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New procedure for optimal design and evaluation of cogeneration system based on advanced exergoeconomic and exergoenvironmental analyses

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ABSTRACT

A systematic procedure is introduced for optimal design and evaluation of cogeneration systems based on the accurate cogeneration targeting model and the development of the *R*-curve concept through advanced exergetic, exergoeconomic and exergoenvironmental analyses.

An advanced exergetic analysis makes this information more accurate and useful and supplies additional information that cannot be provided by the conventional analysis. Moreover, the new graphical representations are proposed based on new concept. Finally, the optimal design of Iran LNG cogeneration plant is performed, in which the usefulness of this method is clearly demonstrated.

1. Introduction

Energy is a main contributor to the site operational costs for many industrial sites. To maximize the profit for a site, reduction of energy cost should be examined. The reduction of energy use will also reduce gaseous emissions and related to the conservation of the environment. A graphical method for the analysis of a total site was first presented by Dhole and Linnhoff [1] which was later modified by Raissi [2]. In their works, graphical tools were developed based on a temperature–enthalpy diagram in order to find targets for cogeneration and fuel saving. The top-down method investigates the utility system first and considers process changes in the last stage, which is the opposite direction of analysis compared with the traditional bottom-up method (Fig. 1a) [3].

The *R*-curve concept was first introduced by Kenney [4] for analyzing the cogeneration potential of a site. However, this original concept is difficult to be applied for complex systems because the original *R*-curve is generated on the basis of simple configuration of a utility system and does not take into account capacities and efficiencies of the existing equipment. To overcome these limitations, new *R*-curves, namely, "retrofit *R*-curve" and "grassroots *R*-curve", have been developed [3]. More information about the *R*-curve concept can be found in Refs. [3,5–7].

Additionally, chemical processes usually require steam at different pressure and temperature values for heating and non-heating purposes. In order to provide steam in the required condition, the designer has to decide whether to provide steam in the extreme condition and then let it down to different levels or produce steams separately in different boilers. Many industrial processes operate within Total Sites [1,2], where they are serviced and linked through a common central utility system. This utility system meets the demands for heat and power of individual process units by their indirect heat integration. However, greater benefits in terms of energy and capital cost can be obtained by looking at the

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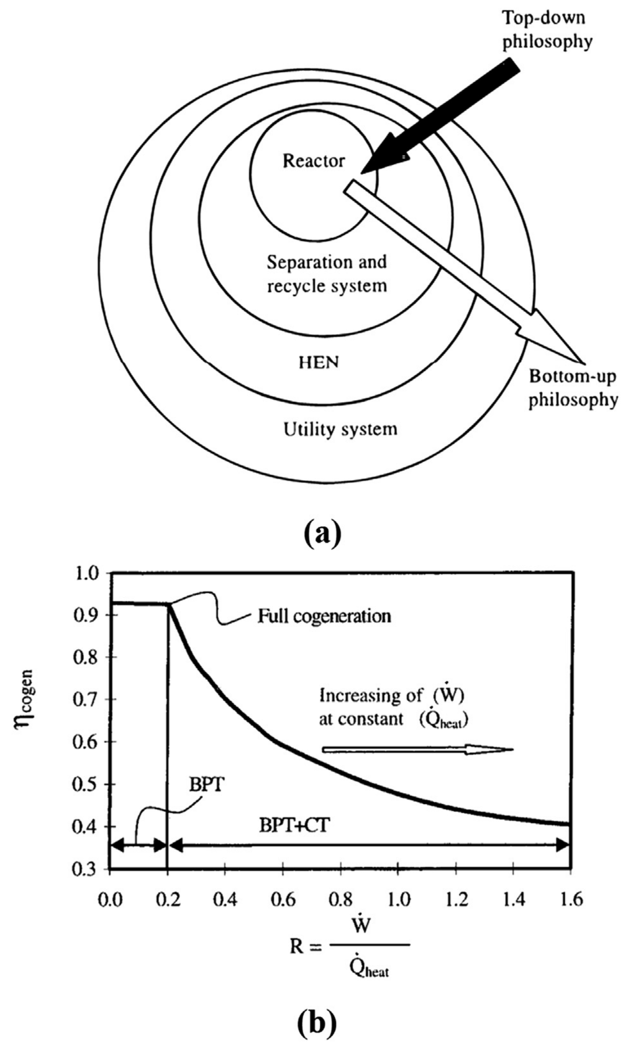

Fig. 1. (a) Top-down philosophy and bottom-up philosophy, (b) Typical *R*-curve [3].

entire site. Total site integration addresses the task of optimizing each process and utility system in the context of the overall site [8]. One of the important tasks for designing utility systems is to target fuel consumption and shaft work production ahead of the design.

A number of models has been proposed for the early estimation of cogeneration for utility systems using STs (steam turbines). Dhole and Linnhoff [1] proposed an exergetic model based on the site source-sink profiles. Raissi [2] presented the T–H model based on the Salisbury [9] approximation, assuming that power is linearly proportional to the difference between the inlet and outlet saturation temperatures. Mavromatis and Kokossis [10] introduced the non-linear model of THM (Turbine Hardware Model) based on the principle of the Willan's line in order to incorporate variation of efficiency with turbine size and operating load. Harell [11] introduced a graphic technique for estimating the cogeneration potential which utilized the concept of extractable power and header efficiency to establish cogeneration potential. Varbanov et al. [12] developed the improved THM. Sorin and Hammache [8] also developed an exergetic model based on thermodynamic insights for the Rankine cycle and showed that power was not linear in saturation temperature differences. Mohan and El-Halwagi [13] presented a linear algebraic approach based on the concept of extractable power and steam main efficiency. Medina-Flores and Picon-Nunez [14] proposed a modified thermodynamic model by keeping the advantages of the THM. Bandyopadhyay et al. [15] developed a linear model based on the Salisbury [9] approximation and energy balance at steam mains. A new shaft work targeting model, termed the IBTM (Iterative Bottom-to-Top Model), was presented by Ghannadzadeh et al. [16]. Kapil et al. [17] introduced a new method for estimating cogeneration potential of site utility systems by a combination of bottom-up and top-down procedures. A new cogeneration targeting model that has been developed to estimate the cogeneration potential of site utility systems. The new procedure has been proposed here provides a consistent, general procedure for determining the mass flow rates and the efficiencies of the turbines used [18]. A detailed description of the new targeting method can be found in Refs. [18–21].

At any given state of technological development, some parts of thermodynamic inefficiencies (exergy destruction) within a component of an energy-conversion system will always be unavoidable by reason of physical and economical constraints [22,23]. The target of the advanced exergy and exergoenvironmental analysis reported here is to estimate the avoidable and endogenous part of the exergy destruction within a LNG and the avoidable and endogenous part of the environmental impact associated with the construction and operation of the plant. This avoidable part is obtained as the difference between actual and unavoidable values of exergy destruction (or environmental impact). The avoidable part represents the real potential for improving each component, and thus the overall system.

Cziesla et al. [24] worked on the exergoeconomic evaluation of a conceptual design of an advanced EFCC (externally fired combined cycle). In their work, air is the working fluid in a GT (gas turbine) system, the CC (combustion chamber) of which is replaced by two high-temperature heat exchangers. Tsatsaronis and Morosuk [22] proposed a paper that consists of two parts. In the first one, a theoretical development is presented, whereas in the second part an application to a gas turbine-based cogeneration system is explained. Meyer et al. [25] worked on exergoenvironmental analysis of a case study about a high-temperature solid oxide fuel cell integrated with an allothermal biomass gasification process. Ahmadi and Dincer [26] introduced an exergoenvironmental analysis and optimization of a cogeneration plant system by using Multimodal Genetic Algorithm. Exergoenvironmental analysis of a steam methane reforming process for hydrogen production was done by Boyano et al. [27]. Petrakopoulou et al. [28] worked on exergoeconomic and exergoenvironmental analyses of a combined cycle power plant with chemical looping technology. Boyano et al. [29] researched to understand the formation of irreversibilities and environmental impacts in an SMR reactor by means of both conventional and advanced exergoenvironmental analyses. Ahmadi et al. [30] researched to understand an exergoenvironmental analysis of an integrated organic Rankine cycle for trigeneration system. Petrakopoulou et al. [31] worked on conventional and advanced exergetic analyses applied to a combined cycle power plant. Ganjeh Kaviri et al. [32] proposed a paper about exergoenvironmental optimization of HRSG (Heat Recovery Steam Generators) in combined cycle power plant through exergy analysis.

Morosuk and Tsatsaronis [33,34] introduced an advanced exergy analysis for chemically reacting systems and advanced exergetic analysis of a refrigeration system for liquefaction of natural gas. Wang et al. [35] researched on advanced thermodynamic analysis and evaluation of a supercritical power plant. Morosuk et al. [36] introduced an advanced exergy-based methods, including advanced exergetic and exergoenvironmental analyses using a LNG regasification system as base case. The exergy destruction within the plant components as well as the cost and environmental impact associated with each component is split into