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Trigeneration System: Visualization through Ternary Diagrams

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Abstract: The simultaneous production of power, heat and refrigeration in trigeneration plants is potentially more efficient than producing these same utilities in separate facilities, mainly due to the increased opportunities for process integration. Hence, trigeneration is also inherently more cost-effective and thermodynamically efficient, resulting in lower CO_2 footprint. Various methods have been developed for the synthesis of such plants. In this study, we propose a graphical approach where power, heat and refrigeration or cooling form the vertices of a ternary diagram. A thermal process unit may thus be represented as a point within the ternary diagram, with its coordinates denoting the ratios of its heat, power and cooling outputs. Thus, units producing two streams lie along the edges of the triangular field while those producing three streams fall inside it. Subsequently sizing of such process units that make up a trigeneration plant can be accomplished using lever-arm mixing rules within this triangular coordinate system. The use of the graphical methodology is illustrated with two case studies.

Key words: Trigeneration, energy systems, ternary diagram, process synthesis

INTRODUCTION

The use of fossil energy is closely associated with the release of greenhouse gases (GHGs). Both the current level of global primary energy consumption (roughly 500 EJ/y) and CO_2 emissions (about 30 Gt/y) are expected to rise as a result of industrialization, population growth and rising standards of living throughout the world. These trends are particularly pronounced in developing countries and especially in Asia. Because of the looming threat of climate change, there is an urgent need to decouple the economic growth from GHG emissions through the deployment of various technologies. Strategies range from increased use of low-carbon energy sources (e.g., renewable or nuclear power), the enhancement of industrial energy efficiency and the use of novel technological interventions such as Carbon Capture and Storage (CCS). These solutions represent "technology wedges" that can each contribute incremental GHG cuts; their simultaneous deployment in various niche markets can then result in substantial cumulative emissions.

The energy efficiency of thermal plants can be enhanced through simultaneous production of multiple utilities. Trigeneration plants, for example, generate electricity as well as heat (as steam or hot water) and cooling (as chilled water for refrigeration or air conditioning). They are also referred to as Combined Heating, Cooling and Power (CHCP) systems. The simultaneous production of these three streams in a single plant results in opportunities for heat integration, thus resulting in increased efficiency and reduced CO_2 footprint. At the same time, additional advantages of compactness and operational flexibility make CHCP plants suitable for unique applications, such as provision of energy for isolated sites (Wu and Wang, 2006). The synthesis and design of CHCP plants requires the selection and optimal sizing of the plant subcomponents (i.e., engines, turbines, boilers and chillers) vis-a-vis expected energy demand. Systematic decision aids have been proposed to select appropriate technologies (Jing *et al*., 2012). Often, the subcomponents may be modelled as "black boxes" with fixed efficiency levels or Coefficients of Performance (COP), thus allowing the use of Linear Programming (LP) models for design purposes (Cardona and Piacentino, 2003; Rong and Lahdelma, 2005; Piacentino and Cardona, 2008). More recent work has attempted to take into account conflicting environmental

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and economic considerations (Carvalho *et al*., 2012). Also, linear models have been proposed for debottlenecking (Tan *et al*., 2012) and operational adjustment (Kasivisvanathan *et al*., 2013) in response to demand changes.

In addition to mathematical approaches to thermal plant synthesis, there is significant potential for insight-based techniques as well (Zhelen, 2007). For example, graphical flow rate-exergy plots have been proposed as an aid for polygeneration systems (Wang *et al*., 2009). In this study, we propose a ternary diagram as an aid for visualizing trigeneration systems. The primary objective is to size various components to meet actual demand. It may be noted that similar diagrams have been used for a long time in various textbook on chemical engineering applications. More recently, ternary diagrams have been proposed as a tool for the synthesis of thermochemical biorefineries (Tay *et al*., 2011). The logical basis for the ternary diagram display is given in the next section. Two case studies are then given to illustrate the methodology. Finally, conclusions are given at the end of the study.

MATERIALS AND METHODS

The proposed methodology is based on a ternary diagram whose vertices represent outputs of cooling (R), heat (H) and power (E) as shown in Fig. 1. The total energy output of any given plant or thermal process unit is may be considered as a "mixture" of these components, with the relative proportions being reflected as spatial coordinates. Thus, energy outputs comprised of any two of the three lie on the edges of the triangular region while outputs comprised of all three components fall inside the triangle itself. It may be noted that right-angled triangle representation has been utilized in this paper; equivalent equilateral triangular representation may also be used.

For example, if we consider a boiler with thermal efficiency of 80%, as specified in Table 1, it may be plotted on the ternary diagram as point A in Fig. 1 which lies at the vertex corresponding to pure heat output. Note that the chemical energy in the fuel input does not play a role in plotting point A at coordinates (0, 1). Likewise, electricity import from the grid may be plotted as point B on the power vertex at (1, 0), as seen in Fig. 1. On the other hand, a module consisting of a Gas Turbine with Heat Recovery Steam Generator (GT-HRSG) with power and heat efficiencies of 30 and 45%, respectively (Table 1) has two output streams. Note that, in energy terms, 40% (i.e., 0.3 MJ/(0.3 MJ+0.45 MJ)) of the total output is power while the remaining 60% is heat. Thus, the GT-HRSG

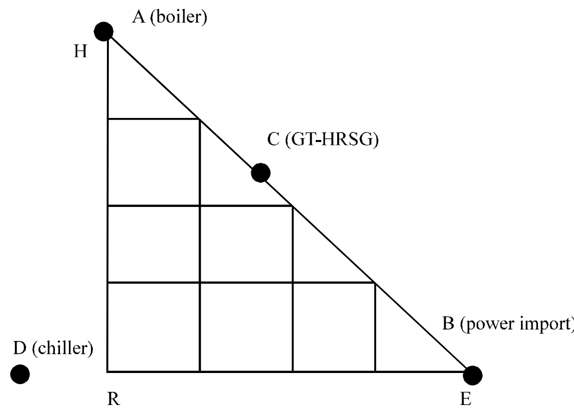

Fig. 1: Ternary diagram representation of trigeneration plant modules

Table 1: Typical trigeneration plant process units

Process unit	Energy input	Energy output
Boiler (η = 0.8)	1 MJ fuel	0.8 MJ heat
Gas turbine with heat recovery steam generator (η_P = 0.3, η_H = 0.45)	1 MJ fuel	0.3 MJ power 0.45 MJ heat
Vapor compression chiller (COP = 5)	1 MJ power	5 MJ cooling

module may be plotted as point C in Fig. 1, along the edge of the ternary diagram connecting the heat and power vertices. The coordinates of this point are (0.4, 0.6).

Plotting the electrically driven vapor compression chiller involves some complications. Based on the assumed coefficient of performance (COP = 5), this unit consumes 1 MJ of power to generate 5 MJ of cooling. This electric power input may be viewed as a negative output stream, so that the corresponding location on the ternary diagram is given by point D in Fig. 1. Note that this point actually lies outside the ternary diagram, along a fictitious horizontal extension of the axis connecting the cooling and power vertices. The precise coordinates of point D are (-0.25, 0). Thus its location is a consequence of the negative value of the power output of the module. The methodology may then be applied directly for trigeneration plant synthesis, specifically for sizing the individual modules, by treating the plant energy output as a mixture of the energy streams from the subcomponents. The mixing rule conforms to lever principles that apply to ternary diagrams. The approach is illustrated in the next section with the aid of two examples.

CASE STUDIES

Case study 1: Suppose the desired plant trigeneration output is 5 MW of power, 25 MW of heat and 10 MW of refrigeration, for a combined 40 MW of total output. Power, heat and refrigeration may thus be computed to

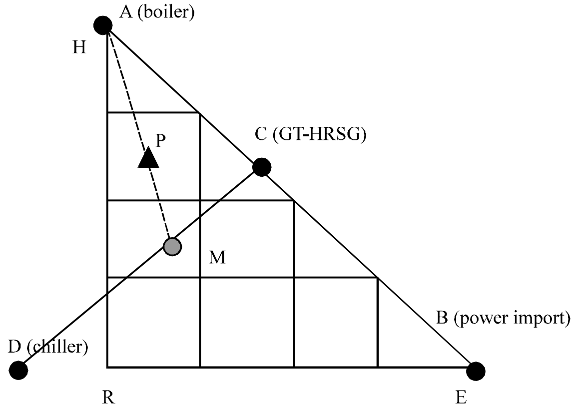

Fig. 2: Ternary diagram for case 1

comprise 12.5, 62.5 and 25% of the total energy produced. This mixture may be plotted as point P, as shown in Fig. 2.

Next, it can be seen from lever principles that a plant comprised only on the GT-HRSG and chiller units as described in Table 1 from the previous section may generate any energy output mix that lies along the line connecting points C and D; the exact position depends only on the relative sizes of the two units. As the desired output, point P, lies above this line, supplementary heat from a boiler is needed. The precise ratios are determined as follows. First, the broken line from point A is drawn through P until it crosses the line CD to determine point M. Using lever-arm rules, the inverse of the ratio HP/PM can be used to find the proportion of the 40 MW output that is contributed by the boiler to give 14.5 MW. Thus, the total output contributed by point M is 25.5 MW. Next, the ratio DM/MC can then be used to determine the proportions of this 25.5 MW from the GT-HRSG and chiller units which are then determined as 17.5 and 8 MW, respectively. Following the convention proposed in the previous section, the 17.5 MW GT-HRSG module actually corresponds to 7 MW of power and 10.5 MW of heat. Likewise, the 8 MW rating of the chiller means a net output of 10 MW of cooling, as well as an input of 2 MW of power drawn from the GT-HRSG.

It can then be seen that the resulting plant configuration is as shown in Fig. 3. Note that, if the heat requirement from the boiler is sufficiently small, then it may be supplied via a firing option within the GT-HRSG unit, instead of using a separate boiler.

Case study 2: Suppose the desired plant trigeneration output is now 8 MW of power, 5 MW of heat and 7 MW of refrigeration, for a combined 20 MW of total output. As

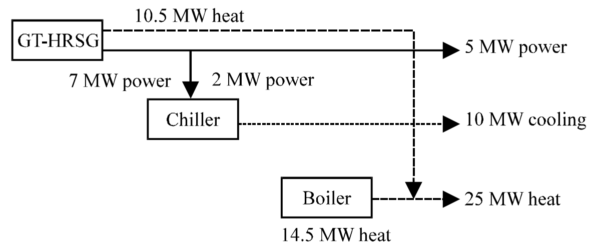

Fig. 3: Trigeneration plant configuration for case 1

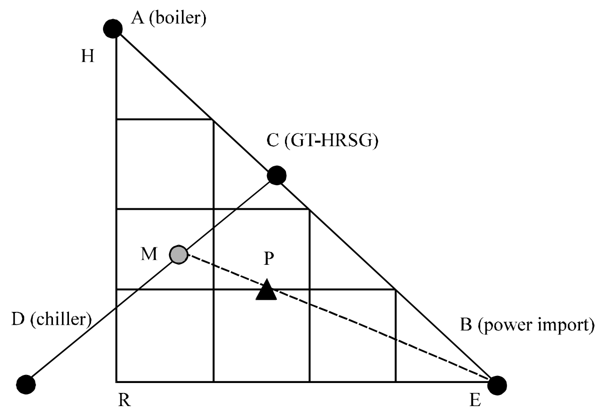

Fig. 4: Ternary diagram for case 2

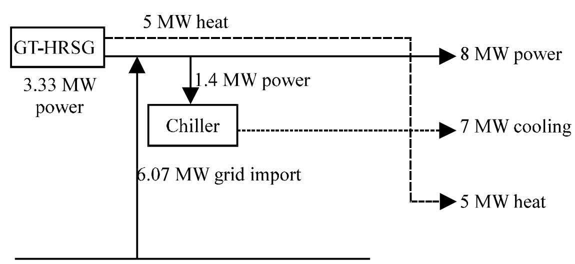

Fig. 5: Plant configuration for case 2

in the previous case study, power, heat and refrigeration may thus be computed to comprise 40, 25 and 35% of the total energy produced and the plotted as point P, as shown in Fig. 4.

Using the same module characteristics, P is found to lie below and to the right of line CD, indicating the need for supplementary power import. The precise ratios are determined as in the previous example to give the result of 8.33 MW for the GT-HRSG (corresponding to 3.33 MW of power and 5 MW of heat), 5.6 MW for the chiller (corresponding to 7 MW of cooling output and 1.4 MW of power demand) and another 6.07 MW of supplementary power drawn from the grid. The trigeneration plant configuration shown in Fig. 5.

CONCLUSION

In this study, a graphical approach for visualizing trigeneration systems has been developed, where power, heat and refrigeration or cooling form the vertices of a ternary diagram. A thermal process unit may thus be represented as a point within the ternary diagram, with its coordinates denoting the ratios of its heat, power and cooling outputs. As demonstrated with two synthesis case studies, the sizing of process units that make up a trigeneration plant can be accomplished using lever-arm mixing rules within this triangular coordinate system. In future work, this methodology may be integrated within an optimization framework, particularly in the case where multiple options exist to produce a given set of streams. Also, this technique may be applied for operational decision-making in addition to synthesis problems.

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