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EXERGY COST ANALYSIS OF A TRIGENERATION GAS TURBINE SYSTEM BASED ON THE STRUCTURAL THEORY OF THERMOECONOMICS

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Abstract: In this paper, an exergy cost analysis method based on the structural theory of thermoeconomics is applied to a gas-fired micro-trigeneration system, which uses a small-scale generator set driven by a gas engine and a new small-scale adsorption chiller (ADC). The thermoeconomic model for the system. based on the fuel–product concept is defined to quantify the productive interaction between various components. The distribution of the resources and costs of all flows in the productive structure are calculated by solving a set of equations according to the experimental data. By adopting the exergy cost analysis method, the production performance of components at design and variable conditions of combined cooling and power are evaluated in detail. Moreover, a comparison between the method of conventional exergy analysis and exergy cost analysis is presented. The results not only reflect that the structural theory is a powerful and effective tool for performance evaluation of complex system, but also prove that the micro-trigeneration system is efficient in utilizing the low-grade waste heat.

I. INTRODUCTION

The successive energy crises have stimulated the study of more efficient ways for the comprehensive utilization of the available energy in fuels. Trigeneration—also called combined cooling, heating and power (CCHP)—is the simultaneous conversion a single primary fuel into mechanical power (electricity), cooling and heating to satisfy the consumption needs. It typically produces electricity through a reciprocating engine or gas turbine and recovers the waste heat energy remained in the exhaust gas and the coolant water, the heat gained can be made available for cooling and heating applications utilizing thermally activated technologies such as absorption chillers and adsorption chillers (ADCs). Trigeneration is generally considered as energy-saving, economic, reliable and environmentally benign. The performance analysis of trigeneration systems is extremely important to China considering that China is just in the process of adjusting the energy structure and improving the energy utilization efficiency. Some scholars have made researches on the experimental study of trigeneration system. Most investigations are based on energy analysis [1–3] and exergy analysis [4,5]. However, the two analysis methods, although useful, have been proved not to be enough. For example, what is the exact cost ofthe different quality of energy outputs and how does energy degrade in trigeneration systems? Which parts of the degradation are most important, and how can designs and operations be improved to reduce resource consumption? Thermoeconomics can provide answers to these questions. Thermoeconomics, originated by Tribus and Evans [6], combines the second law of thermodynamics with economics by applying the concept of cost to exergy, in order to achieve a better production management with a more cost-effective operation. Exergy is the most adequate thermodynamic property to associate with cost since it contains information from the second law of thermodynamics and accounts for energy quality. In the subsequent period of time, the main and more general thermoeconomic methodologies developed include the exergetic cost theory of Lozano and Valero [7], the last in first out method of Lazzaretto and Tsatsaronis [8], the average cost method of Bejan et al. [9], the specific exergy costing method of Tsatsaronis and Pisa [10], the thermoeconomic functional method of Frangopoulos [11,12] and the engineering functional analysis of Spakovsky and Evans [13]. To a certain extent, multiple methodologies with different theories and nomenclatures cause confusion and impede the development of thermoeconomics. Based on the achievements of predecessors, Valero et al. [14] developed the structural theory of thermoeconomics, which provides a general mathematical formulation using a linear model and encompasses all the thermoeconomic methodologies developed up to now, and is considered as standard formalism of thermoeconomics [15,16]. It would be specially mentioned, in the same era two research methods which are easily to be confused with the structural theory of thermoeconomics appeared: Wang [17] proposed ‘‘structural’’ thermodynamics approach to decouple the structure of a thermodynamic process set with its working medium, and introduce optimization to the thermodynamic reasoning; Bejan [18] put forward ‘‘constructal’’ theory, which tries to deduce the optimal-access between volume to point or point to volume flow problems by optimizing volume shape at every length scale, in a hierarchical geometric flow structure that begins with the smallest elemental system, and proceeds toward larger constructs. These two methodologies are different from the structural theory of thermoeconomics in nature. The nomenclature ‘‘structure’’ in structural theory of thermoeconomics means productive structure, which attributes well-defined functional relationship for each exergy flow entering or leaving the subsystems in terms of fuel and product. Thermoeconomic analysis distinguishes between exergy costs and exergoeconomic costs. The exergy cost of an energy flow represents the units of external resources exergy used to produce it. The exergoeconomic cost is defined as the

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amount of money consumed to generate an energy flow. Several authors have applied the structural theory of thermoeconomics to performance analysis of complex energy systems: combined cycle power plants [15], conventional coal fired power plants [19] and multi-stage flash desalination plants [20]. But all the prime movers in these plants are gas turbines or steam turbines; no work adopting this general theory has been published on performance analysis of energy systems driven by internal combustion engines. In the case of an internal combustion engine, work, flue gases and heat (water) are not produced separately and all of them come from the same device, they are very much connected and very much interdependent. In order to evaluate the performance of a micro-trigeneration system which is mainly composed of a gas engine and an ADC, the exergy cost analysis method based on the structural theory of thermoeconomics is presented in this paper. The thermoeconomic models of the units of the system are defined properly; the interactive relationships among components of the system and the causality chains processes of product formation have been quantified. After solving the characteristic equations, the unit exergy costs of all components are obtained. The production performance of each component at design and variable conditions is analyzed in detail, and then a comparison between the method of conventional exergy analysis and exergy cost analysis is performed.

II. THE MICRO-TRIGENERATION SYSTEM

The schematic diagram of the micro-trigeneration system which is developed by the Institute of Refrigeration and Cryogenics of Shanghai Jiao Tong University [3] is depicted in Fig. 1. The system can supply 12 kW electricity power and has a cooling capacity of 9 kW or heating capacity of 28 kW. It is composed of an internal combustion gas engine, a novel ADC, heat exchangers, a cooling tower, pumps, etc. The engine is a doublecylinder, four-stroke, water-cooled, liquefied petroleum gas (LPG) or natural gas fired engine. For the generator set at rated power of 12 kW, its generating efficiency is 21.4% and the temperature of exhausted gas is 580 1C. The refrigeration coefficient of performance (COP) of the ADC reaches 0.3–0.4 for 13 1C evaporation temperature with a heat source of 60–95 1C water [21]. The working pair is silica gel–water in which water is used as the refrigerant.

The engine jacket cooling water passes through the exhaust heat exchanger (EHE) and is reheated by the exhaust gas, and then passes through an ADC to produce chilled water in summer, or, passes a heat exchanger (heating water heat exchanger, HWHE) toproduce heating water in winter. Then the jacket water returns to the engine. Finally, the produced chilled water and heating water are supplied to the existing cooling or heating network.

The test facility and measurement methodology are carried out in previous work [3,22]. Basic thermodynamic properties of the plant are determined by energetic analysis utilizing main operation parameters, which are listed in Table 1. Due to a little difference between the test and rated condition, the real refrigerating power of ADC is lower than the rated one. When the generator runs at rated power and the inlet temperature of cooling water is kept at 30.7 1C, the refrigerating power of ADC is
8.32 and 9.01 kW when the chilled water inlet temperatures are 15.6 and 20.3 1C, respectively (the corresponding outlet temperatures are 10.2 and 14.4 1C, respectively). Simultaneously, the corresponding heat-source water inlet temperatures are 88.9 and 83.7 1C, and the outlet temperatures are 83.0 and 78.0 1C, respectively. Accordingly, the COP of ADC increases from 0.30 to 0.35. Here, the heat transfer rate interactions of heating and cooling are computed by the following equation:

$$Q = mCp\,\Delta T \qquad (1)$$

where m is the mass flow rate of media; c_p is the specific heat capacity at constant pressure and DT is the temperature difference of outlet and inlet. The refrigeration COP of ADC is defined as:

$$COP = \frac{Qc}{Qb} \qquad (2)$$

where Q_c is the cooling power of ADC and Q_h is the heating power to drive ADC. In order to perform a thermoeconomic analysis of the system, an exergy analysis is accomplished to calculate the exergy of the flows based on the following assumptions:

For simplicity, only steady-state processes are considered in the discussion. The data of calculation parameters are the average values in one cycle of the ADC. The kinetic and potential energy effects of jacket cooling water are ignored.

Air and fuel gas are considered as perfect gases. The pressure and temperature of the reference environment are p_0 ¼ 0.1013 MPa, T_0 ¼ 308.15 K in summer and T_0 ¼ 273.15 K in winter. The gain and loss of heat, pressure and exergy in the pipe connections have been neglected. Therefore, in this analysis the physical exergy is mainly associated with the heat transfer out of or into a control surface called thermal exergy. When the temperature T at the location where heat transfer is taking place is variable, the exergy transfer accompanying heat transfer is determined by:

$$Eh = \int \left(1 - \frac{T0}{T}\right) \delta Q0 \qquad (3)$$

when $T4T_0$ and Q is the heat output from the energy flow to the environment, and

$$Ec = \int \left(\frac{T0}{T} - 1\right) \delta Q0 \qquad (4)$$

T when ToT_0 and Q_0 is the heat input from the cooling load to the energy flow. If the specific heat capacity of the fluid can be considered as constant, Eqs. (3) and (4) become

$$Eh = \int \left(1 - \frac{T0}{T-T0}\, ln\frac{T}{T0}\right) \qquad (5)$$

and

$$Ec = \int \left(\frac{T0}{T-T0}\, ln\frac{T}{T0} - 1\right) \qquad (6)$$

respectively. As LPG is easy to get, LPG is used as the test fuel for the trigeneration system. The molar analysis of LPG used is: 27.5% C_3H_6, 7.0% C_3H_8, 43.0% C_4H_8 and 22.5% C_4H_{10}. The chemical exergy per mole of LPG is determined as follows̅ [9,̅23]: $e^{-CH} = \sum Xke_K^{-CH} + RT0 \sum XklnXk + \sum Xk\xi(k)(T0 - 298.15$ (7)

where x_k is the mole fraction of gas k; x(k) is the revised

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coefficient of temperature of gas k. Since the tabulated standard chemical exergy values in most references are based on a standard exergy reference environment exhibiting standard values of the environmental temperature T_0 ¼ 298.15 K (25 1C) and pressure P_0 ¼ 0.1 MPa, the revised coefficient of temperature is introduced to make up the deviating of temperature from the standard condition:

$$\xi = \frac{\bar{e}_{c}(T_0) - \bar{e}_0}{T_0 - 298.15} \quad (8)$$

T_0 298*:*15 where the chemical exergy under standard condition ise_0, and the chemical exergy under envirōnmental condition is e_cðT$_0$Þ. The coefficient x of various sūbstances can be obtained from Tables 4.3 and 4.4 of reference [23].

III. THERMOECONOMIC MODELING BASED ON THE STRUCTURAL THEORY

When applying a thermoeconomic analysis, it is necessary to define a thermoeconomic model for the analyzed system, which is the mathematical representation of the productive structure. The general analysis procedure based on the structural theory of thermoeconomics formalism is: (1) building a physical structure of the analyzed plant, (2) selecting the fuel–product definition for each subsystem of the plant, (3) transforming the plant's physical structure into a productive structure, and finally (4) constructing the thermoeconomic model.

A. Physical structure

By aggregating several units into one subsystem or disaggregating one unit into several individual components, the microtrigeneration system's thermodynamic model is converted into a physical structure for a more detailed analysis. The finally chosen adequate aggregation level should take into account that the thermoeconomic analysis will start from those real measured or simulated data, such as temperatures, pressures, mass flow rates and compositions of all mass flows together with the heat and power rates of the energy flows in a real plant. Fig. 2 shows an appropriate disaggregation level of the analyzed trigeneration plant just for presenting the idea. The cylinder (CYL) and jacket (JAC) are separated from the engine and considered as individual components. The cooling water pump and cooling tower are combined with the ADC. The jacket water pump is considered together with JAC that it serves. Each component and energy flow in the physical structure is numbered for the following thermoeconomic analysis.

B. Fuel– product definition

A productive purpose expressing component function can be defined for each component in an overall production process. The productive purpose of a component measured in terms of exergy is called product. To create this product, another exergy flow(s) is consumed, and it is called fuel(s) of that component. The fuel–product definitions for each component of the trigeneration system depicted in Fig. 2 is shown in Table 2. It is necessary to point out that in order to maintain a working order of the engine's high temperature parts, the function of jacket cooling system is to extract some heat from the engine and reject it to a radiator. In the micro-trigeneration system, the heat of jacket water is recovered, hence the heating process in JAC could be considered reversible and all the irreversibilities should be apportioned to the generated power, while the minimum theoretical exergy required for heating the jacket water (provided by the fuel entering to the system) should be considered as one part fuel of JAC, i.e. the difference of exergy value between the outlet water of JAC and jacket water pump. For this reason, the exergy flow 5 is expressed as broken line in Fig. 2. The other fuel of JAC is the consumed electricity of jacket water pump. From a

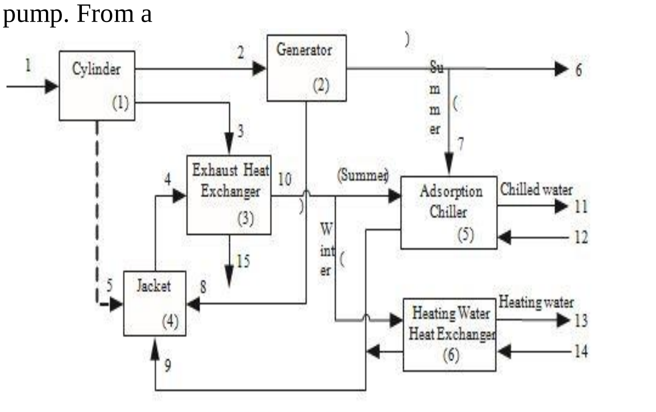

Fig. 2. Physical structure of the micro-trigeneration system.

Table 2: Fuel and product definitions for the micro-trigeneration system

Subsystem	Fuel	Product
CYL (1)	The part of chemical exergy of LPG used to generate work	Generated mechanical work
GEN (2)	Mechanical work	Electric power
EHE (3)	Exergy removed from the exhaust gases flow entering EHE	Exergy supplied to the jacket water flow
JAC (4)	Minimum theoretical exergy required for heating the water of JAC and the electricity consumed by jacket water pump	Exergy supplied to the jacket water flow
ADC (5)	Exergy removed from the hot water flow and the consumed electricity	Exergy supplied to the chilled water flow
HWHE (6)	Exergy removed from the hot water flow	Exergy supplied to the cold water flow

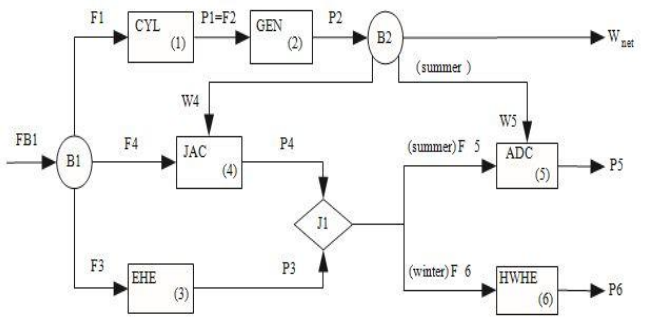

Fig.3: Productive structure of the micro-trigeneration system.

thermodynamic point of view, the function of cooling water pump and cooling tower is to reject the condensing and adsorbing heat of ADC to the environment. The cost is the electricity they consumed, which is another fuel of ADC. As to EHE, the outlet exhaust gas is disposed off into the environment but it has been produced by the gas engine and has an effect on EHE. In this case, the exergy of the outlet

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exhaust gas should be allocated to CYL for the cost of the generated power.

C. Productive structure

When using the fuel–product definition presented above to describe the analyzed system, the physical structure of the system is converted into productive structure, as presented in Fig. 3. The productive structure is a graphical representation of resource distribution throughout the system, based on the functional diagram introduced by Frangopoulos [11,12]. The inlet arrows going into squares are the fuels of the corresponding components, and the outlet arrows represent the products. Each component has one output product and one or more input fuels. Apart from components representing equipment items of the system represented by squares, two types of fictitious components appear in the productive structure—junctions (represented by rhombus), where the products of two or more components are united to form the fuel of another component, and branching points (represented by circles), where an exergy flow is distributed between two or more components. In all of the junctions and branching points, there is no irreversibility, and the exergy resources of the inlet and outlet flows are subject to conservation. Note that the productive structure provides to the analyst a new perspective of the system. Fig. 1 shows the physical connections between the different plant subsystems, and the productive structure shows the productive process picture, i.e. the resources distribution, among the different components when converting them into final products. Table 3 (column ''Fuel'' and ''Product'') shows that exergy is taken in the trigeneration system to perform the flows, which are previously defined in Table 2 for the F and P definition. The values of fuel and product of various components corresponding to the design conditions are shown in Table 4.

D. Characteristic equations

The thermoeconomic model that is the mathematical representation of the productive structure consists of a set of mathematical functions called characteristic equations. They express each inlet flow as a mathematical function of the outlet flows for all the productive structure process units and a set of internal parameters xl, i.e. Ei ¼ gi(xl, Ej), where the index i, j refers to the input and output flows of the process unit l, respectively. By adopting linear equations of exergy, the characteristic equations can also be denoted as [14,16]:

$$E_i = \sum_{j \in S_i} \kappa_{ij} E_j, \quad \kappa_{ij} = \frac{\partial g_i}{\partial E_j}, \tag{9}$$

where i ¼ 1, y, m; l ¼ 1, y, n; m is the number of flows in the productive structure and n is the number of process units. kij is called marginal exergy consumption and represents the thermodynamic efficiency of the conversion of the ith process unit fuel into its product. The sum of kij coefficients of a unit is the unit exergy consumption of that unit

$$k_j = \sum_{i=0}^{n} \kappa_{ij} = \frac{\sum_{i=0}^{n} F_i}{P_j} = \frac{F_j}{P_j}. \tag{10}$$

The characteristic equations for the productive structure in Fig. 3 are presented in Table 3. There are two kinds of characteristic equations in exergy cost analysis: (1) those connecting each fuel of physical component to its product (Fi ¼ kiPi). They inform about the relation of product, fuel and unit exergy consumption in the subsystem. (2) Structural equations which describe the productive model of junctions and branches. The former adopts exergy rate (rij) to describe the portion of the ith flow of fuel in the product of the jth junction (Fi ¼ rijPj). The latter one shows how the fuel of a branch is distributed through the other components (Fi ¼ P Pi). After solving the characteristic equations in Table 3, the unit exergy consumption k and the junction/exergy rate r can be calculated as shown in Table 4.

IV. EXERGY COST ANALYSIS

The unit exergy cost of a mass and/or energy flow represents the amounts of resources exergy required to obtain one unit of exergy. It can be further divided into unit average exergy cost and unit marginal exergy cost [14,16]. Unit average exergy cost k is the average amount of required resources exergy per unit of product exergy; unit marginal exergy cost k* is a derivative and indicate the additional resources exergy required to obtain one more unit of product exergy under specified conditions. Mathematically they are defined as:

$$\overline{k^*} = \frac{E_0}{E_i}, \quad k^* = \left(\frac{\partial E_0}{\partial E_i}\right)_{\text{conditions}}. \tag{11}$$

It is important to state that the unit average exergy cost and unit marginal exergy cost coincide when the characteristic equations of the thermoeconomic model are first homogeneous functions. This result is very important since both costs can be calculated using the same procedure. The inverse of unit exergy cost of the final plant product is the well-known exergy efficiency:

$$\varepsilon_{ec} = \frac{1}{\overline{k^*}} = \frac{E_i}{E_0}. \tag{12}$$

Once the thermoeconomic model has been defined and the characteristic equations corresponding to the productive structure of the system are solved, the costs of all flows in the productive structure can be calculated using the chain rule of mathematical derivation [14,20]:

$$k^*_{P,i} = \kappa_{0i} + \sum_{j=1}^{n} \kappa_{ji} k^*_{P,j}, \tag{13}$$

where kP;i is the unit marginal exergy cost of product of the ith component; i ¼ 1, y, n. The exergy cost equations for the micro-trigeneration system are presented in Table 3, and then the unit marginal cost kfor each flow can be obtained by solving these equations. There are no resource losses when the resources enter into the inlet of the system, thus kF;B1 ¼ 1. The unit marginal costs of fuels (kF) and products (kP) are presented in Table 4 corresponding to the design conditions, i.e. the generator runs at rated power in summer and winter. These exergy costs are expressed in energy units and represent the amount of resources (LPG) exergy consumed to obtain each significant mass and energy flow stream. They only represent the operation costs—they do not include the investment cost of each component. Flow streams further down the productive process are more costly. All processes in the system are irreversible and the total exergy destruction

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continuously increases throughout the productive process, and thus, the final products have the highest exergy cost.

V. ERROR ANALYSIS

The main measuring devices, calibrated range, accuracy or relative error of various instruments involved in the experiment for various parameters are listed in Table 5. All the measuring instruments were calibrated recently before starting the measurements. They were used in the acceptable working condition limits of the instruments and usually operated for more than an hour before starting the reading. Therefore, only occasional errors are considered during the experiment. An error analysis based on the accuracies of the direct measurements is conducted to determine the maximum possible errors of these deduced parameters, such as the fuel exergy, product exergy, unit exergy consumption and unit marginal exergy cost of product of every component. The adopted analysis method is the differential method of propagating errors based on Taylor's theorem. It gives the maximum error Dy of a function y ¼ f(x1, x2, y, xn) as follows:

$$\Delta y = \sqrt{\sum \left(\frac{\partial f}{\partial x_i}\Delta x_i\right)^2}. \quad (14)$$

As a result, the maximum relative root mean square errors of every component during the experiment are tabulated in Table 6. It can be seen that the greatest possible error was 75.68% for the unit marginal exergy cost of product of EHE, and each of the estimated relative errors is less than 6%. It should be clearly noted that the estimated errors in the measurements of the derived quantities do not significantly influence the final results.

Table 5 Specification of the different measuring devices

VI. RESULTS AND DISCUSSION

As shown in Fig. 3 and Table 4, the productive process can be simply divided into two sequential groups. The first group consists of the CYL, JAC and EHE, each of which has the same unit exergy cost of fuel (1.0). The second group is composed of GEN, ADC and HWHE that consume the products provided by the components in the first group. In other words, the unit cost of the chilled water is a weighted sum of the k_P of JAC, EHE and GEN; the unit cost of the heating water is a weighted sum of the k_P of JAC and EHE. Moreover, it can be seen that besides ADC and HWHE, the corresponding variation of k_P of other components are not obvious in summer and winter operating mode. The unit exergy cost of electricity is about 4.155, and the exergy cost of cooling is the highest 17.194, whereas the exergy cost of heating is the lowest, only 3.290. According to Eq. (12), the exergy efficiency of cooling $_{ec;c}$; heating $_{ec;h}$ and power $_{ec;e}$ of the micro-trigeneration system are 5.82%, 30.40% and 24.07%, respectively. As a consequence, the method of exergy cost analysis can provide the exact cost of cooling, heating and power, and indicates the relative degree of difficulty in producing them.

Since more research has been done for utilizing recovered thermal energy for building heating, the emphasis of this paper will be placed on the performance of combined cooling and power. Several cases have been analyzed using the exergy cost analysis in the structural theory of thermoeconomics. First, the production performance of each component at rated load conditions has been compared; and then, the effects of main operating parameters on the performance of each component have been analyzed by varying some significant physical parameters of the components while keeping other parameters constant; finally, the difference between conventional exergy analysis and exergy cost analysis are discussed.

6.1. Combined cooling and power performance at rated electricity load conditions. According to the data in Table 4, the k_F and k_P of components in summer are compared in Fig. 4. The k_P of JAC is the smallest, just because the irreversibilities during the heat transfer process of JAC.

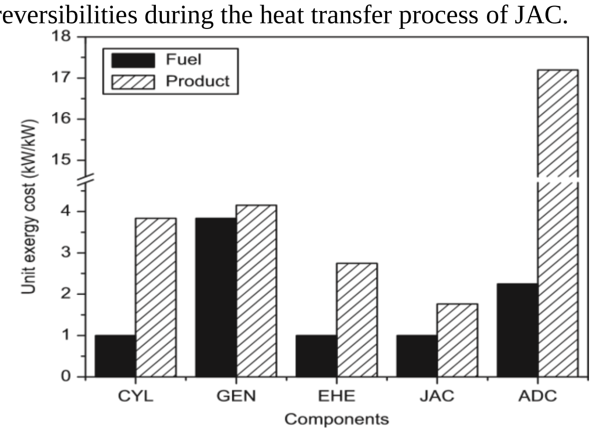

Fig. 4. Unit exergy cost for the design conditions.

make the temperature of exhausted gas decrease from former 116 1C to a lower temperature. Thus, more recovered thermal exergy helps to make the performance of EHE better. The k_P of ADC is the biggest, and it seems that the production performance of ADC is not good. Actually, due to the energy quality coefficient of cooling is very low (about 0.078 when the supplying and returning chilled water temperature are 10 and 15 1C), this leads to that the thermal exergy of cooling is very small, so the kP of all kinds of chillers are inherently higher than those of other kinds of devices. Here, ADC is compared with a small is apportioned to the power generation, as presented in the fuel–product definition of Section 3.2. The kP of CYL and GEN are nearly equal, but the kF of GEN is very high, so the production performance of GEN is better than CYL. In order to reduce the exergy cost of power, much effort is necessary to improve the performance of CYL above all. Emphasis should also be placed on the improvement of EHE, since it is easier than that of CYL. For example, adopting heat exchanger with condensation could electricity powered water chiller as follows. Under the condition of consuming the same chemical exergy of fuel as ADC, in order to produce the same quality of cooling power,

the COP of electricity powered water chiller could be calculated according to the equation below:

$$\frac{Q_C/(COP \times \varepsilon_{er})}{E_C} = k^*_{p,5}, \quad (15)$$

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where assuming that the reference generation exergy efficiency $_{er}$ is 0.3. The result is that the value of COP is equal to 2.51, while the COP of market available water chillers at rated cooling power of 9kW is about 3.0. This reveals that the cooling capacity of the micro-trigeneration system which recovers the low-grade waste heat for cooling is fruitful. Similarly, if a higher COP ¼ 0.4 of ADC is developed, then $k_{p;5}$ reduces to 13.548 and the equivalent COP of water chiller rises to 3.18. As a result, it is evident that the smallscale ADC is energy-efficient in utilizing the recovered waste heat of the micro-trigeneration system, and this green environmental protection technology will have a wide application prospect.

6.2. Effects of various operating parameters on the performance of componentsWhen the chilled water inlet and outlet temperatures are kept at 15.6 and 10.2 1C, respectively, the k_P of all components are calculated for various electricity output conditions which is shown in Fig. 5. It can be seen that the k_P of all components drop from a higher value to a lower one when electricity output increases from 7.02 to 12.0 kW. This can be explained by the fact that the k_F of each component drops, and also, the exergy destruction of each component drops as electricity output increases. Especially for the k_P of ADC reduces remarkably due to it's k_F, i.e. the k_P of EHE and JAC decreases rapidly when electricity output increase from 8.12 to 10.3 kW. Therefore, the production performance of ADC is better when the electricity output is above 10.3 kW. Moreover, the k_P of ADC could further decrease to a lower value if a higher efficiency of EHE is used when electricity output increases from 10.3 to 12 kW. That will promote the production performance of ADC.

Fig. 6 shows how the inlet temperature of chilled water affects the k_P of each component when the electricity output is kept at rated power of 12 kW. It can be observed that the k_P of ADC is affected more significantly than the other components when the inlet temperature of chilled water changes from 15.6 to 20.3 1C. For an ADC, the evaporation temperature and pressure of

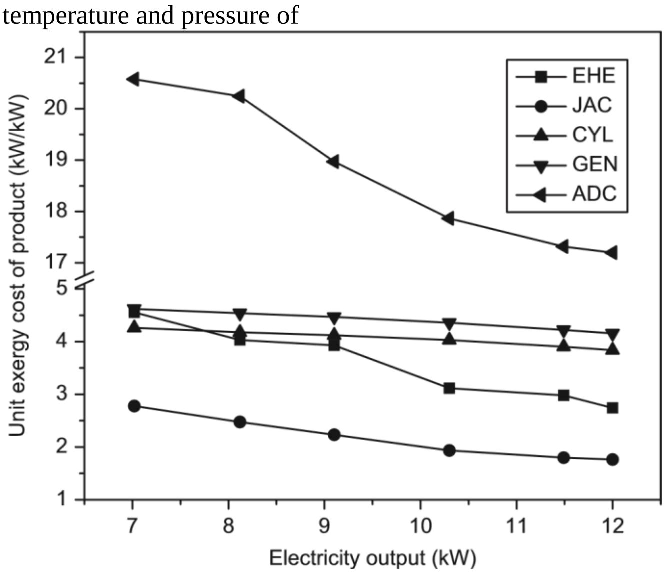
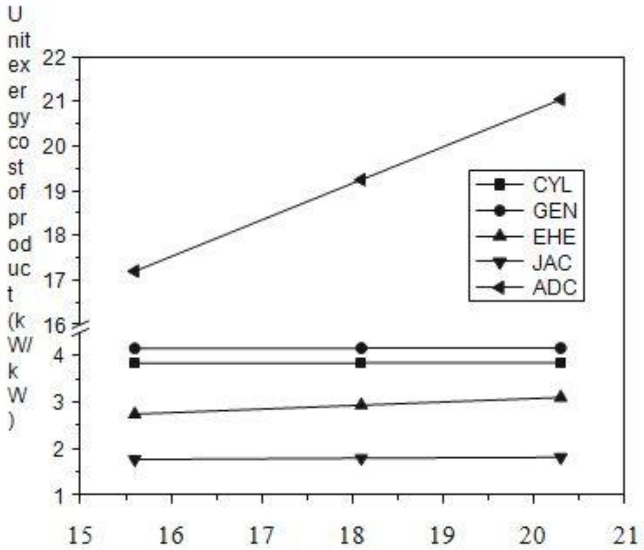


Fig. 5. Effect on the $k_P$due to change in the electricity output.



Inlet temperature of chilled water (°C)

Fig. 6. Effect on the $k_P$due to change in the inlet temperature of chilled water.

refrigerant become higher with the increasing chilled water inlet temperature. As a result, the circulating adsorption capacity of adsorbent increases, and the demand of desorption heat increases correspondingly. Thus, when the heat demand of ADC and the recovered heat from JAC and EHE reaches a new equilibrium, the inlet and outlet hot water temperature of EHE and ADC become lower. Therefore, the output exergy of EHE decreases, which leads to the increase of the k_P of EHE finally. At the same time, the output exergy of ADC decreases gradually. These two factors together make the k_P of ADC to increase rapidly and this reduces the efficient utilization of exergy of LPG. Although increasing the chilled water inlet temperature improves the COP of ADC and consequently it is beneficial from a local scope, it is disadvantageous to the energy savings operation of the whole trigeneration system from a global viewpoint.

6.3. Cooling performance comparison between the method of conventional exergy analysis and exergy cost analysis

Determining exergy efficiencies for an overall system and the individual components constitutes a major part of conventional exergy analysis. Conventional exergy efficiency is defined as a ratio of the desired exergy output to the exergy used [24]. So the overall exergy efficiency and the exergy efficiency of ADC can be expressed as below: As pointed out by Lior and Zhang [25], ''the overall exergy efficiency evaluates the efficiency of a process giving equal consideration to all outputs and inputs regardless of whether they are being used or paid for,'' thus the overall exergy efficiency is not effective to assess the efficiency of the single energy vector production, such as, how well the system performs in individually producing cooling. While the conventional exergy efficiency of ADC (Eq. (17)) measures only the ratio of output usable cooling exergy to the sum of exergy of heating water and electricity. For these

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reasons, the exergy cost analysis is employed to evaluate the cooling production exergy efficiency of the trigeneration system. In order to differentiate the two methods, the cooling production performance under the variable cooling output conditions is evaluated as an example according to Eqs. (12) and (17). The calculated results of exergy efficiency of cooling are shown in Fig. 7. It can be seen that the difference is obvious: the exergy efficiency of ADC resulted from conventional exergy analysis decreases from 0.240 to 0.161 as the cooling output increases; whereas the cooling production exergy efficiency of system resulted from exergy cost analysis increases from 0.048 gradually, and rises to 0.058 when the system reaches design conditions.

Along with the micro-trigeneration system reaches rated power gradually, the waste heat recovered from JAC and EHE increases continually, as does the temperature of heat-source water which drives ADC. As a result, the difference in temperature of heat exchange grows, which leads to the increase of exergy destruction and the fall of exergy efficiency of ADC. This can easily make us to mislead that the performance of ADC in the trigeneration system is depressed gradually. Therefore, a conventional exergy analysis which calculates the efficiency of the units only quantifies the irreversibilities from a local point of view. This is the deficiency of simple exergy analysis. Actually, considering that the factor of the exergy cost of heating water, because the fuel exergy consumed by heating water is decreased

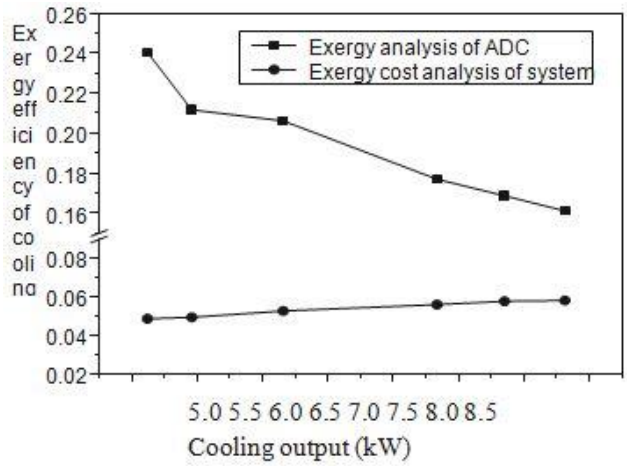

Fig. 7. Comparison of exergy efficiency of cooling between exergy analysis of ADC and exergy cost analysis of system.

gradually. Hence, it can be obtained that the cooling production exergy efficiency of system is increased continuously. This reflects the thermodynamic value of cooling exergy and the characteristics of trigeneration truly. It also illustrates that the exergy cost analysis can evaluate the performance of trigeneration system effectively.

VII. CONCLUSIONS

This paper analyzes a micro-trigeneration system using the exergy cost analysis method based on the structural theory of thermoeconomics. The major focus is on the construction of thermoeconomic model and the exergy cost analysis of combined cooling power and electricity. According to analysis and discussion, some conclusions are reached. Structural theory of thermoeconomics is a systematic analysis tool that provides in-depth information related to the costs and efficiency of energy conversion processes and the interactions between various components. The thermoeconomic methodology used in this paper can be beneficial in the analysis and design of similar complex systems. The unit exergy cost of electricity and cooling power of the trigeneration system is 4.155 exergy of LPG per exergy of electricity and 17.194 exergy of LPG per exergy of cooling at design conditions, respectively. The function of the ADC equals to an electricity powered water chiller with COP ¼ 2.51. If an ADC with a COP higher than 0.4 is used, the trigeneration system is more efficient in utilizing the recovered low-grade waste heat.The unit exergy cost of product of all components drops gradually as electricity output increases, and the production performance of ADC is better when the electricity output is above 10.3 kW. The inlet temperature of chilled water has a great impact on the unit exergy cost of product of ADC. Lower inlet temperature of chilled water is advantageous to the energy savings operation of the whole system. Compared with conventional exergy analysis, exergy cost analysis can embody the performance of trigeneration system more effectively from a global point of view.

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