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Reduced Exergy Method for Heat-Electricity Cost Allocation in Combined Heat and Power Plants

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Abstract

Although the cost allocation method does not change the total benefits of CHP, the use of various cost allocation methods generally results in significant differences in costs allocated for CHP products. In order to overcome the inadequacy of existing cost allocating methods in theory and in practice, according to the different roles of anergy and exergy in heat supply process of CHP plant, the reduced exergy method for cost allocation is formulated by introducing the concepts of the available anergy and reduced exergy. The contribution of the available anergy is expressed with a user factor, which can reflect different utilization for different practical conditions. Some practical conditions for typical CHP units are computed and compared with existing methods. Calculations show that the cost allocation by using the reduced exergy model is more rational and practical than those by using existing models in terms of embodying the physical meaning.

Keywords: exergy, anergy, cost allocation, combined heat and power plant

1. Introduction

Combined heat and power (CHP) is defined as the simultaneous production of power (either electrical or mechanical) and useful heat (e.g. steam and /or heat water), with the reject heat of one process thus becoming energy input a subsequent process so that the same fuel is used for two purposes [1-4]. It saves money by using a single fuel source to produce two forms of useful energy. CHP, as an important part of a sustainable development strategy, offers greater efficiency and less pollution than conventional plants, and has the flexibility to meet a variety of thermal and electric power requirements. A major reason for the potential growth of CHP is the need for the world to improve efficiency of power generation, while at the same time reducing pollution and increasing capacity. Conventional power plants have generating efficiencies of approximately 32 percent compared to CHP efficiencies of up to 70 percent. Because of the economic, efficiency and environment benefits of CHP, more and more governments are working with industrial partners to finance the development of state-of-the-art CHP technologies and increase the use of CHP [1-7].

In order to fully realize CHP's potential and to exert its advantages, it is most important to establish a reasonable cost allocation method for heat production and electricity generation in CHP plants. So far, many kinds of methods were proposed and each had its relative merits and limitations [1,8-10]. Although the cost allocation method does not increase or decrease the total benefits of CHP, the use of various cost allocation methods generally results in significant differences in costs allocated for CHP products. Therefore, it is still controversial that which method should be adopted, and the existing methods can not meet the requirements for practical applications [1,9,10].

In this paper, the merits and limitations of main existing methods are firstly discussed. Based on the energy analysis in CHP system, the reduced exergy method for cost allocation is formulated by introducing the concepts of the available anergy and reduced exergy. Some typical CHP units with different parameters are investigated and compared with different methods.

2. Description of Existing Methods

At present, the main proposed methods include the Btu equivalence method, actual enthalpy drop method, heat discount method, weighting method, exergy method, etc [1, 8-10]. We give a detailed account of above methods in the following.

The Btu equivalence method is based on the first law of thermodynamics. Under this method, the costs for both steam production and electricity generation are allocated in proportion to Btu equivalents of heat produced and electricity generated annually [1,9]. Simplicity is the greatest advantage of this method. However, due to the fact that only energy quantity but not energy quality of different forms of energy is being considered, this method treats different forms of energy equally with respect to quality and efficiency, and as a result favoring heat production over electricity generation. This method represents an extreme case, which is considered as an upper limit of heat cost allocation, with all fuel savings attributed to electricity generation [1].

The actual enthalpy drop method distributes the overall heat consumption in accordance with the ratio of the actual enthalpy drop of process-steam and/or heating steam to that of live steam [1,9,10]. This method takes essential distinctions in energy qualities of process-steam and/or heating steam into account, but it totally distributes low temperature receiver loss to electricity generation except heat production. So, all fuel savings attribute to heat production, which is contrary to the Btu equivalent method. That leads heat consumers to ameliorate production process and to degrade steam parameters as far as possible. However, the enthusiasm of electricity generation may be influenced to some extent without the consideration of interests of electricity generation.

The heat discount method allocates the overall heat consumption following the ratio of fuel use for steam production and that for electricity generation [1,9,10]. The annual fuel use for electricity generation is accounted as the product of electricity cogenerated and the average heat rate of a conventional condensing turbine unit. The fuel use for heat production is the difference between the total fuel use and computed fuel use for electricity generation. If taking this method, electricity cost is identical to that of conventional power plants and heating cost is very low. This method represents another extreme case, which is considered as a lower limit of heat cost allocation, with all fuel savings attributed to heat productions [1].

The weighting method compromises heat cost allocations with different weight factors, which are computed from the Btu equivalence and actual enthalpy drop methods. The recommended weight factors are 0.5, 0.6 and 0.7, respectively. Due to the lack of objective evidence and being up to researchers to a large extent, the rationality of this method will be determined by further investigations [9,10].

The exergy method is based on the second law of thermodynamics. This method allocates the overall heat consumption in accordance with the ratio of process-steam exergy and/or heating steam exergy to live steam exergy [1,9,10]. Exergy is a measure of the maximum capacity of an energy system to perform useful work as it proceeds to a specified final state in equilibrium with surroundings [8]. Exergy accounts not only for energy quantity but also for energy quality. Under this method, the quality of different forms of energy can be differentiated with exergy. At present, the cost allocation with exergy method is considered to be reasonable when taking heat and electricity as a joint product in some countries [9].

As we know, energy can be divided into two parts, one is exergy and the other is anergy. In fact, exergy is only a significative parameter in devices where heat energy is converted into power, and anergy is an inevitable waste. However, two parts of energy should be utilized in heating process because anergy is not a negative but a very positive factor [9,11-13]. Anergy can degrade the energy grade of high-quality energy as a thinner, and increase the energy quantity (e.g. heat pump). On the other hand, anergy, as a main component in a separated part ‘concentrated’ from low-quality energy, can upgrade the energy grade of low-quality energy for advanced consumers, but also make anergy meet the requirement of primary consumers (e.g. CHP). This can reduce the energy grade difference between the input energy and consumers, and make the full use of energy [12]. Moreover, the role of anergy depended on the state of surroundings is different in different heat energy utilization processes. Under the exegy method, the positive role of anergy is completely neglected in determining cost allocation, and the benefits of energy savings may be accrued mostly to heat customer over electricity generation in heat utilization. Therefore, the exergy method has theoretical and practical limitations [9,10].

Based on the concept of heat pump and considering the role of anergy, a combined heat-electricity method was presented by Feng, at el. [9]. But he thought that anergy play same roles in different heat energy utilizations of CHP units, which are not agree with practical conditions. So, this method has also theoretical limitation.

Therefore, it is absolutely necessary to consider essential distinctions in energy quantity and energy quality and to compromise benefits between heat production and electricity generating when establishing a sound heat-electricity cost allocation in CHP. The purpose of present study, based on the analysis of available energy in CHP system, is to establish a novel and reasonable model for determining the heat-electricity costs, with a view to rationally distributing of total benefits among cogenerated products.

3. Analysis of the available energy in CHP system

Figure1 presents an energy distribution of a double automatic extraction turbine unit in CHP system. The thermodynamic system only includes two stage extractions for heating supply. The output energy consists of two parts. One is electric energy, and the other is heat energy including process-steam and heating steam. Due to the complexity of practical objects and processes in CHP system, the present paper neglects the exergy loss of process owing to internal irreversibility for founding a simplified and universal allocation method.

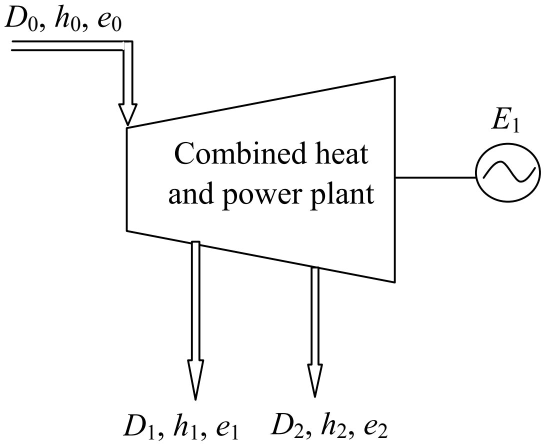

Fig.1 Energy Distribution diagram in CHP

As shown in Fig.1, the electric energy can be formulated as follows:

$$E_1 = D_0 e_0 - D_1 e_1 - D_2 e_2 \tag{1}$$

where, E_1 is the electric energy output. D, e, h are the steam flow, specific exergy and specific enthalpy, respectively. The subscripts 0, 1, 2 represent the live steam, process-steam and heating steam, respectively.

The total heat energy output in CHP system is expressed as:

$$E_2 = D_1 q_1 + D_2 q_2 \tag{2}$$

where, E_2 is the total amount of heat energy output. q_1, q_2 are the heat energy corresponding to process-steam and heating steam.

The total energy output in CHP system can be written as:

$$E = E_1 + E_2 \tag{3}$$

where, E is total energy output in CHP system.

In total energy output, the available part is electric energy and the available heat energy. As we know, the electric energy is exergy, which is convertible in all situations. However, heat energy is utilized partially, and the available part is exergy of heat energy. Under the exergy method, cost allocation is determined on the basis of exergy parameter. As mentioned above, during the practical process of heat energy utilization, part of the anergy plays an efficient role (or anergy plays a part efficient role). Namely, anergy is not a pure waste, and we define this partial anergy as the available anergy. Therefore, the total availability of heat energy output in CHP system should be composed of exergy and the available anergy. And the contribution of the available anergy must be taken into account when establishing a sound heat-electricity cost allocation method in CHP plants.

The specific available anergy is defined as:

$$a' = k(q - e) = k\frac{1-\Omega}{\Omega}e \tag{4}$$

where, a' is specific available-anergy. $k = a/e$, is the ratio of usevalue of specific anergy to that of specific exergy in practical process, $0 \le k \le 1$. a is specific anergy. $\Omega = e/q$, is energy level, $0 \le e \le 1$. q is heat energy per unit mass of process-steam/heating steam.

The reduced exergy is defined as the sum of the available anergy and exergy [14]. The reduced exergy per unit mass can be expressed as:

$$m = e + a' = \left(1 + k\frac{1-\Omega}{\Omega}\right)e \tag{5}$$

where, m is specific reduced exergy.

So, the avialable part of heat energy output is the total amount of the reduced exergy of process-steam and heating steam:

$$E_2' = D_1 m_1 + D_2 m_2 \tag{6}$$

And the total amount of available energy output in CHP system is rewritten as:

$$E' = E_1 + E_2' \tag{7}$$

where, E_2' is the avialable part of heat energy output. E' is the total amount of available energy output in CHP system.

4. Reduced exergy method

Since the reduced exergy takes different effects of exergy and available anergy into account in heat energy utilization in CHP system, the cost allocation based on the reduced exergy should be more rational and feasible than existing methods. Accordingly, a novel heat cost allocation in present paper is defined as:

$$\text{heat cost allocation} = \frac{\text{total amount of the reduced exergy of process - steam and heating steam}}{\text{electric energy} + \text{total amount of the reduced exergy of process - steam and heating steam}} \tag{8}$$

For the case of double automatic extraction turbine unit, its heat cost allocation is written as:

$$\alpha_{\text{REM}} = \frac{E_2^{'}}{E^{'}} = \frac{D_1 m_1 + D_2 m_2}{D_0 e_0 - (D_1 e_1 + D_2 e_2) + (D_1 m_1 + D_2 m_2)} \tag{9}$$

where, α is heat cost allocation. The subscripts REM represents the reduced exergy method.

After substituting Eq.(5) into Eq.(9), the heat cost allocation can be expressed as:

$$\alpha_{\text{REM}} = \frac{D_1 e_1 \left(1 + k_1 \dfrac{1-\Omega_1}{\Omega_1}\right) + D_2 e_2 \left(1 + k_2 \dfrac{1-\Omega_2}{\Omega_2}\right)}{D_0 e_0 + D_1 e_1 \left(k_1 \dfrac{1-\Omega_1}{\Omega_1}\right) + D_2 e_2 \left(k_2 \dfrac{1-\Omega_2}{\Omega_2}\right)} \tag{10}$$

The formulation $D_1 e_1 \left(k_1 \dfrac{1-\Omega_1}{\Omega_1}\right) + D_2 e_2 \left(k_2 \dfrac{1-\Omega_2}{\Omega_2}\right)$ represents the contributions of available anergy of process-steam and heating steam in heat energy utilization.

Once the CHP system is selected, the parameters of *D*, *e* and Ω can be determined. But it is difficult to determine parameter *k* due to the different roles of the available anergy in different heat energy utilization processes. In other words, the parameter *k* is determined from the actual conditions. Moreover, it is extremely difficult to assess the coefficient *k* accurately in theory. Consequently, the most challenging difficulty in applying the reduced exergy method is to determine coefficient *k* in Eq.(10) for allocating heat-electricity cost.

Based on the following pricinples and assumption of $k = \Omega$ [15]:

(1) When the reduced exergy is completely exergy or anergy, the usevalue of available anergy is zero in practical process.

(2) For the convenience of calculation, the reduced exergy is formulated as a state function.

(3) The available anergy is described as a function of energy level.

On these grounds, the re-deduced expressions are universally applicable. Eqs. (4) and (5) can be simplified as:

$$a' = (1 - \Omega)e \tag{11}$$

$$m = (2 - \Omega)e \tag{12}$$

Through simplifying, Eq. (10) can be formulated as:

$$\alpha_{\mathrm{REM}} = \frac{D_1 e_1 (2 - \Omega_1) + D_2 e_2 (2 - \Omega_2)}{D_0 e_0 + D_1 e_1 (1 - \Omega_1) + D_2 e_2 (1 - \Omega_2)} \tag{13}$$

If taking the exergy method, the heat cost allocation can be written as:

$$\alpha_{\mathrm{EM}} = \frac{D_1 e_1 + D_2 e_2}{D_0 e_0} \tag{14}$$

where, the subscripts EM represents the exergy method.

The reduced exergy method includes the contribution of the available anergy comparing with the exergy method, and its superiority can be expressed by the ratio of heat cost allocation calculated from the reduced exergy method to that from the exergy method. The ratio is defined as a user factor and expressed as:

$$\zeta = \frac{\alpha_{\mathrm{REM}} - \alpha_{\mathrm{EM}}}{\alpha_{\mathrm{EM}}} = \frac{\dfrac{D_1 e_1 (2 - \Omega_1) + D_2 e_2 (2 - \Omega_2)}{D_0 e_0 + D_1 e_1 (1 - \Omega_1) + D_2 e_2 (1 - \Omega_2)}}{\dfrac{D_1 e_1 + D_2 e_2}{D_0 e_0}} - 1 \tag{15}$$

where, ζ is user factor.

5. Applications And Discussions

For comparing the reduced exergy method with existing methods, some typical CHP units with different parameters and capacities from 6 MW to 100MW are investigated in Table1. h_{fw}, h_{n} h_{rw} are the enthalpy of feed water, enthalpy of exhaust steam and enthalpy of return water, respectively. Table2 presents the heat cost allocations computed with present method and existing methods. It is clearly showed from Table2 that there are great differences among these results for above methods, especially those from the Btu equivalence method are from 3 to 10 times than those from the heat discount method. Computed results show that heat cost allocations calculated with the Btu equivalence and heat discount method are maximum and minimum among all the methods, which represent the two extreme distribution cases. As mentioned above, the Btu equivalence method completely attributes all fuel savings to electricity generation, and heat discount method attributes all fuel savings to heat production [1,9]. The heat cost allocations with the other existing methods are within between those from the Btu equivalence and heat discount method, but the differences are still remarkable. Although the existing methods do not increase or decrease the total benefits of CHP, it is obvious that the significant differences using existing methods can not meet the requirements in costs allocated for CHP products.

Table1 Practical parameters for different units

Unit type	D_0	h_0	h_{fw}	D_1	h_1	D_2	h_2	h_{rw}	h_{n}	e_0	Ω_0	e_1	Ω_1	e_2	Ω_2
BJIT-50-2	276.8	3475	994	24	2627	0	0	435	2307	1623	0.654	670	0.306	0	0
B25-90/1.75	145	3475	984	115	2700	0	0	335	2392	1623	0.652	737	0.312	0	0
B12-90/39	280	3475	984	275	2700	0	0	335	2392	1623	0.652	1140	0.482	0	0
B25-90/13	221.8	3475	984	178	3024	0	0	419	2270	1623	0.652	1121	0.43	0	0
B50-90/2	285	3475	984	233	2705	0	0	335	2307	1623	0.652	760	0.321	0	0
34-12-1	120	3305	716	50	2945	40	2687	335	2392	1401	0.541	748	0.287	624	0.265
54-25-1	164.8	3389	867	72	2945	54	2684	335	2392	1567	0.621	748	0.287	690	0.294
C6-35/5	57.5	3305	600	45	2957	0	0	335	2392	1401	0.518	691	0.264	0	0
C6-35/10	66.4	3305	634	45	3076	0	0	335	2307	1401	0.525	838	0.306	0	0
C12-35/5	89.4	3305	729	50	2930	0	0	335	2392	1401	0.544	672	0.259	0	0
C12-35/10	95.6	3305	729	50	3061	0	0	335	2392	1401	0.544	831	0.305	0	0
C12-50/1.2	75	3305	730	45	2684	0	0	335	2392	1431	0.556	687	0.292	0	0
C12-50/16	105	3305	730	60	3077	0	0	335	2392	1431	0.556	1177	0.429	0	0
C50-90/1.2	266.6	3475	983	180	2620	0	0	335	2392	1623	0.651	672	0.294	0	0
C50-90/13	310	3475	957	160	3089	0	0	418	2392	1623	0.645	1154	0.432	0	0
CB6-35/16/7	109.4	3305	930	45	3156	0	0	335	2307	1401	0.544	1217	0.431	0	0
CB10-50/10/5	141.5	3284	730	70	2984	0	0	335	2392	1431	0.56	795	0.3	0	0
CB10-50/16/10	183.5	3284	730	100	3082	0	0	335	2392	1431	0.56	1177	0.428	0	0
CB12-35/5/1.75	136	3305	729	65	2938	0	0	335	2392	1401	0.544	682	0.262	0	0
CB12-35/10/3	141.8	3305	729	80	3051	0	0	335	2307	1401	0.544	827	0.304	0	0
CB12-50/10/5	131.4	3284	730	50	2984	0	0	335	2392	1431	0.56	795	0.3	0	0
CB12-50/13/5	150.5	3284	730	100	3056	0	0	418	2392	1431	0.56	1136	0.431	0	0
CB12-50/16/5	162.8	3284	730	81	3082	0	0	335	2392	1431	0.56	1177	0.428	0	0
CB25-90/10/1.2	171.8	3475	931	80	2992	60	2684	335	2392	1623	0.638	795	0.299	687	0.292
CC12-35/10/1.2	85.52	3305	729	50	3030	10	2681	335	2307	1401	0.544	1092	0.405	687	0.293
CC50-90/10/1.2	300	3475	957	125	2970	90	2620	335	2392	1623	0.645	1062	0.403	672	0.294
CC50-90/13/1.2	311	3475	957	140	3030	100	2620	335	2392	1623	0.645	1123	0.417	672	0.294
CC100-90/10/1.2	460	3475	957	170	2933	100	2715	335	2392	1623	0.645	1043	0.401	760	0.319

Exergy parameters in calculations can be found in reference [16].

Table2 heat cost allocations calculated from present and existing methods

Unit type	Btu equivalence method	Reduced exergy method	Combined heat-electricity method	Weighting method	Exergy method	Actual enthalpy drop method	Heat discount method	User factor
BЛT-50-2	0.07660	0.05917	0.03946	0.05017	0.03579	0.02375	0.01118	0.65326
B25-90/1.75	0.74971	0.48556	0.39067	0.48714	0.35858	0.22457	0.09764	0.35412
B12-90/39	0.93246	0.77151	0.68756	0.60589	0.68986	0.27932	0.12144	0.11835
B25-90/13	0.84096	0.66229	0.57328	0.67207	0.55543	0.50318	0.24341	0.19239
B50-90/2	0.77783	0.51021	0.41433	0.52821	0.38283	0.27858	0.13062	0.33273
34-12-1	0.72287	0.50380	0.41955	0.54147	0.37093	0.36008	0.12698	0.35822
54-25-1	0.75733	0.48255	0.39660	0.54781	0.35283	0.33830	0.13374	0.36764
C6-35/5	0.75860	0.52191	0.44767	0.62145	0.38600	0.48431	0.16347	0.35210
C6-35/10	0.69547	0.53597	0.44957	0.60884	0.40537	0.52220	0.19512	0.32217
C12-35/5	0.56341	0.38961	0.31028	0.44649	0.26826	0.32957	0.11681	0.45233
C12-35/10	0.55347	0.43259	0.34295	0.46835	0.31022	0.38324	0.13583	0.39444
C12-50/1.2	0.54734	0.40858	0.32100	0.36962	0.28805	0.19189	0.06804	0.41845
C12-50/16	0.60849	0.58210	0.48002	0.51861	0.47000	0.42873	0.15201	0.23852
C50-90/1.2	0.61909	0.39829	0.30794	0.38061	0.27955	0.14214	0.06177	0.42475
C50-90/13	0.54749	0.47616	0.37921	0.43983	0.36698	0.33217	0.14287	0.29751
CB6-35/16/7	0.48858	0.46584	0.36261	0.41925	0.35731	0.34992	0.14704	0.30372
CB10-50/10/5	0.51310	0.39182	0.30650	0.42071	0.27483	0.32832	0.11467	0.42566
CB10-50/16/10	0.58627	0.56085	0.45883	0.50395	0.44833	0.42164	0.14726	0.25099
CB12-35/5/1.75	0.48295	0.34511	0.26818	0.38439	0.23266	0.28582	0.10130	0.48331
CB12-35/10/3	0.59484	0.45846	0.36821	0.50771	0.33303	0.42059	0.16294	0.37664
CB12-50/10/5	0.39467	0.31304	0.23575	0.32361	0.21140	0.25254	0.08820	0.48080
CB12-50/13/5	0.68631	0.63661	0.54268	0.59046	0.52748	0.49461	0.17275	0.20690
CB12-50/16/5	0.53514	0.52121	0.41881	0.46001	0.40923	0.38487	0.13442	0.27364
CB25-90/10/1.2	0.80881	0.50644	0.41854	0.58048	0.37593	0.35215	0.14991	0.34719
CC12-35/10/1.2	0.71814	0.62872	0.53264	0.59275	0.51304	0.46736	0.18107	0.22550
CC50-90/10/1.2	0.70827	0.51766	0.42032	0.49690	0.39686	0.28553	0.12281	0.30439
CC50-90/13/1.2	0.77359	0.56463	0.46877	0.55324	0.44461	0.33289	0.14317	0.26994
CC100-90/10/1.2	0.58678	0.45461	0.35719	0.41812	0.33929	0.24945	0.10729	0.33988

The previous literatures indicated that the rational heat cost allocation should be within between the Btu equivalence and actual enthalpy drop methods, which can correctly reflect the practical process in CHP system [1,9]. The results computed in Table2 illustrate that only the exergy method, weighting method, combined heat-electricity method and reduced exergy method meet this requirement. However, under the exergy method, the benefits of energy savings may be accrued mostly to heat customer over electricity generation due to neglecting the contribution of anergy. The weight factors in weighting method are affected by researchers to a large extent. And the same roles of anergy played in different heat energy utilizations are taken in the combined heat-electricity method. So the above three methods are not perfect in theory. By including the different contributions of available anergy in determining heat-electricity cost allocation, the reduced exergy method can evaluate the availability level of energy in different qualities more accurately than existing methods. So, the results calculated with reduced exergy method are higher than those with exergy method, and more rational than those with combined heat-electricity method.

As indicated by Eqs. (13) and (15), the use factor is closely related to the parameters of the live steam, process-steam and heating steam. For above units listed in Table1, the user factor ζ is within the range from 0.12 to 0.65, which is the contribution of available anergy in heat energy utilization. Since those CHP units have different extraction parameters and outputs in practical conditions, the available anergy has a distinct role for each unit. The different values of user factor can exactly reflect the different levels of heat energy utilization in CHP system.

Based on theoretical analysis and computed results, it can be seen that, for determining the heat-electricity cost allocation, whether rationally considering the contributions of exergy and available anergy will evidently affect the calculated results, and directly related to how to distribute the benefits for electricity generation and heat production. When establishing a reasonable cost allocation method, the effects of exergy and available anergy should be taken into account in different utilization of heat energy. Therefore, the reduced exergy method presented in this paper is more reasonable than existing methods for determining cost allocation in CHP system.

6. Conclusions

Due to the intimate relationship with the benefits of the power plant and those of heat customers, a reasonable cost allocation method in CHP plants is still a disputed problem theoretically and practically. In order to overcome the deficiencies with existing heat-electricity cost allocation methods, the concepts of the available anergy and reduced exergy are introduced. The reduced exergy method is established according to the different effects of exergy and available anergy in heat energy utilization process in CHP system. Cost allocation with the reduced exergy method considers not only the differences in energy quantity and energy quality, but also the role of available anergy. Furthermore, the contribution of available anergy is expressed as a user factor, which can reflect energy utilization levels for different practical conditions.

For some CHP units in different types and capacities, heat cost allocations are compared with the reduced exergy method and existing methods. Computed results verify the feasibility of reduced exergy method, and indicate that the cost allocation calculated from the reduced exergy method is more rational and accurate than those from existing methods in terms of embodying the physical meaning of available anergy.

7. References and Notes

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