International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 721

EQUIVALENT EXERGY-BASED MODELING OF MULTI-HETEROGENEOUS ENERGY POWER GENERATION SYSTEM

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ABSTRACT

In this paper, a novel approach is proposed to build model for a multi-heterogeneous energy power generation system (MHEPGS) including wind power, solar power and hydro power. The exergy flux, exergy flow potential, exergy flow potential difference and exergy resistance are firstly defined based on exergy theory. The exergy equivalent model for the MHEPGS is constituted by exergy source series with the exergy resistance, which are represented by exergy flow potential and exergy resistance from the angle of force and resistance. Results show that the equivalent exergy model can correctly reflect the output of the MHEPGS.

Keywords: exergy, exergy resistance, the exergy loss, exergy equivalent model

NONMENCLATURE

Abbreviation	
MHEPGS	multi-heterogeneous energy power generation system
PV	photovoltaic
MAE	mean absolute percentage error
RMSE	root mean square percentage error
KCL	Kirchhoff's current law
KVL	Kirchhoff's voltage law
Symbols	
Ex	exergy
F	exergy flux
EFP	exergy flow potential
ΔEx	difference exergy value
ΔEFP	exergy flow potential difference
R_{Ex}	exergy resistance
I	electric current
ΔU	electromotive potential difference
R_e	electrical resistance
ψ	exergy flow
Q	heat transfer rate
ξ	coefficient of energy and quality
m	mass flow of air
c_a	specific heat capacity
c	heat capacity
r	ideal air constant
Pa	pressure
γ_{cell}	emission of the PV cell
σ	Stefan-Boltzmann constant
τ	transmission rate or transfer coefficient
ε	exergy motive force
ρ	density
A	area
v	velocity of air
η	efficiency
T	temperature
G	solar radiation
q	flow rate
P	power
g	gravitation acceleration
h	height of water head
t	time
Δt	time difference
Cap	install capacity
n	number of samples

1. INTRODUCTION

Nowadays, integrating the wind power, solar power and hydro power to constitute the multi-heterogeneous energy power generation system (MHEPGS) is an effective way to improve the efficiency of overall power system and promote comprehensive utilization of large amounts of renewable energy. To improve the utilization of sustainable energy resources efficiently and economically, many studies have been reported on multi-generation based on the exergy theory.

The concept of exergy and the exergy analysis method not only were progressively included in the engineering thermodynamics for using energy more efficiently, but also have been applied to multi-energy systems. Recently, many studies report about exergy and exergy analysis utilized in renewable energy power generation system. Sunil Kumar Sansaniwal et al. in Ref [1] summarize the achievements of previous research on energy analysis and exergy analysis of various typical solar energy technologies, the results have substantiated that exergy efficiency is more accurate than energy efficiency in some studies because the former is based on the second law of thermodynamics which consider the quality of energy. M.A. Ehyaei et al. report advanced exergy analysis and extended exergy analysis applied to a wind turbine, the advanced exergy and the extended exergy analysis show different focus field for the wind turbine [2]. Sergio Usón et al. propose complementary methods of exergy and exergy cost analyses to analyze a hybrid tri-generation system constituted by renewable energy sources [3], which offers assessment and better understanding to the efficiency of energy. However most of the existing articles concern on the model of small capacity multi-energy complementary generation system. For large capacity renewable energy generation systems, few papers have been reported. And few studies have considered the concept of exergy into building the model of renewable energy generation systems. So, the unified model based the concept of exergy for MHEPGS is innovative and should be settled urgently.

This paper introduces the concept of exergy into the homogeneous characterization of multi-heterogeneous energy such as wind energy, solar energy and water energy, puts forward a novel approach to build model for the MHEPGS, and builds a unified exergy equivalent model of the MHEPGS based on the defined terms such as exergy flux, exergy flow potential, exergy flow potential difference and exergy resistance. The proposed model is simulated in the software platform, and the verification of results is reported.

2. METHODOLOGY

2.1 Exergy

In general, exergy refers to the useful energy that can be reversibly converted into other forms of energy in any state to the state in balance with a given environment [4]. Exergy can be used to evaluate the energy from the combination of quantity and quality in a system, so exergy has the physical property of energy.

The exergy balance of a system is expressed based on its input exergy, output exergy and exergy loss, signed Ex_{in}, Ex_{out} and Ex_{loss} respectively. The exergy loss stands for losses in energy quality.The general exergy balance should meet the following equation[5]:

$$\sum Ex_{loss} = \sum Ex_{in} - \sum Ex_{out} \tag{1}$$

2.2 Exergy flow potential and exergy resistance

Based on the concept of exergy, some terms have be defined in this paper:

Exergy flux: Exergy flux is the exergy value in per unit area and per unit time, marked F with the unit of J/(m^2·s).

Exergy flow potential: Exergy flow potential is the exergy value in per unit exergy flux, used to describe the force that generates exergy flow, likely electromotive force and magnetomotive force in electromagnetism, marked EFP with the unit of J/(W/m^2), its calculation is:

$$EFP = \frac{Ex}{F} \tag{2}$$

Exergy flow potential difference: Exergy flow potential difference is the exergy flow potential difference at two points, which is the source of motivation for exergy flow, marked ΔEFP, its calculation is:

$$\Delta EFP = \frac{\Delta Ex}{F} \tag{3}$$

where, ΔEx is the difference exergy value at the two points.

The exergy loss exists in the conversion process of the MHEPGS irreversibly. The exergy loss means the losses of energy quantity and quality inter energy conversion, which can be considered to be resistance for exergy flow runs from one point to another. Hence, this paper defines exergy resistance to represent the exergy loss by analogy with electrical resistance in an electric circuit.

For an electrical resistance R_e in an electric circuit, the electric energy dissipation per unit time is:

$$E_d = I^2 R_e = \frac{(\Delta U)^2}{R_e} \tag{4}$$

where, I is the electric current; ΔU is the electromotive potential difference across the resistance R_e.

Similar to electrical resistance, the exergy loss per unit time in energy conversion can be related to the exergy resistance as:

$$Ex_{loss} = F^2 R_{Ex} = \frac{(\Delta EFP)^2}{R_{Ex}} \tag{5}$$

where, F is the exergy flux; ΔEFP is the exergy flow potential difference across the exergy resistance. So, R_{Ex} with the unit of $(m^2\cdot s)^2/J$, can be calculated as:

$$R_{Ex} = \frac{Ex_{loss}}{F^2} = \frac{(\Delta EFP)^2}{Ex_{loss}} = \frac{\Delta EFP}{F} \tag{6}$$

where, Ex_{loss} is the exergy loss. So, the exergy resistance is defined as the ratio of the exergy flow potential difference to the exergy flux. The exergy resistance is nonlinear.

For different power generation systems, the exergy loss in the course of energy conversion in wind power system, solar power system and hydro power system are characterized by wind exergy resistance, solar exergy resistance and water exergy resistance respectively.

3. EXERGY MODEL FOR MHEPGS

3.1 Exergy model of wind power

The input wind energy exergy of wind power system comes from the kinetic energy of the wind, which can be calculated as [6]:

$$Ex_{in,w} = \frac{1}{2}\xi_w \rho_a A_w v^3 \Delta t \tag{7}$$

where, ξ_w is the coefficient of energy quality character for wind energy; ρ_a is the air density; A_w is the swept area; v is the velocity of air; Δt is the period of time.

In the process of wind energy converting into electricity, its exergy balance equation is:

$$Ex_{in,w} = Ex_e + Ex_{h,w} + Ex_{cutout,w} \tag{8}$$

where, Ex_e is electric energy exergy, $Ex_{h,w}$ and $Ex_{cutout,w}$ are heat exergy and cutout wind energy exergy, they are calculated by the following equations [7].

$$Ex_{h,w} = m_a c_a (T_2 - T_1) \tag{9}$$

$$Ex_{cutout,w} = m_a T_a \left(c_a ln\frac{T_2}{T_1} - r ln\frac{Pa_2}{Pa_1} - \frac{Q_{loss}}{T_a}\right) \tag{10}$$

where, Q_{loss} is heat loss of wind turbine; m_a is the mass flow of air; c_a is the specific heat capacity; r is ideal air constant; T_a is the ambient temperature; T_1 and T_2 are temperature at the inlet and outlet of the wind turbine; Pa_2 is the outlet pressure; Pa_1 is the inlet pressure.

The exergy loss in wind power system includes two parts except for electric exergy:

$$Ex_{loss,w} = Ex_{h,w} + Ex_{cutout,w} \tag{11}$$

3.2 Exergy model of solar PV

The input exergy of solar power system received from the sun is calculated by equation (12)[8].

$$Ex_{in,pv} = \xi_{sun} G A_{plate} \Delta t \tag{12}$$

where, G is the solar radiation; A_{plate} is the area; ξ_{sun} is the coefficient of solar energy quality character, which is related to the temperature.

In the solar photovoltaic system, exergy balance equation is [9]:

$$Ex_{in,pv} = Ex_e + Ex_{h,loss} + Ex_{op,loss} \tag{13}$$

where, Ex_e is electric energy exergy; $Ex_{h,loss}$ is the heat loss of the heat exchange between the photovoltaic cell and the environment; $Ex_{op,loss}$ is the optical loss absorbed and reflected by the photovoltaic panel and the covered glass, which can be calculated by equations(14)-(15)[9].

$$Ex_{h,loss} = (\tau_h (T_{cell} - T_{glass}) + \gamma_{cell}\sigma(T_{cell}^4 - T_a^4))A_s\left(1 - \frac{T_a}{T_{cell}}\right) \tag{14}$$

$$Ex_{op,loss} = (1-\tau_c)(1-\tau_{glass})Ex_{in,pv} \tag{15}$$

where, T_{cell} and T_{glass} are the temperature of the PV cell and the temperature of the covered glass plate respectively; γ_{cell} is the emission of the PV cell; τ_h is the equivalent heat transfer coefficient of the PV cell and covered-glass; σ is the Stefan-Boltzmann constant; τ_c and τ_{glass} are the transmission of the photovoltaic panel and the covered-glass.

The exergy loss in the photovoltaic power system is:

$$Ex_{loss,pv} = Ex_{h,loss} + Ex_{op,loss} \tag{16}$$

3.3 Exergy model of hydro power

In hydro power system, the input exergy is the water potential energy got by the hydroelectric power station, which is expressed as:

$$Ex_{in,water} = \xi_{water} h \rho_{water} g q \Delta t \tag{17}$$

where, ξ_{water} is the coefficient of energy quality character for water potential energy; h is the height of water head; ρ_{water} is the water density; g is the gravitation acceleration; q is the flow rate of water.

The exergy balance equation for hydro power generation is [10]:

$$Ex_{in,water} = Ex_e + Ex_{h,loss} + Ex_{water,out} \tag{18}$$

where, Ex_e is electric energy exergy; $Ex_{h,loss}$ is the heat loss of the heat exchange between the turbine and the environment; $Ex_{water,out}$ is the outflow exergy from the water turbine. $Ex_{h,loss}$ and $Ex_{water,out}$ can be calculated by equations(19)-(20).

$$Ex_{h,loss} = m_{water,out} c_{water} (T_2 - T_1) \tag{19}$$

$$Ex_{water,out} = \sum m_{water,out} \psi_{water,out} \tag{20}$$

where, c_{water} is the specific heat capacity of water; T_1 and T_2 are the inlet and outlet temperatures of water turbines respectively; $m_{water,out}$ and $\psi_{water,out}$ are the outlet water mass and water exergy flow.

The exergy loss in the hydro power system is:

$$Ex_{loss,water} = Ex_{h,loss} + Ex_{water,out} \tag{21}$$

4. EXERGY EQUIVALENT MODEL

4.1 Equivalent model of MHEPGS

The sketch of the MHEPGS and the overall research framework are shown in Fig 1.

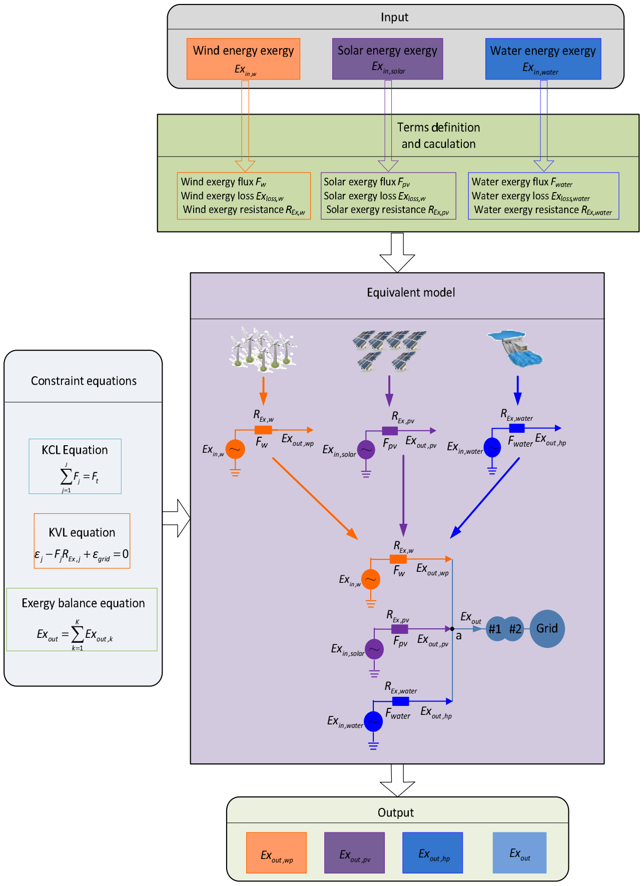


Fig 1 Sketch of the exergy equivalent model for MHEPGS

The procedure to obtain the exergy equivalent model for MHEPGS is proposed. Different power generation station can be equivalent to generating unit respectively by analogizing power source model in electric circuit. The detailed steps are followed:

Step 1) Firstly, define the terms: exergy flux, exergy flow potential, the exergy loss and exergy resistance based on the concept of exergy. These parameters are the foundation of constructing homogeneous model.

Step 2) Calculate the terms for all power generation systems including wind power, solar power and hydro power with actual parameters in various power stations.

Step 3) By analogizing power source model in electric circuit, each power generation system is equivalent to the form of exergy source in series with the exergy resistance, the exergy source value is the input resource exergy of each generation station. Output exergy of each generation plant is integrated to the power grid at the point of common coupling.

Step 4) Build exergy equivalent model of the MHEPGS based on the step 3).

Step 5) Verify the exergy equivalent model conform to constraint equations and transportation conservation or not, otherwise, examine the terms of each power generation system.

4.2 Constraint equations and transportation conservation

The Kirchhoff's laws are used to describe the exergy transport law of the exergy equivalent model.

Exergy resistances meet the equation(22),

$$\Delta EFP = F R_{Ex} \tag{22}$$

where, R_{Ex} is the exergy resistance, ΔEFP is the exergy flow potential difference on the exergy resistance, F is the exergy flux through the exergy resistance.

For exergy sources,

$$EFP = \varepsilon \tag{23}$$

where, EFP is the exergy flow potential on the exergy source, ε is the exergy motive force.

In Fig 1, at node a, the Kirchhoff's current law (KCL) equation is:

$$\sum_{j=1}^{J} F_j = F_t \tag{24}$$

where, J is the number of exergy flow, F_j is the exergy flux in the j-th exergy flow branch, F_t is the total electric exergy flux.

For each independent loop, the Kirchhoff's voltage law (KVL) equation can be written as:

$$EFP_{\varepsilon_j} - \Delta EFP_{R_{Ex,j}} + EFP_{\varepsilon_{grid}} = 0 \tag{25}$$

Substituting equation (22) and equation (23) into equation(25):

$$\varepsilon_j - F_j R_{Ex,j} + \varepsilon_{grid} = 0 \tag{26}$$

where, EFP is the exergy flow potential on the exergy source, ε is the exergy motive force.

The exergy balance equation for the equivalent model of the MHEPGS is:

$$Ex_{out}=\sum_{k=1}^{K}Ex_{out,k}\qquad k=1,2,\cdots,K \tag{27}$$

$$Ex_{out,k}=Ex_{in,k}-F_k^2R_{Ex,k} \tag{28}$$

where, K is the number of power generation stations, $Ex_{out,k}$ is the output exergy of the k-th type power generation station.

5. CASE STUDY

5.1 *Output exergy*

In the paper, a practical engineering of the MHEPGS from a province in northwest of China was considered. The rated capacities of wind farm, solar power station and hydro power station are 50MW, 20MW and 20MW respectively. The input exergy of each power generation system in a typical day are shown in Fig 2.

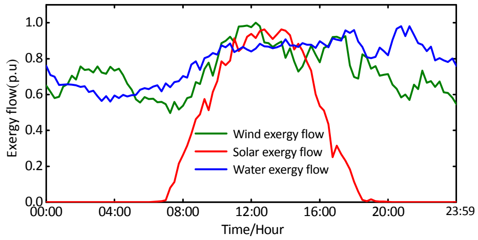
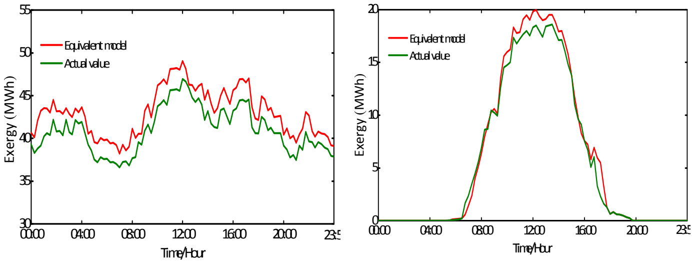


Fig 2 The input exergy of generation stations

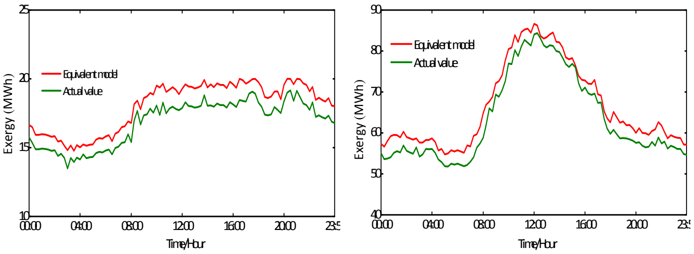
To verify the correctness of output results from the equivalent model, the actual values are used to compare with the results from the exergy equivalent model of the MHEPGS. The actual value is electric energy, which can be converted into electric exergy completely.

The results are shown as Fig 3. It can be seen that the output exergy from exergy equivalent model are consistent with the actual value. The exergy equivalent model in the paper can correctly reflect the output of multiple energy power generation system.



(a) Output exergy from the wind power farm

(b) Output exergy from the solar power station



(c) Output exergy from the hydropower station

(d) Output exergy from the MHEPGS

Fig 3 Output electric exergy and actual value

Mean absolute percentage error (*MAE%*) and root mean square percentage error (*RMSE%*) are used to estimate accuracy of the equivalent model.

$$MAE(\%)=\frac{\sum_{i=1}^{n}\left|Ex_{act,i}-Ex_{m,i}\right|}{Cap\cdot n}\times 100\% \tag{29}$$

$$RMSE(\%)=\frac{\sqrt{\sum_{i=1}^{n}\left(Ex_{act,i}-Ex_{m,i}\right)^{2}}}{Cap\times\sqrt{n}}\times 100\% \tag{30}$$

where, $Ex_{act,i}$ is the actual value at the i-th moment (MWh); $Ex_{m,i}$ is the output exergy calculated by model at the i-th moment (MWh); *Cap* is the install capacity of generation station(MWh); *n* is the number of samples.

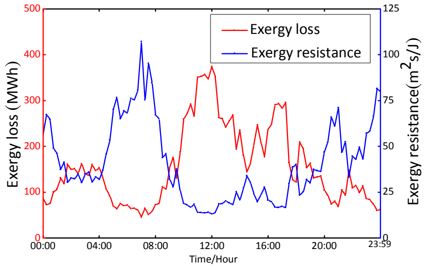
A smaller value of error means that the output value is closer to the actual value and the model is more accurate. The *MAE%* and *RMSE%* in Tab 1 represent small errors, which prove the correctness of the exergy equivalent model. Therefore, the exergy equivalent model of the MHEPGS established in this paper can guarantee the accuracy.

Tab 1 Errors of each output exergy

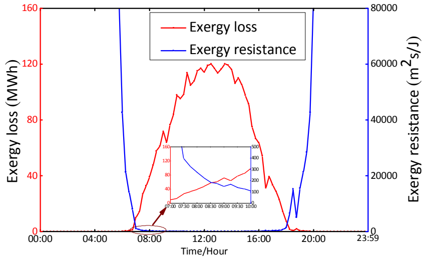
Power station	*MAE%*	*RMSE%*
Wind power	6.34	7.89
Solar power	5.96	6.28
Hydropower	5.83	5.99
MHEPGS	6.09	6.49

5.2 *Exergy resistance*

The exergy resistance can present the exergy loss in the course of energy conversion, and exergy resistance can be used to reflect the irreversibility in exergy transmission and describe the relationship between exergy flow potential difference and exergy flow. The larger exergy resistance represents, the more the exergy loss. The variations of exergy resistances are shown in Fig 4.

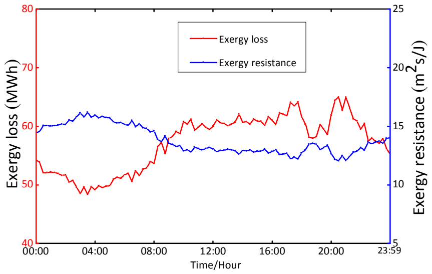


(a)Wind exergy loss and wind exergy resistance



(b) Solar exergy loss and solar exergy resistance

Tab. 2 show the value of some key terms at typical moment. By calculating, these parameters at any time are in accordance with the constraint equations. For example, at 10:00 o 'clock, the sum of wind exergy flux (it's value is 7029.29), solar exergy flux (it's value is 1799.18) and water exergy flux (it's value is 2171.19) is equal to the total exergy flux (it's value is 10999.66),



(c) Water exergy loss and water exergy resistance

Fig 4 The exergy loss and exergy resistance potential

From Fig 4, the exergy resistance of each generation system is inversely proportional to the exergy loss. At the same time, combining the output exergy in Fig 3 with the exergy resistance in Fig 4, the output exergy of each generation system is with reversly trend compared with the exergy resistance. The larger the exergy resistance, the smaller the output exergy.

5.3 Verification of transportation conservation

The results in

which satisfy to the equation (24); the values of input exergy, the exergy loss and output exergy of each power generation system satisfy to the equation(28); the exergy loss, exergy resistance and exergy flux satisfy to the equation(5). So, the exergy equivalent model of MHEPGS is suitable to express the transportation conservation of exergy in the whole system.

Tab. 2 The value of parameters at typical moment

Terms / Time	Exergy Flux (J/(m^2·s))				Input Exergy (MWh)		
	F_w	F_{pv}	F_{water}	F_t	$Ex_{in,w}$	$Ex_{inpv,}$	$Ex_{in,water}$
0:00	2368.88	0.00	1936.88	4305.76	126.80	0.00	69.98
1:00	2883.57	0.00	1864.31	4747.88	146.74	0.00	67.12
2:00	4058.28	0.00	1847.73	5906.01	190.71	0.00	66.54
3:00	3823.23	0.00	1733.98	5557.21	181.96	0.00	62.04
4:00	4147.94	0.00	1755.56	5903.5	195.13	0.00	63.30
5:00	1898.58	0.00	1781.25	3679.83	107.66	0.00	64.20
6:00	1949.23	4.59	1846.89	3800.71	109.63	0.39	66.51
7:00	1240.29	183.63	1841.86	3265.78	82.43	11.42	66.63
8:00	1979.30	721.64	1916.37	4617.31	110.80	45.68	69.06
9:00	4143.59	1318.85	2069.05	7531.49	193.97	82.43	75.27
10:00	7029.29	1799.18	2171.19	10999.66	303.40	113.96	78.87
11:00	9503.52	1927.90	2137.28	13568.7	396.66	122.87	77.67
12:00	10129.56	2097.69	2143.64	14370.89	421.10	134.07	77.90
13:00	6553.85	2086.12	2147.38	10787.35	286.34	132.70	78.03
14:00	6383.36	2131.79	2166.91	10682.06	278.99	134.02	78.72
15:00	5531.14	1792.79	2175.06	9498.99	247.61	111.38	79.00
16:00	6406.68	1169.18	2179.41	9755.27	279.87	71.26	79.16
17:00	7662.34	612.78	2208.13	10483.25	327.30	39.33	80.17
18:00	3315.00	137.71	2199.95	5652.66	163.03	8.13	79.88
19:00	4420.32	12.62	2080.42	6513.36	204.51	1.19	75.67
20:00	2835.81	2.30	2211.52	5049.63	143.91	0.13	80.29
21:00	1868.43	0.00	2320.58	4189.01	106.48	0.00	84.12
22:00	2978.33	0.00	2124.32	5102.65	149.64	0.00	77.22
23:00	2328.98	0.00	2052.58	4381.56	125.36	0.00	74.69
23:59	1631.86	0.00	2005.37	3637.23	98.24	0.00	73.03

Table.2 Continued

Terms / Time	The exergy loss (MWh)			Exergy resistance ((m^2·s)^2/J)			Output Exergy (MWh)			
	$Ex_{loss,w}$	$Ex_{loss,pv}$	$Ex_{loss,water}$	$R_{Ex\ w}$	$R_{Ex,pv}$	$R_{Ex,water}$	$Ex_{out,wp}$	Ex_{outpvr}	$Ex_{out,hp}$	Ex_{out}
0:00	87.50	0.00	54.23	56.13	--	14.46	39.30	0.00	15.75	55.05
1:00	106.51	0.00	52.20	46.11	--	15.02	40.24	0.00	14.92	55.16
2:00	149.90	0.00	51.74	32.76	--	15.15	40.82	0.00	14.80	55.62
3:00	141.21	0.00	48.55	34.78	--	16.15	40.75	0.00	13.48	54.23
4:00	153.21	0.00	49.16	32.06	--	15.95	41.93	0.00	14.14	56.07
5:00	70.13	0.00	49.88	70.04	--	15.72	37.53	0.00	14.33	51.86
6:00	72.00	0.25	51.71	68.22	42741.77	15.16	37.63	0.14	14.80	52.57
7:00	45.81	10.00	51.57	107.21	1067.69	15.20	36.62	1.42	15.06	53.1
8:00	73.11	39.30	53.66	67.18	271.69	14.61	37.69	6.38	15.40	59.47
9:00	153.05	71.83	57.93	32.09	148.66	13.53	40.92	10.60	17.34	68.86
10:00	259.63	97.99	60.79	18.92	108.97	12.90	43.77	15.97	18.07	77.81
11:00	351.02	105.00	59.84	13.99	101.70	13.10	45.64	17.87	17.83	81.34
12:00	374.14	114.24	60.02	13.13	93.47	13.06	46.96	19.83	17.87	84.66
13:00	242.07	113.61	60.13	20.29	93.98	13.04	44.26	19.09	17.90	81.25
14:00	235.77	116.10	60.67	20.83	91.97	12.92	43.21	17.92	18.04	79.17
15:00	204.30	97.64	60.90	24.04	109.36	12.87	43.32	13.74	18.10	75.16
16:00	236.64	63.68	61.02	20.75	167.69	12.85	43.23	7.58	18.13	68.94
17:00	283.01	33.37	61.83	17.35	319.95	12.68	44.29	5.95	18.34	68.58
18:00	122.44	7.50	61.60	40.11	1423.79	12.73	40.59	0.63	18.28	59.5
19:00	163.27	0.69	58.25	30.08	15538.88	13.46	41.24	0.50	17.42	59.16
20:00	104.74	0.13	61.92	46.89	85409.19	12.66	39.16	0.00	18.36	57.52
21:00	69.01	0.00	64.98	71.17	--	12.07	37.47	0.00	19.15	56.62
22:00	110.01	0.00	59.48	44.65	--	13.18	39.63	0.00	17.74	57.37
23:00	86.02	0.00	57.47	57.09	--	13.64	39.33	0.00	17.22	56.55
23:59	60.27	0.00	56.15	81.48	--	13.96	37.97	0.00	16.88	54.85

6. CONCLUSIONS

In the paper, the exergy equivalent model of MHEPGS is built based on the new terms such as exergy flux, exergy flow potential, exergy flow potential difference and exergy resistance. Model of multiple energy power generation system is proposed and has been verified in case studies. Meanwhile, the exergy equivalent model of MHEPGS is suitable to express the constraint equations and transportation conservation in the whole system.

ACKNOWLEDGEMENT

This work is supported by the National Key R&D Program of China (No. 2017YFB0902200), Science and Technology Project of SGCC (No. 5228001700CW).

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