which limits their applicability to other processes. This is despite the fact that that some comprehensive exergy analysis methodologies have been developed in the literature, a couple of which are given below.

One of the first methodologies developed is, the "*approach of tackle the biggest avoidable loss first*". This methodology in its original form requires the exergy losses (both external and internal) to be calculated before visualizing the possible process improvements [29–32] and make in necessary to propose improvements based on the highlighted largest avoidable loss only. This approach was later modified by applying a new classification of exergy losses, so that a new presentation of exergy analysis results can be provided to set targets [33]. As this approach divides the exergy losses into avoidable and inevitable, it can consider the economic and technical constraints imposed on each unit operation. Later, a dimensionless parameter was introduced as the ratio of exergy consumption over the total fuel exergy input in order to quantify the overall efficiency of each process [34].

The "*exergy load distribution*" is another methodology developed, although this is not widely used in the literature. The methodology is based on the idea that there is a simple relationship between local and overall efficiencies [35]. The "exergy load distribution" method was then broadened to synthesize the alternative process structures in a study by Sorin et al. [36]. This study combined a reducible superstructure, and "exergy load distribution" analysis to develop a new procedure for process synthesis.

These two general classes of methodologies have been already applied to the ammonia production process, where it has been proved that exergy analysis can be used as a tool to evaluate the efficiency and sustainability of the process. Exergy analysis of Texaco synthetic ammonia system [13], energy-integrated and non-integrated ammonia plants [14], a synthetic ammonia converting process including waste heat recovery equipment [15], an industrial ammonia production plant [16], an ammonia synthesis reactor in a solar thermochemical power system [17], and conventional systems [18,19] were among the examples which were used to demonstrate the applicability of such approaches.

However, one of the main shortcomings of the previous studies is that although they have just identified the unit operations that were mainly responsible for the exergy losses, they did not go until proposing practical ways to reduce the losses. In other words, most of the current studies do not provide a comprehensive approach starting from the diagnosis of the process according to the exergetic criteria and resulting in a set of modification and improvement proposals. Moreover, the described methodologies have not been implemented in commercial process simulators that can promote their widespread use. These limitations can cause serious issues when a more rigorous approach is required; for example, when an industrial process comprises of several blocks each possessing different process constraints [21].

This would mean that although exergy analysis by definition aims to serve as a tool for conceptual process design, the current methodologies do not give a real engineering approach towards achieving this objective. To overcome the main limitations of existing approaches which can then promote a more widespread use of exergy analysis, a novel general methodology [20] was developed. This methodology provides an exergy balance integrated in a process simulator which is then used to propose specific process improvement on each class of unit operations based on both all the exergy losses sources [37] and the existing numerous relevant publications [38–43].

The current study aims at performing exergy analysis on the ammonia production process based on the panel of solutions proposed in this general methodology [20] mentioned above. This means that in contrast with the existing exergy analyses of ammonia processes, this study therefore does not only find the worst unit operations through exergy analysis as the major scope for improvement, but it also proposes practical ways to improve them based on their major sources of irreversibilities. Although some of these improvements can be identified by competent ammonia process developers, we applied a developed panel of solutions [20] to move towards a systematic exergy analysis for finding ways to improve low-exergy-efficient unit operations in the ammonia production process. In other words, the major contribution of this work is that after exergy analysis of ammonia process flowsheet and presenting the results in the form of visualized exergetic process flowsheet, the guidelines are given for a retrofitting. This will pave the way ultimately for further development of sustainable ammonia production.

2. Methods and process data

2.1. Exergetic methodologies

The present paper aims at performing exergy analysis of the ammonia production process based on the panel of solutions presented in the general methodology developed by Ghannadzadeh et al. [20]. This section provides a brief summary of the methodology. As mentioned earlier, the main advantage of the general exergy balance methodology developed by Ghannadzadeh et al. [20] is that it overcomes the limitations existed in previous methodologies and provides a systematic approach to exergy analysis. Later, Ghannadzadeh [21] extended the methodology so that it can cover the modeling and the diagnosis of existing processes based on the exergetic criteria and proposed a set of improvements and optimization solutions for the studied processes.

First, for the general methodology [20,21] all the necessary data for mass and heat balances of both the process and the existing utility system is gathered. The data is then used to model the process and the utility system in a process simulation software. The complex process is then divided into a number of major functional blocks, which makes the analysis easier. Next, an exergy balance on the global process and as a result, on the unit operations in each functional block is conducted. In the next step, the calculated exergy losses of each block are provided in the form of a graphical representation. This would order the blocks in terms of their exergy losses and makes it possible to determine the critical points of the system. Finally, a panel of solutions enumerating the major sources of irreversibility is used to propose practical process improvement methods for each specific class of unit operations. This final step is based on the identified exergy loss sources in the prior steps [37] but also previously published studies that