The Modified Productive Structure Analysis of Afyon Geothermal District Heating System for Economic Optimization

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Abstract- This study deals with exergetic and exergoeconomic analysis of geothermal district heating system (GDHS) which offers nowadays many disadvantages in the aspect of high heat losses and costs. The Afyon GDHS located in the city of Afyonkarahisar/Turkey is selected as a case study. The modified productive structure analysis (MOPSA) is used for exergy-cost evaluation. In these analyses, mass and energy conservation laws are applied to each component of the system. Quantitative balances of the exergy and exergetic cost for the whole system and its each component is carefully considered. The results show that about 52.49% of the input cost of the Afyon GDHS is lost from the heat exchangers, 16.26% from pipes, and 7.22% from pumps. The heat exchangers and their effectiveness should be improved as high as possible to decrease the system costs. The unit cost of heating from geothermal water in the Afyon GDHS is about 711.491 US$/h at 100% load conditions.

Keywords- Geothermal energy, district heating, exergy, economy, MOPSA method.

1. Introduction

Energy is one of the most important inputs required to maintain social and economic improvement in a country. It is necessary that energy demand should occur at the right time economically, and should be of good quality and respectful of increasing environmental consciousness in order to preserve national development and a high standard of living [1].

In general, energy consumption can be examined under four main sectors: industrial, building (residential), transportation and agriculture. Energy consumption in the residential sector is one of the main parts of the total energy consumption in most countries. According to Buyukalaca and Bulut [2], approximately 25-30% of the total energy consumption in Turkey is used by the residential sector. The energy consumption of space heating is approximately two times more than that of the other consumption sources (such as water heating, cooking, food refrigeration and freezing) in residential sector [3]. Therefore, improvement in performance of geothermal district heating system (GDHSs) is a very effective mean to decrease energy consumption. The importance of energy efficiency is also linked to environmental problems, such as global warming and air pollution.

Energy efficiency is a rather general term and in practice various energy performance indicators are used, usually grounded in thermodynamics or economics. The thermodynamic indicators can measure either the first law efficiency (energy) or the second law (exergy) efficiency. The economic indicators measure the performance in terms of economic values, such as energy prices [4].

Thermodynamic indicators of performance based on the second law are nowadays commonly accepted as the most natural way to measure the performance of systems (especially, GDHSs). An important development to couple exergy and economy was the formulation of “exergoeconomic” where efficiencies are calculated via an exergy analysis [5, 6]. Different approaches for formulating efficiencies and costing equations have been suggested in the literature. These approaches can be divided into two groups [7]: (i) The exergoeconomic accounting methods aim at the costing of product streams, the evaluation of components and systems, and the iterative optimization of energy systems (e.g. the modified productive structure analysis (MOPSA) developed by Oh et al. [8] and Kim et al. [9]; the specific exergy costing (SPECO) presented by Lazzaretto and Tsatsaronis [7, 10] (e.i., [11, 12]); (ii) The Lagrangian-based approaches have as a goal the optimization of the overall system and the calculation of marginal costs (e.g., Exergy, cost, energy and mass (EXCEM) method proposed by Rosen and Scott [13]) (e.i., [14-16]).

In this regard, the modified productive structure analysis (MOPSA), which was known as exergoeconomic analysis, has been applied by a number of investigators. Kim et al. [9] provided a theoretical basis for the exergy costing method suggested by Lozano and Valero [17] to a cogeneration system based on a 1000 kW gas turbine with a waste heat boiler as thermal system. Kwon et al. [18] developed a thermodynamic for the effect of the annualized cost of a component on the production cost in 1000 kW gas turbine cogeneration system by utilizing the generalized exergy balance and cost balance equations developed previously. Kwak et al. [19] performed exergetic and thermoeconomic analyses for a 500 MW combined cycle plant using the MOPSA. Kwak et al. [20] performed exergetic and thermoeconomic analysis for a 200 kW phosphoric acid fuel cell plant which offers many advantages for co-generation in the aspect of high electrical efficiency and low emission. This fuel cell system may be viable economically when the initial investment cost per power is reduced to the level of the gas turbine co-generation plant of 1500 US$/kW. Kwak et al. [21] investigated the cost structure of the CGAM system by using the MOPSA. Oktay and Dincer [22] presented an application of an exergoeconomic model, which included both exergy and cost accounting analyses for a GDHS in Balikesir/Turkey. They applied cost balance equation to each component of the system and to each junction while they solved a set of equations to calculate unit costs of various exergies. They obtained the lost cost of each component of the system. Some configurations for the GDHS were also considered and compared in the analysis, which used appropriate exergy and cost balance equations. Hepbasli [23] reviewed the GDHSs in terms of three aspects, namely energetic, exergetic and exergoeconomic analyses and assessments. Coskun et al. [24] proposed a modified exergoeconomic model for geothermal power plants using exergy and cost accounting analyses. They presented a case study for the Tuzla geothermal power plant system in Turkey to illustrate an application of the modified exergoeconomic model.

This paper is the study on modified productive structure analysis (MOPSA) of a GDHS for economic optimization. The Afyon GDHS located in the city of Afyonkarahisar/Turkey is selected for exergy-cost evaluation. The system operation is described based on Refs. [16, 25-27]. Exergoeconomic analysis procedure and formulations are developed for the present Afyon GDHS using methods in Refs. [9, 17-24]. The MOPSA of thermal systems are utilized for this purpose. This procedure is used for obtaining exergetic cost values for the system and its components.

2. The Afyon GDHS

The Afyon geothermal district heating system (GDHS) was founded in 1994 to provide residential heating for buildings by using geothermal water and to provide hot water for commercial greenhouses by using re-circulated geothermal fluid. The Afyon GDHS was initially designed for 10000 residences equally but today, 4613 of these residences are heated. The heat source of the Afyon GDHS originates from the Omer-Gecek geothermal field, 15 km northwest of Afyonkarahisar City. An average reservoir temperature of wells in this field is 105 °C. Potential of the Afyon GDHS is 48.333 MW_t. The Afyon GDHS consists mainly of three cycles: (a) energy production cycle (EPC), (b) energy distribution cycle (EDC), and (c) energy consumption cycle (ECC). A schematic of the Afyon GDHS is shown in Fig. 1.

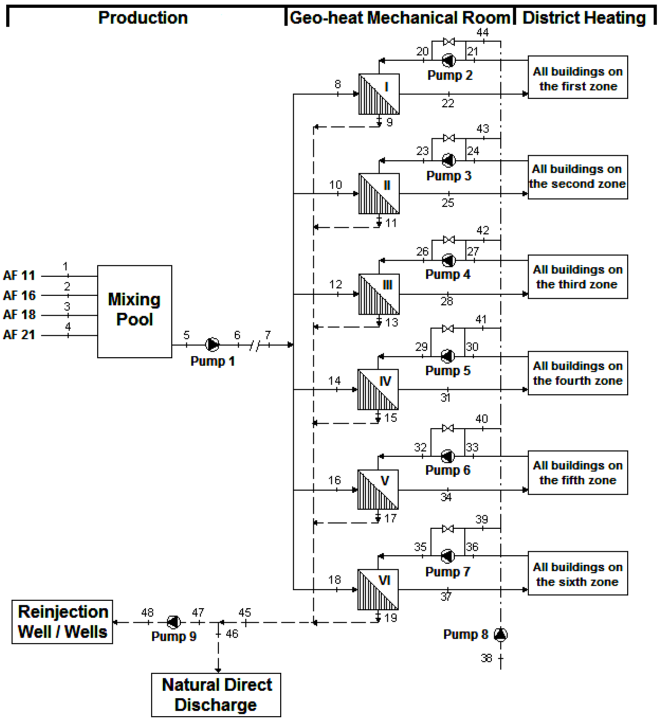

Fig. 1. Schematic diagram of the Afyon GDHS (I-VI: heat exchangers).

As can be seen in the figure, the geothermal fluid collected from the four production wells is stored in the mixing pool with a total mass flow rate of about 175 kg/s. The geothermal fluid is then pumped through the main pipeline to the geo-heat mechanical room of the Afyon GDHS in Afyonkarahisar. And the geothermal fluid is sent to the six heat plate exchangers at a 16 million kcal/h total capacity in the geo-heat mechanical room and is cooled to about 45-50 °C. The geothermal fluid is then discharged via natural direct discharge and re-injected. Also, the clean hot water is pumped to the six exchangers and then outgoing water is sent to the heat exchangers which are constructed under all buildings on the zones. The mean temperatures of clean hot water obtained during the operation of the Afyon GDHS are 60/45 °C for this cycle.

3. Mathematical Analysis

The balance equations for mass, exergy and cost can be written for the Afyon GDHS and its components under steady-state steady-flow control volume conditions. Also, these equations were used by some earlier researchers [25-29]. For the Afyon GDHS, the mass balance equation is written as follows

$$\sum_{i=1}^{n} \dot{m}_{w,i,Tot} - \dot{m}_{mp} - \dot{m}_{r} - \dot{m}_{d} = 0 \tag{1}$$

where $\dot{m}_{w,i,Tot}$ is the total mass flow rate at wellhead, $\dot{m}_r$ is the flow rate of the reinjected geothermal fluid, $\dot{m}_{mp}$ is the flow rate of the remained geothermal fluid in mixing pool, and $\dot{m}_d$ is the mass flow rate of the natural direct discharge.

The general exergy rate balance can be expressed as

$$\dot{E}x_{heat} - \dot{E}x_{work} + \dot{E}x_{mass,in} - \dot{E}x_{mass,out} = \dot{E}x_{dest} \tag{2}$$

and

$$\begin{aligned} &\sum \left(1 - \frac{T_0}{T_k}\right) \dot{Q}_k - \dot{W} + \sum \dot{m}_{in} \psi_{in} \\ &\qquad - \sum \dot{m}_{out} \psi_{out} = \dot{E}x_{dest} \end{aligned} \tag{3}$$

The geothermal fluid exergy inputs from the production field of the Afyon GDHS are calculated from

$$\begin{aligned} \dot{E}x_{in} = \dot{E}x_{brine} &= \dot{m}_{w,Tot} \\ &\times \left[\left(h_{brine} - h_0 \right) - T_0 \left(s_{brine} - s_0 \right) \right] \end{aligned} \tag{4}$$

The exergy destructions in the pump, heat exchanger, mixing pool and system itself of the Afyon GDHS are calculated as follows

$$\dot{E}x_{dest,pump} = \dot{W}_{pump} - (\dot{E}x_{out} - \dot{E}x_{in}) \tag{5}$$

$$\dot{E}x_{dest,he} = \dot{E}x_{in} - \dot{E}x_{out} \tag{6}$$

$$\dot{E}x_{dest,mp} = \dot{E}x_{in} - \dot{E}x_{out} \tag{7}$$

$$\dot{E}x_{dest,system} = \sum \dot{E}x_{dest,pump} + \sum \dot{E}x_{dest,he} \tag{8}$$

The exergy efficiency of the Afyon GDHS can be defined respectively as

$$\begin{aligned} \varepsilon_{system} &= \frac{\dot{E}x_{useful,he}}{\dot{E}x_{brine}} \\ &= 1 - \frac{\dot{E}x_{dest} + \dot{E}x_{r} + \dot{E}x_{d} + \dot{E}x_{mp}}{Ex_{brine}} \end{aligned} \tag{9}$$

The exergy efficiency of a heat exchanger is basically defined as

$$\varepsilon_{he} = \frac{\dot{m}_{cold} \left(\psi_{cold,out} - \psi_{cold,in} \right)}{\dot{m}_{hot} \left(\psi_{hot,out} - \psi_{hot,in} \right)} \tag{10}$$

The exergy-cost-balance equations, developed by Oh et al. [8] and Kim et al. [9], were applied to the Afyon GDHS for performance assessment purposes. Using this methodology, the cost-balance equation was written for each component of the whole system and to each junction. Thus a set of equations for the unit costs of various exergies was obtained for solution. Solving such equations provided the monetary evaluations of various exergy (thermal, mechanical, etc.) costs, as well as the unit cost of useful heat of the thermal system. The exergy-balance equation for the non-adiabatic components is modified to reflect the exergy losses due to heat transfer. The general exergy-balance equation applicable to cost equation is written as [14]

$$\begin{aligned} &\dot{E}x_{tw}^{Q} + \dot{E}x^{W} + \left(\sum_{input} \dot{E}x_{i}^{T} - \sum_{outlet} \dot{E}x_{j}^{T} \right) \\ &\quad + \left(\sum_{input} \dot{E}x_{i}^{P} - \sum_{outlet} \dot{E}x_{j}^{P} \right) \\ &\quad + T_0 \left(\sum_{input} \dot{S}_i - \sum_{output} \dot{S}_j + \frac{Q_{CV}}{T_0} \right) = \dot{E}x_{usf}^{Q} \end{aligned} \tag{11}$$

where $\dot{Q}_{CV}$ denotes the heat transfer interaction between a component and environment. Considering a unit exergy cost to every separated exergy stream, the exergetic cost-balance equation can be written, according to the exergy-balance equation as given above, as:

$$\begin{aligned} &\dot{E}x_{tw}^{Q} + \dot{E}x^{W} C_W + \left(\sum_{input} \dot{E}x_{i}^{T} - \sum_{outlet} \dot{E}x_{j}^{T} \right) C_T \\ &\quad + \left(\sum_{input} \dot{E}x_{i}^{P} - \sum_{outlet} \dot{E}x_{j}^{P} \right) C_P \\ &\quad + T_0 \left(\sum_{input} \dot{S}_i - \sum_{output} \dot{S}_j + \frac{Q_{CV}}{T_0} \right) C_S \\ &\quad + \dot{Z}_{(k)} = \dot{E}x_{usf}^{Q} C_Q \end{aligned} \tag{12}$$

where $\dot{Z}(k)$ stands for all financial charges associated with owning and operating the kth plant component. The stream exergy is also separated into thermal and mechanical exergies. Here, the exergy costing method based on the above given equations MOPSA (modified productive structure analysis), developed by Lozano and Valero [17], was employed. In order to calculate annualized cost of the equipment $\dot{Z}(k)$ inside the control volume, the annualized (or levelized) cost method is employed, as presented in Bejan et al. [5], to calculate the capital costs of system components

$$\dot{Z}_{(k)} = \frac{\varphi_k C_k}{3{,}600\, a} \tag{13}$$

with

$$\dot{C}_k = PW_k \, CRF(i,n) \tag{14}$$

and

$$PW_k = c_k - S_{k,n} \, PWF(i,n) \tag{15}$$

Table 1. Thermal and mechanical exergy rates and entropy production rates at various system locations for the Afyon GDHS.

State no.	T (°C)	P (kPa)	$\dot{m}$ (kg/s)	$\dot{E}x^T$ (kW)	$\dot{E}x^P$ (kW)	$\dot{S}$ (kW)
0	2.3	101.32	-	-	-	-
1	99	183.34	100.0	5800.862	5.801	129.584
2	96	127.56	40.0	2189.918	2.190	50.470
3	98	212.21	40.0	2276.869	2.277	51.379
4	93	83.40	45.0	2320.939	2.321	55.233
5	95	94.85	175.0	9390.687	28.172	218.820
6	95.7	799.30	175.0	9523.831	142.857	220.212
7	93	70.56	175.0	9025.874	72.207	214.795
8	93	70.56	37.5	1934.116	15.473	46.028
9	51	48.87	37.5	604.886	6.654	26.873
10	93	70.56	38.8	2001.165	16.009	47.623
11	49	52.05	38.8	577.068	6.348	26.803
12	93	70.56	41.7	2150.737	17.206	51.183
13	52	46.45	41.7	698.933	7.688	30.420
14	93	70.56	27.8	1433.824	11.471	34.122
15	49	47.91	27.8	413.466	4.548	19.204
16	93	70.56	16.7	861.326	6.891	20.498
17	48	48.54	16.7	238.831	2.627	11.318
18	93	70.56	12.5	644.705	5.158	15.343
19	56	50.50	12.5	242.424	2.667	9.759
20	47.7	645.24	125.0	1765.193	26.478	84.225
21	47	331.23	125.0	1712.767	5.138	83.088
22	61	660.56	125.0	2867.130	43.007	105.475
23	47.7	635.45	138.9	1961.482	29.422	93.591
24	47	350.67	138.9	1903.227	5.710	92.327
25	60	650.90	138.9	3082.492	46.237	115.468
26	49.7	625.45	138.9	2124.100	31.861	97.216
27	49	370.20	138.9	2065.844	6.198	95.952
28	61	660.56	138.9	3186.940	47.804	117.176
29	49.7	580.67	97.2	1489.088	22.336	68.021
30	49	400.54	97.2	1445.645	4.337	67.146
31	60	610.89	97.2	2157.078	32.356	80.802
32	52.7	590.43	55.6	956.927	14.354	41.061
33	52	500.40	55.6	931.910	2.796	40.560
34	60	600.65	55.6	1233.884	18.508	46.220
35	52.7	555.34	41.7	717.696	10.765	30.795
36	52	510.90	41.7	698.933	2.097	30.420
37	60	560.00	41.7	925.413	13.881	34.665
38	12.4	220.45	10.0	7.604	18.250	1.863
39	-	-	-	-	-	-
40	-	-	-	-	-	-
41	12.4	410.45	1.9	1.445	4.334	0.354
42	12.4	410.45	2.8	2.129	6.387	0.522
43	12.4	410.45	2.8	2.129	6.387	0.522
44	12.4	410.45	2.5	1.901	5.703	0.466
45	50	70.56	175.0	2707.607	29.784	123.165
46	50	70.56	52.8	816.924	8.986	37.161
47	50	70.56	122.2	1890.683	20.798	86.004
48	50.7	800.45	122.2	1945.667	214.023	87.104

State numbers refer to Fig. 1 for the Afyon GDHS. The values based on the measurements are taken in January 20, 2010.

where φ is the maintenance factor, $\dot{C}$ is the annualized cost ($/year), a is annual operating hours (h/year), PW is the amortization cost (present worth) for any particular plant component, CRF(i,n) is the capital recovery factor, S is the salvage value and PWF is the present worth factor. In this regard, the salvage values are taken as 10% of the capital cost. The maintenance cost is taken into consideration through the factor φ_k=1.06 for each of the system components whose average expected life is assumed to be 15 years [24]. The interest (i) rate and the unit electricity price are taken as 12% and 0.2233 US$/kWh according to Turkey's 2010 year status, respectively.

Table 2. Exergy balances data of each component in the Afyon GDHS.

Component no.	$\dot{E}x^W$ (kW)	$\dot{E}x^T$ (kW)	$\dot{E}x^P$ (kW)	$\dot{S}$ (kW)
Heat exchanger				
I	0	-227.29	-25.35	197.29
II	0	-303.09	-26.48	273.09
III	0	-388.96	-25.46	358.96
IV	0	-352.37	-16.94	322.37
V	0	-345.54	-8.42	315.54
VI	0	-194.56	-5.61	164.56
Booster Pump				
Pump 1	-315	133.14	114.69	67.17
Circulation Pumps				
Pump 2	-90	52.43	21.34	16.23
Pump 3	-90	58.26	23.71	8.03
Pump 4	-90	58.26	25.66	6.08
Pump 5	-70	43.44	18.00	8.56
Pump 6	-50	25.02	11.56	13.42
Pump 7	-50	18.76	8.67	22.57
Pump of pressurized water tank				
Pump 8	-20	0.00	4.56	15.44
Reinjection pump				
Pump 9	-315	54.98	193.23	66.79
Pipes				
Pipes	0	-565.96	-71.40	505.56
TOTAL	-1090	-1933.48	241.77	2361.67

4. Results and Discussion

The exergetic and exergoeconomic analyses are performed for the Afyon GDHS. In these analyses, mass and energy conservation laws are applied to each component of that system. To calculate various aspects of mass, exergy and cost accounting parameters in terms of exergy flow rates and entropy generation rates (or exergy destruction rates) using Engineering Equation Solver (EES) software package; the actual pressures, temperatures, and mass flow rates were measured at various points in accordance with their state numbers as specified in Fig. 1, on January 20, 2010. Therefore, all these actual data and calculated mechanical and thermal exergy flow rates and entropy production rates at various state points of the system are given in Table 1, at 100% loading condition.

The net flow rates of mechanical, thermal and work related exergies for each component in the Afyon GDHS are given in Table 2. In here, positive values of exergies indicate the exergy flow rate of "products" while negative values represent the exergy flow rate of "resources". The product of a component corresponds to the "added" exergy whereas the resource to the "consumed" exergy [30]. Negative values of the work exergies represent that work was done on the components, simply work inputs to the pumps. Thermal water coming from the wells is treated as input, and useful exergy appears as output, based on the conversion from the resource to the product, respectively. In the system, 17.25% of the exergy input (13691.18 kW) is destroyed. This corresponds to 2361.67 kW, which is the total exergy destruction (or irreversibilities) in the Afyon GDHS. 69.10% of this is destroyed in the heat exchangers, 9.50% in the pumps and the remaining in the pipes as 21.40%, respectively. This shows that the most considerable entropy production (exergy destruction) occurs in the heat exchangers as there is an urgent need for improvement.

Table 3. Initial investments, annualized costs and monetary flow rates of each component in the Afyon GDHS.

Component no.	Inital investment cost (US$)	Annualized cost (US$/year)	Monetary flow rate (US$/h)
Heat exchanger			
I	186852	26933.19	5.665
II	186852	26933.19	5.665
III	186852	26933.19	5.665
IV	127320	18352.14	3.860
V	127320	18352.14	3.860
VI	71766	10344.48	2.176
Booster Pump			
Pump 1	15318	2207.96	0.464
Circulation Pumps			
Pump 2	3868	557.54	0.117
Pump 3	3868	557.54	0.117
Pump 4	3868	557.54	0.117
Pump 5	3352	483.16	0.102
Pump 6	2281	328.79	0.069
Pump 7	2281	328.79	0.069
Pump of pressurized water tank			
Pump 8	469	67.60	0.014
Reinjection pump			
Pump 9	15318	2207.96	0.464
Pipes			
Pipes	6920930	997595.42	209.812
Pipes	7583950	1093164.32	229.912
TOTAL	15442465	2225904.94	468.147

It is obvious that the economic and performance of a GDHS can be improved enormously if the heat exchangers, pumps, pipes losses exergy flow rate are recovered accordingly. In Table 3, the initial investments, the annuity including the maintenance cost, and the corresponding monetary flow rates for each component of the system are taken from managements of the Afyon GDHS and the producers of heat exchangers, pumps and pipes components for construction and other costs.

Quantitative balance of the exergies and exergy costs for each component and for the whole system was carefully considered. The exergy-balance equation developed by Oh et al. [8] and the corresponding exergy cost-balance equation developed by Kim et al. [9] are used in the MOPSA. The cost-balance equations for each component of the Afyon GDHS can be derived from the general cost-balance equation as given in Eq. (12). Once exergy balances for the components, junctions and the plant boundary are established, the unit cost of various exergies and products are calculated by solving from the matrix representation of the cost balance equations simultaneously. This is done as suggested by Kwak et al. [19].

Sum of the cost flow rates of each component in the Afyon GDHS equals zero, as shown in Table 4, and shows that cost balances for the each component are suitable. In the total system, the sum of the cost flow rates of electricity and capital expenditures of the GDHS equals zero, which is in fact a content of Eq. (12). Such result confirms that the overall cost balance as given in Eq. (12) is fully correct.

Table 4. Cost flow rates of thermal, mechanical and entropy production of each component in the Afyon GDHS.

Component no.	$\dot{C}_W$(US$/h)	$\dot{C}_T$(US$/h)	$\dot{C}_P$(US$/h)	$\dot{C}_S$(US$/h)	$\dot{Z}$(US$/h)
Heat exchanger					
I	0	-11.296	-12.751	29.712	-5.665
II	0	-22.139	-13.323	41.127	-5.665
III	0	-35.583	-12.812	54.060	-5.665
IV	0	-36.164	-8.525	48.549	-3.860
V	0	-39.426	-4.236	47.522	-3.860
VI	0	-19.786	-2.821	24.783	-2.176
Booster Pump					
Pump 1	-70.324	-0.283	60.955	10.116	-0.464
Circulation Pumps					
Pump 2	-20.093	-0.113	17.878	2.445	-0.117
Pump 3	-20.093	-0.129	19.129	1.210	-0.117
Pump 4	-20.093	-0.128	19.422	0.916	-0.117
Pump 5	-15.628	-0.092	14.533	1.289	-0.102
Pump 6	-11.163	-0.053	9.263	2.022	-0.069
Pump 7	-11.163	-0.038	7.871	3.399	-0.069
Pump of pressurized water tank					
Pump 8	-4.465	0	2.154	2.325	-0.014
Reinjection pump					
Pump 9	-70.324	-0.118	60.847	10.059	-0.464
Pipes					
Pipes	0	169.602	-35.928	76.138	-209.812
Boundary	0	-4.254	-121.656	-355.669	-229.912
TOTAL	-243.344	0.000	0.000	0.000	-468.147

In the study, the system was operated with the exergy output of 3469.88 kW and the unit electricity cost of 0.2233 US$/kWh at that dates. The unit exergy costs are found as $c_P > c_T > c_S > c_Q$ for the studied actual data sets. The cost structure discussed is a result of the expensive mechanical exergy which is derived from electricity. As can be shown in Tables 4, about 52.49% of the input cost of the Afyon GDHS is lost in the heat exchangers, followed by the losses associated with 16.26% in pipes and 7.22% in pumps. The cost flow rates lost in the components can be recovered completely in the form of thermal exergy.

Finally, such a exergoeconomic optimization process (MOPSA) will be useful in thermal engineering field. Especially, by calculating the exergy input, losses and output with economic parameters with good accuracy, the degradation of the performance and economic points of view of the GDHS can be implemented.

5. Conclusion

The following main concluding remarks are drawn from the present study:

- The results allow us better understand how the exergy cost is distributed among the components.
- The exergy efficiency is found to be 25.34% on January 20, 2010.
- The unit exergy costs are also found as $c_P > c_T > c_S > c_Q$ for the studied actual data sets.
- About 52.49% of the input cost of the Afyon GDHS is lost from the heat exchangers, 16.26% from pipes, and 7.22% from pumps.
- The unit cost of heating from geothermal water in the Afyon GDHS is 711.491 US$/h at 100% load conditions.

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Nomenclatures

a: annual operating hour (h/year)
C: unit cost (US$/kWh)
$\dot{C}$: monetary flow rate (US$/year or US$/h)
Ex: exergy (kJ)
$\dot{E}$: exergy rate (kW)
h: specific enthalpy (kJ/kg)
i: interest rate (%)
$\dot{m}$: mass flow rate (kg/s)
n: lifetime (year)
P: pressure (kPa)
s: specific entropy (kJ/kg K)
S: salvage value
$\dot{S}$: entropy rate (kW/K)
T: temperature (°C or K)
$\dot{W}$: work rate, power (kW)
$\dot{Z}$: capital cost rate

Greek symbols
ε: exergy or second law efficiency (%)
η: energy or first law efficiency (%)
φ: maintenance factor
ψ: flow exergy (kJ/kg)

Subscripts
cv: control valume
d: natural direct discharge
dest: destroyed
he: heat exchanger
i, j: successive number of elements
in: inlet
k: location
mp: mixing pool
out: outlet
P: mechanical
Q: heat
r: re-injected geothermal fluid
T: thermal
Tot: total
tw: thermal water
usf: useful
w: well-head
W: work or electricity
0: reference state

Superscripts
P: mechanical
Q: heat
T: thermal
W: work or electricity

Abbreviations
CRF: capital recovery factor
ECC: energy consumption cycle
EDC: energy distribution cycle
EPC: energy production cycle
GDHS: geothermal district heating system
MOPSA: the modified productive structure analysis
PW: present worth
PWF: present worth factor

References

[1] S. Erdogmus, H. Aras, E. Koc, "Evaluation of alternative fuels for residential heating in Turkey using analytic network process (ANP) with group decision making", Renewable and Sustainable Energy Review, vol. 10, pp. 269-279, 2006.

[2] O. Buyukalaca, H. Bulut, "Detailed weather data for the provinces covered by the Southeastern Anatolia Project (GAP) of Turkey", Applied Energy, vol. 77, 187-204, 2004.

[3] O. Kaynakli, "A study on residential heating energy requirement and optimum insulation thickness", Renewable Energy, vol. 33, pp. 1164-1172, 2008.

[4] K. J. Ptasinskia, M. N. Koymansb, H. H. G. Verspagen, "Performance of the Dutch Energy Sector based on energy, exergy and extended exergy accounting", Energy, vol. 31, pp. 3135-3144, 2006.

[5] A. Bejan, G. Tsatsaronis, M. J. Moran, "Thermal design and optimization", Wiley, New York, USA, 1996.

[6] G. Tsatsaronis, M. Winhold, "Exergoeconomic analysis and evaluation of energy conversion plants. 1. A new general methodology", Energy, vol. 10, pp. 69-80, 1985.

[7] A. Lazzarettoa, G. Tsatsaronis, "SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems", Energy, vol. 31 pp. 1257-1289, 2006.

[8] S. Oh, H. Pang, S. Kim, H. Kwak, "Exergy analysis for a gas-turbine cogeneration system", Journal of Engineering for Gas Turbines and Power, vol. 118, pp. 782-791, 1996.

[9] S. M. Kim, S. D. Oh, Y. H. Kwon, H. Y. Kwak, "Exergoeconomic analysis of thermal systems", Energy, vol. 23, pp. 393-406, 1998.

[10] A. Lazzaretto, G. Tsatsaronis, "On the calculation of efficiencies and costs in thermal systems", Proceedings of the ASME Advanced Energy Systems Division, vol. 39, pp. 421-430, 1999.

[11] M. Kanoglu, A. Ayanoglu, A. Abusoglu, "Exergoeconomic assessment of a geothermal assisted high temperature steam electrolysis system", Energy, vol. 36, pp. 4422-4433, 2011.

[12] A. Abusoglu, S. Demir, M. Kanoglu, "Thermoeconomic assessment of a sustainable municipal wastewater treatment system", Renewable Energy, vol. 48, pp. 424-435, 2012.

[13] M. A. Rosen, D. S. Scott, The enhancement of a process simulator for complete energy-exergy analysis. In: R. A. Gaggioli, editor. Analysis of energy systems-design and operation AES, New York: American Society of Mechanical Engineers, vol. 1, pp. 71-80, 1985.

[14] M. A. Rosen, I. Dincer, "Thermoeconomic analysis of power plants: An application to a coal-red electrical generating station", Energy Conversion and Management, vol. 44, pp. 1633-1651, 2003.

[15] L. Ozgener, O. Ozgener, "Monitoring of energy exergy efficiencies and exergoeconomic parameters of geothermal district heating systems (GDHSs)", Applied Energy, vol. 86, pp. 1704-1711, 2009.

[16] A. Kecebas, "Performance and thermo-economic assessments of geothermal district heating system: A case study in Afyon, Turkey", Renewable Energy, vol. 36, pp. 77-83, 2011.

[17] M. A. Lozano, A. Valero, "Theory of the exergetic cost", Energy, vol. 18, pp. 939-960, 1993.

[18] Y. H. Kwon, H. Y. Kwak, S. D. Oh, "Exergoeconomic analysis of gas turbine cogeneration systems", International Journal of Exergy, vol. 1, pp. 31-40, 2001.

[19] H. Y. Kwak, D. J. Kim, J. S. Jeon, "Exergetic and thermoeconomic analyses of power plants", Energy, vol. 28, pp. 343-360, 2003.

[20] H. Y. Kwak, H. S. Lee, J. Y. Jung, J. S. Jeon, D. R. Park, "Exergetic and thermoeconomic analysis of a 200-kW phosphoric acid fuel cell plant", Fuel, Vol. 83, pp. 2087-2094, 2004.

[21] H. Y. Kwak, G. T. Byun, Y. H. Kwon, H. Yang, "Cost structure of CGAM cogeneration system", International Journal of Energy Research, Vol. 28, pp. 1145-1158, 2004.

[22] Z. Oktay, I. Dincer, "Exergoeconomic analysis of the Gonen geothermal district heating system for buildings", Energy and Buildings, vol. 41, pp. 154-163, 2009.

[23] A. Hepbasli, "A review on energetic, exergetic and exergoeconomic aspects of geothermal district heating systems (GDHSs)", Energy Conversion and Management, vol. 51, pp. 2041-2061, 2010.

[24] C. Coskun, Z. Oktay, I. Dincer, "Modified exergoeconomic modeling of geothermal power plants", Energy, vol. 36, pp. 6358-6366, 2011.

[25] A. Kecebas, M. Kayfeci, E. Gedik, "Performance investigation of the Afyon geothermal district heating system for building applications: Exergy analysis", Applied Thermal Engineering, vol. 31, pp. 1229-1237, 2011.

[26] A. Kecebas, I. Yabanova, "Thermal monitoring and optimization of geothermal district heating systems using artificial neural network: A case study", Energy and Buildings, vol. 50, pp. 339-346, 2012.

[27] A. Kecebas, I. Yabanova, M. Yumurtaci, "Artificial neural network modeling of geothermal district heating system thought exergy analysis", Energy Conversion and Management, vol. 64, pp. 206-212, 2012.

[28] L. Ozgener, A. Hepbasli, I. Dincer, "Performance investigation of two geothermal district heating systems for building applications: Energy analysis", Energy and Buildings, vol. 38, pp. 286-292, 2005.

[29] L. Ozgener, A. Hepbasli, I. Dincer, "Exergy analysis of two geothermal district heating systems for building applications", Energy Conversion and Management, vol. 48, pp. 1185-1192, 2007.

[30] A. Lazzaretto, G. Tsatsaronis, "On the quest for objective equation in exergy costing", Proceedings of the ASME Advanced Energy Systems Division, New York: American Society of Mechanical Engineers, vol. 37, pp. 197-210, 1997.