Journal of Energy and Environmental Sustainability, 3 (2017) 37-42

An official publication of the International Society for Energy, Environment and Sustainability (ISEES)

Journal of Energy and
Environmental Sustainability

Journal homepage : www.jees.in

Performance of a Biomass Based Polygeneration: Second Law Analysis

Kuntal Jana[a]*, Avishek Ray[a], Sudipta De[a], Mohsen Assadi[b], Subha Mondal[c]

[a] *Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, India*
[b] *Faculty of Science and Technology, University of Stavanger, Stavanger, Norway*
[c] *Department of Mechanical Engineering, Aliah University, Kolkata-156, India*

ARTICLE INFO

Received : 01 May 2017
Revised : 27 May 2017
Accepted : 31 May 2017

Keywords:
polygeneration, exergy, biomass, ethanol

ABSTRACT

Biomass based energy system play an important role for developing countries like India which is rich in biomass. In this work, biomass is utilized in decentralized way for multiple utility generation through polygeneration. However, for the maximum utilization of biomass, proper design of energy system is necessary. For this purpose, exergy analysis shows better insight about the scope of the possible improvement. Results indicate the critical components and processes of the polygeneration from the viewpoint of exergy. Most of the exergy losses and destructions occur in gasification, ethanol production and combustion processes. Thermodynamic parameters for all state points of the polygeneration are reported in this paper.

Nomenclature

Ex	Exergy (kJ)
$\dot{Ex}$	Exergy rate (kW)
ex	Specific exergy (kJ/kg)
	Enthalpy (kJ/kg)
$\dot{m}$	Mass flow rate (kg/s)
η	Efficiency
p	pressure (bar)
$\dot{Q}$	Heating/cooling (kW)
R	Gas constant (kJ/kg-K)
s	Entropy (kJ/kg-K)
T	Temperature (K)
$\dot{W}$	Power (kW)
x	Mass fraction

Subscript

0	reference state
b	boiler
c	cooling
c	chemical
D	destruction
f	fuel
	heating
p	physical
Q	heat
ref	reference

1. Introduction

Biomass can be a good source of secondary energy if it is used properly [Bentsen et al., 2014]. However, design of energy system using locally available biomass is crucial for maximum utilization of biomass [Jana and De, 2015a]. As biomass have less energy density than fossil fuel, system should be efficient for the bettermentof performance which is reflected on its environmental and economic parameters [Jana and De, 2015b]. For proper utilization of biomass, suitable conversion technologyis also required. For maximum utilization of biomass to cater to the needs of local people polygeneration is an promising option [Chicco and Mancarella, 2009]. Polygeneration is an efficient energy system for obtaining multiple utility outputs from a single unit by proper process

---

* Corresponding Author: *kuntaljana@gmail.com*

integration [Serra et al., 2009]. Energy efficiency is the simplest thermodynamic way to measure the performance of polygeneration. However, possible improvement in energy efficiency can be measured through the exergy analysis.Exergy analysis shows the components where the maximum work potential is lost within the polygeneration. It also grossly measure the sustainability of an energy system [Dincer and Rosen, 2013].

Biomass input to the polygeneration should be selected for long-run operation [Jana and De, 2015a]. Rice straw is a good source of ligno-cellulosic biomass with reasonable calorific value [Bentsen et al., 2014]. Plenty of rice straw is available in developing countries like India, China etc [Gadde et al., 2009]. This straw can be used to cater to the needs of local people through polygeneration. Secondary energy demand in the locality is mainly electricity. Apart from electricity, cooling utility is required for cold storage to preserve the agro-products or food products. Another important secondary energy demand is transportation fuel. It is the second largest form of secondary energy demand after electricity [IEA, 2016]. Heating is another utility demand for room heating or food processing. Use of biomass as a input to the polygeneration was reported in literature [Chen et al., 2016; Vidal and Martin, 2015; Trippe et al., 2011; Li et al., 2014]. Jana and De [2017] reported the polygeneration for electricity and ethanol by thermochemical conversion of biomass.

The main objective of this work is exergy analysis of a polygeneration plant which produces electricity, ethanol, heating and cooling. This polygeneration is fuelled by rice straw. For the exergy analysis, thermodynamic state points are calculated through simulation. The simulation is done in Aspen Plus®. Destruction and/or losses of exergy within the various components of polygeneration are shown in this paper. These results will help to identify the components for possible improvement. This improvement increase the thermodynamic efficiency of the polygeneration plant.

2. Materials and method

The performance of polygeneration plant depends on thermo-chemical properties of rice straw. The properties of rice straw are HHV 14.56 MJ/kg, LHV 13.76 MJ/kg, FC 13.33%, VCM 62.31%, Ash 24.36%, C 34.6%, H 3.93%, O 35.38%, N 0.93%, S 0.16%, Residue 25% [Domalski et al., 1986].

2.1 System description

In this work, an energy system is modeled to deliver power, ethanol, heating and ccoling. The schematic of the system is shown in Fig.1.From this figure, it is noted that there are several blocks associated in this system. Discussion on this blocks are given below. Operating parameters of the polygeneration is given in Table 1.

2.1.1 Gasification

Firstly, biomass i.e., rice straw enters to the atmospheric pressure gasifier. Before entering to the gasifier, moisture of the straw is reduced by suitable drying process. Solid biomass is converted into the gaseous products. The main reactions occurs in the gasifier are given as follows-

$2C + O_2 \leftrightarrow 2CO$	Partial combustion ofchar
$2H_2 + O_2 \leftrightarrow 2H_2O$	Hydrogen combustion
$C + H_2O \leftrightarrow H_2 + CO$	Water gas reaction
$CO_2 + C \leftrightarrow 2CO$	Boudouard reaction
$CO + H_2O \leftrightarrow CO_2 + H_2$	CO shift reaction
$C + 2H_2 \leftrightarrow CH_4$	Methanation reaction
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	Steam-meathane reforming
$2N_2 + 3H_2 \leftrightarrow 2NH_3$	NH_3 formation
$H_2 + S \leftrightarrow H_2S$	H_2S formation

The products of the gasification is calculated by Gibbs free energy minimization method in Aspen Plus. Temperature of the gasification process is kept below the ash agglomeration and silica sand agglomeration temperature of rice straw (~800 ^{o}C). Assumptions for this simulation are obtained from literature [Jana and De, 2015c].

Table 1: Operating parameters of the polygeneration plant [Jana and De, 2015c]

Configurations	**Parameters**	**Value**
Biomass feed	Mass flow rate	1 t/h
Reaction in gasification	Pressure	1 atm
	Equivalence ratio	35 % of stoichiometric air
Air compression,	Pressure ratio	10
Syngas compression	Isentropic efficiency	0.9
Gas cleaning	Separation efficiency of solids particles	85 %
Gas turbine combustor	Pressure	10 atm
	Heat duty	0
Gas turbine	Discharge pressure	1atm
	Isentropic efficiency	0.9
Heat recovery steam generator (HRSG)	HP stage temperature	480 ^{o}C
	HP stage pressure	7MPa
	LP stage temperature	500 ^{0}C
	LP stage pressure	3.2 MPa
HP and LP Steam turbine	Isentropic efficiency	0.92
	LP-ST discharge pressure	0.07 MPa
NH_3-H_2O mixture feed to refrigerant pump	Total mass flow rate	2000 kg/h
	NH_3 mass fraction	0.5
Evaporator	Temperature	-5 ^{0}C
Water gas shift reactor	Pressure	4 MPa
	Temperature	215 ^{o}C
Ethanol synthesis reactor	Pressure	9.6 MPa
Two phase separator of liquid (water-ethanol) and gas mixtures	Temperature	220 ^{o}C
	Temperature	40 ^{o}C
CO_2 capture	Efficiency	90 %

2.1.2 Power generation

After gasification, syngas is cooled and cleaned. During the cooling, heat of the syngas is utilized for superheating of steam and generating process heat for subsequent use. Then 60% of the produced syngas is used in combined cycle (CCGT) power generation and rest is used for ethaol production. However, this can be varied according to demand of the utilities. Power required in the ethanol production unit is supplied from the power generating unit of CCGT.

2.1.3 Ethanol production

A fraction of the syngas (40%) from the splitter is utilized for ethanol production. Cleaned syngas is compressed to 4MPa for the subsequent water gas shift (WGS) reaction. This WGS reaction is necessary to achieve the desired ratio of H_2 and CO (i.e., 2:1) as a gas mixture for conversion to ethanol.

To obtain the desired H_2 and CO ratio (2:1), WGS reaction is done before ethanol synthesis as given below.

$$\mathrm{CO+H_2O \leftrightarrow CO_2+H_2} \qquad \Delta H_{298}= -41.0\,\mathrm{kJ/mol}$$

Ethanol synthesis is done by the reaction between CO and H_2 as given below in presence of catalyst (MoS_2) as the reaction given below.

$$\mathrm{2CO+4H_2 \leftrightarrow C_2H_5OH+H_2O} \qquad \Delta H_{298}= -255.7\ \mathrm{kJ/mol}$$

Both rections are exothermic, hence, heat can be obtained from this reaction. This heat is used for process steam generation.

2.1.4 Process steam generation

Part of the process steam is generated during cooling of the syngas. Another part is obtained from the ethanol production process. In this process heat is obtained from two exothermic reactions as stated in previous section. Latent heat of this steam is used for refrigeration and sensible heat is used for utility heating.

2.1.5 Refrigeration

Vapor absorption method is used for this refrigeration process. Ammonia-water solution is the working fluid for this process. Input heat to this refrigeration is given by generated process steam in the polygeneration process. Latent heat of the process steam is used in the generator of the vapor absorption refrigeration. Cooling temperature of this process is kept constant at -5 °C.

2.2 Exergy analysis

Exergy analysis was done for both overall system performance and individual equipment within the system. Exergy balance for each component was done by following equations,

$$\sum_{in} \dot{Ex}_k + \dot{Ex}_Q = \sum_{out} \dot{Ex}_k + \dot{Ex}_D + \dot{Ex}_w \tag{1a}$$

$$\sum_{in} \dot{Ex}_k + \dot{Ex}_Q = \sum_{useful} \dot{Ex}_k + \sum_{loss} \dot{Ex}_k + \dot{Ex}_D + \dot{Ex}_w \tag{1b}$$

Equation (1b) was used when a part of output exergy from a component was lost to environment (e.g. in the form of ash from gasifier or flue gas through stack).

$$\dot{Ex}_Q = \left(1 - \frac{T_o}{T}\right)\dot{Q} \tag{2}$$

$$\dot{Ex}_w = \dot{W} \tag{3}$$

Total exergy input to a component was in the form of physical and chemical exergies (neglecting kinetic and potential exergies). Total exergy through a stream is,

$$\dot{Ex} = \dot{Ex}_p + \dot{Ex}_c \tag{4}$$

If a stream consists of multi component, then exergy flow rates of individual species were calculated by the following equation,

$$\dot{Ex}_i = \dot{m}_i ex_i\ . \tag{5}$$

Exergy of a stream consists of physical and chemical exergy. Physical and chemical exergies were calculated by equations (6) and (7) respectively.

$$ex_p = (\mathrm{h} - \mathrm{h}_0) - T_0(s - s_0) \tag{6}$$

$$ex_c\mathrm{h} = \sum_{i=1}^{n} x_i ex_{c\ ,i} + RT_0 \sum_{i=1}^{n} x_i \ln x_i \tag{7}$$

Enthalpy and entropy values were obtained from Aspen Plus® simulation. Enthalpy and entropy at the reference state were obtained by using temperature and pressure of the dead state of respective streams [Jana and De, 2015b]. Chemical exergies of individual species were obtained from literature [Kotas, 1985]. Exergy of cooling is calculated by the equation (8).

$$\dot{Ex}_c = \dot{Q}_c \left|\left(1 - \frac{T_0}{T_{evp}}\right)\right| \tag{8}$$

Exergy of biomass was calculated using following equation [Kotas, 1985]

$$Ex_f = \beta \cdot LHV_f \tag{9}$$

$$\text{where, } \beta = \frac{1.0438+0.1882\left(\frac{H}{C}\right)-0.2509\left(1+0.7256\left(\frac{H}{C}\right)\right)+0.0383\left(\frac{N}{C}\right)}{1-0.3035\left(\frac{O}{C}\right)}, \qquad \text{for } 2.67> (O/C)> 0.667.$$

3. Results and discussion

Polygeneration is an energy system for delivering multiple utilities from a single unit. Exergy is an indicator to measure the design efficieny of an energy system by the second law of thermodynamics. Exergy analysis shows the possible improvement of the design parameters on an absolute thermodynamic scale. Exergy analysis also identifies exergy losses and destruction in different components of the whole process. To calculate the exergy of different streams, state points of Fig.1 is used.

The designed polygeneration is simulated by using Aspen Plus®. Input for this simulation is given in Table 1 [Jana and De, 2015c]. Outputs of the polygeneration are power, heating, cooling and ethanol. Production rate of these outputs are given in Table 2. From the Table 2, it is noted thatsignificant power can be obtained from this polygeneration and it is obtained through combined cycle i.e., in gas turbine, high pressure steam turbine and low pressure steam turbine.For a given fraction of syngas, energy input though syngas to the power island depends on both mass flow and calorific value. Depending on the input feedstock and operating conditions, properties and mass flow rate of the produced syngas from gasification process varies.64% of total power is produced from gas turbine. Rest is produced from HPST (6%) and LPST (30%). However, significant power is required in ethanol production process.In the ethanol production unit 18% of the generated power is consumed. Production rate of ethanol is more than 700 t per year. However, this rate can be varied by changing the way of syngas utilization. Cooling and utility heat are the other two significant outputs of this polygeneration as noted in Table 2. Cooling is obtained from the residual heat of the syngas. Utility heat is obtained from the syngas cooling process and exothermic reaction during ethanol production process.

Table 2: Outputs of the polygeneration for feed rate of 1 t/h

Outputs	Value
Net GT power	560 kW
HPST power	52 kW
LPST power	263 kW
Power input for ethanol	160 kW
Ethanol production rate	734 t/y
Refrigeration	235 kW
Utility heat	105 kW

In Table 3, mass flow rate, temperature and pressure of each state points are given. These values are used to calculate the exergy of each state points. From the table, it is noted that biomass enters to the gasifier at atmospheric temperature and pressure. Then temperature increases in the gasifier due to exothermic reactions. Then syngas is cooled and temperature is reduced. Then mass of the syngas is splitted into two parts- for power generation and for ethanol synthesis. Then pressure of the syngas is increased in the syngas compressor and temperature is increased due to combustion of syngas. Then hot flue gas is expanded in the gas turbine for power output. Additional power is obtained though bottoming steam cycle.

In previous section, it is staed that exergy has two components- chemical exergy and physical exergy. In Table 4, values of chemical and physical exergy are given.From Table 4, it is noted that the maximum exergy input in the polygeneration process is done through biomass. Exergy is consumed in the pump and the compressor. Product exergies are obtained

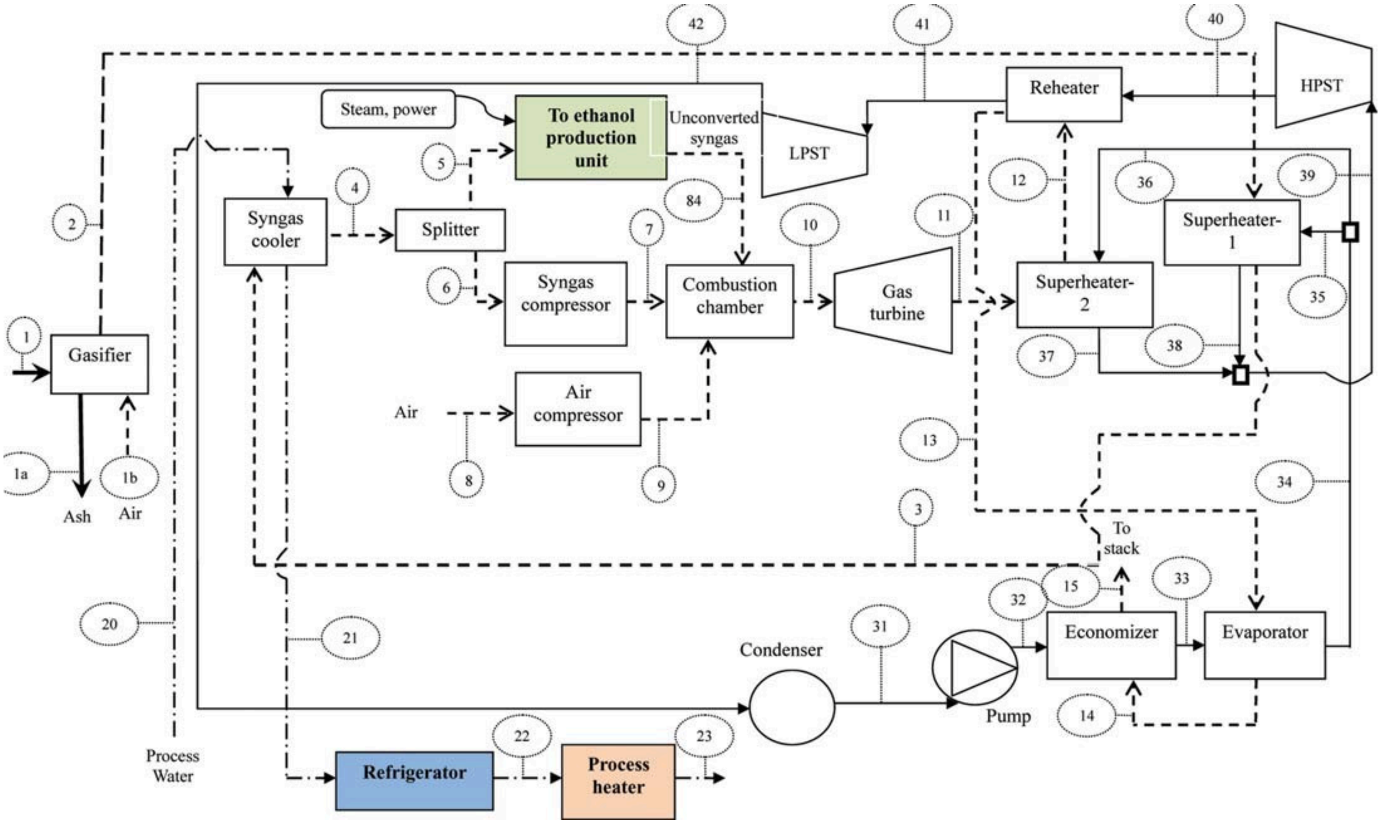

Fig.1. Schematic of the polygeneration process with associated state point [Jana and De, 2015c]

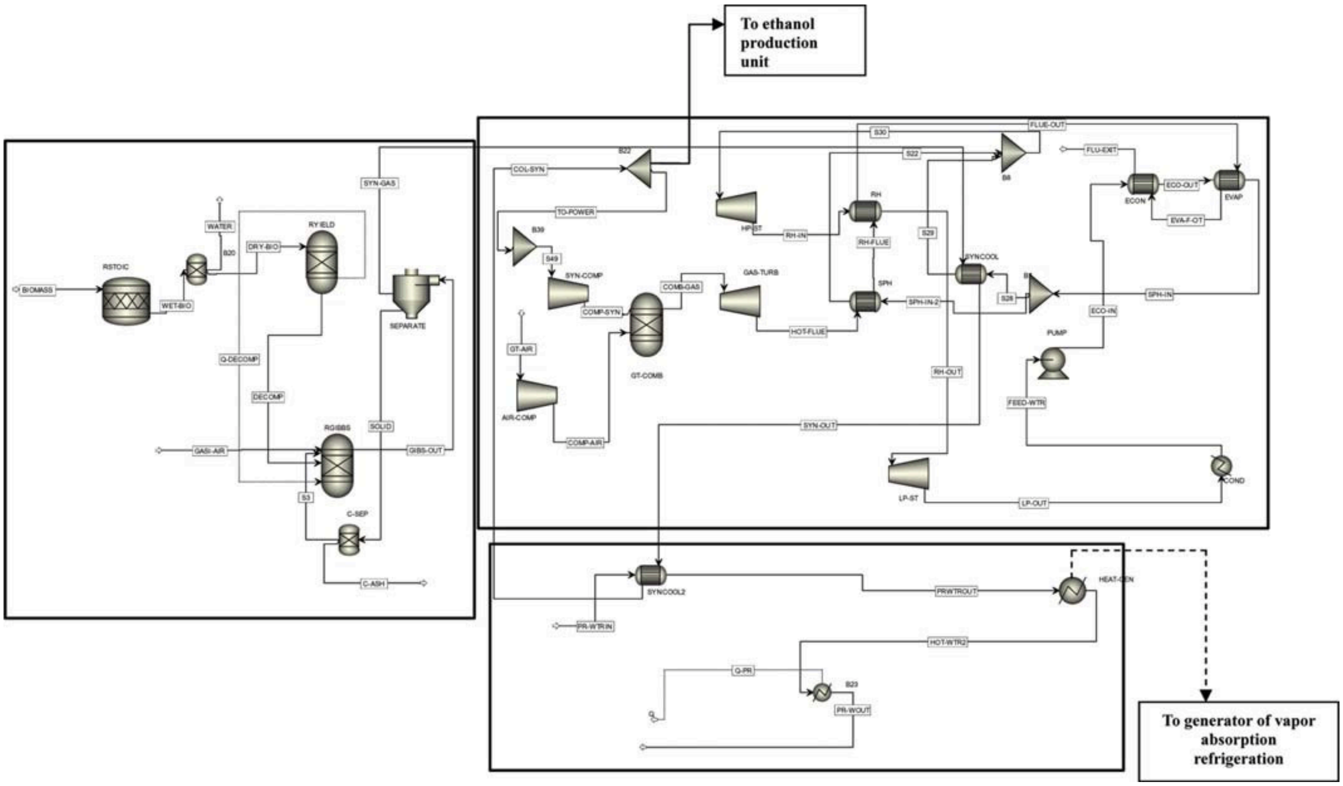

Fig.2. Aspen Plus® model of the polygeneration [Jana and De, 2015c]

Table 3: Temperature, pressure and mass flow rate of the state points of Fig.1

State point	Connecting from	Connecting to	mass flow rate (kg/s)	Temperature (K)	Pressure (Pa)
1	Atmosphere	Gasifier	0.2777778	298.15	101353
1a	Gasifier	Atomsphere	0.0625	996.3491	101353
1b	Atmosphere	Gasifier	0.3371716	298.15	101325
2	Gasifier	Superheater-1	0.5378295	996.3491	101325
3	Superheater-1	Syngas cooler	0.5378295	922.9179	101325
4	Syngas cooler	Splitter	0.5378295	404.9064	101325
5	Splitter	Ethanol production unit	0.2151318	404.9064	101325
6	Splitter	Syngas compressor	0.3226977	404.9064	101325
7	Syngas compressor	Combustion chamber	0.3226977	771.1384	1013250
8	Atmosphere	Aircompressor	0.7323935	298.15	101325
9	Aircompressor	Combustion chamber	0.7323935	599.2628	1013250
10	Combustion chamber	Gas turbine	1.159728	1640.88	1013250
11	Gasturbine	Superheater-2	1.159728	1054.276	101325
12	Superheater-2	Reheater	1.159728	993.9797	101325
13	Reheater	Evaporator	1.159728	948.7956	101325
14	Evaporator	Economizer	1.159728	679.9093	101325
15	Economizer	Atmosphere	1.159728	472.3493	101325
20	Atmosphere	Syngas cooler	0.1393611	298.15	101325
21	Syngas cooler	Refrigerator	0.1393611	384.8972	101325
22	Refrigerator	Process heater	0.1393611	374.5936	101325
23	Process heater	Hot water exit	0.1393611	298.15	101325
31	Condenser	Pump	0.245	312.1747	7000
32	Pump	Economizer	0.245	312.8031	7000000
33	Economizer	Evaporator	0.245	558.9774	7000000
34	Evaporator	Splitter	0.245	558.9774	7000000
35	Splitter	Superheater-1	0.098	558.9774	7000000
36	Splitter	Superheater-2	0.147	558.9774	7000000
37	Superheater-2	Mixer	0.147	753.15	7000000
38	Superheater-1	Mixer	0.098	753.15	7000000
39	Mixer	HPST	0.245	757.4013	7000000
40	HPST	Reheater	0.245	637.6114	3200000
41	Reheater	LPST	0.245	753.15	3200000
42	LPST	Condenser	0.245	312.1747	7000
84	Ethanol production unit	Combustion chamber	0.104637	472.2642	1013250

Table 4: Exergy values of the state points of Fig.1

State point	Physical exergy (J/kg)	Physical exergy (kJ/s)	Chemical exergy (kJ/s)	Total exergy (kJ/s)
1	0	0	4404	4404
2	465852.9	250.5494	2284.9	2535.449
3	392868.3	211.2962	2284.9	2496.196
4	21802.69	11.72613	2284.9	2296.626
5	21802.69	4.690451	914.6	919.2905
6	21802.69	7.035677	1372	1379.036
7	489531.2	157.9706	1372	1529.971
9	294610.3	215.7707	0	215.7707
10	1234134	1431.26	1.44E+02	1574.96
11	446223.2	517.4976	1.44E+02	661.1976
12	393270.6	456.0869	1.44E+02	599.7869
13	354972.6	411.6716	1.44E+02	555.3716
14	154199.7	178.8297	1.44E+02	322.5297
15	43686.24	50.66415	1.44E+02	194.3642
21	517990.4	72.18771	0.00E+00	72.18771
22	37760.01	5.262276	0.00E+00	5.262276
31	1731.05	0.424107	0.00E+00	0.424107
32	9229.566	2.261244	0.00E+00	2.261244
33	341439	83.65256	0.00E+00	83.65256
34	1044295	255.8523	0.00E+00	255.8523
35	1044295	102.3409	0.00E+00	102.3409
36	1044295	153.5114	0.00E+00	153.5114
37	1358888	199.7565	0.00E+00	199.7565
38	1358888	133.171	0.00E+00	133.171
39	1357207	332.5158	0.00E+00	332.5158
40	1135074	278.0931	0.00E+00	278.0931
41	1284340	314.6634	0.00E+00	314.6634
42	98392.57	24.10618	0.00E+00	24.10618

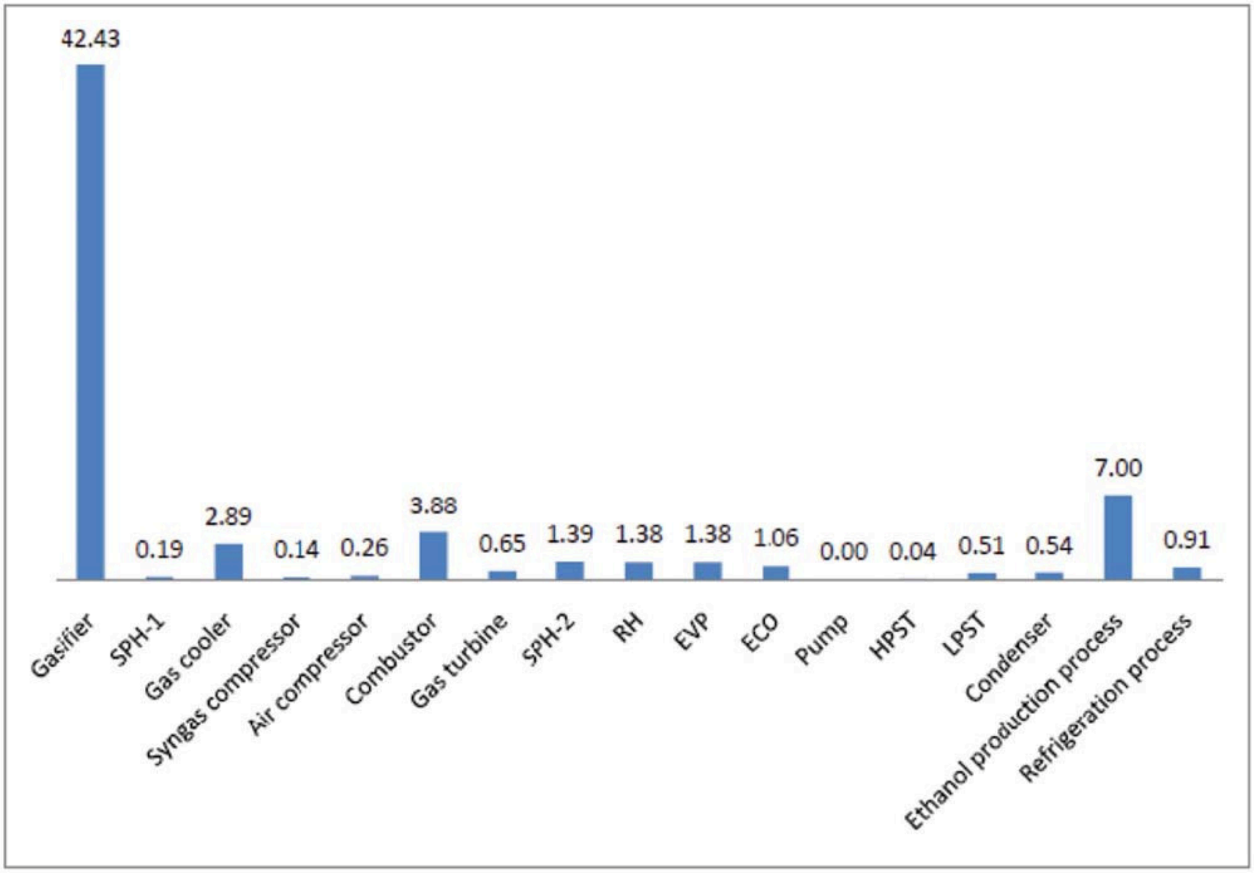

Fig.3. Percentage of exergy losses and/or destructions in different components of the polygeneration

in the form of gas turbine power, steam turbine power, ethanol, cooling and hot water. Exergy is lost from the system through ash including unconverted char and flue gas from stack. Exergy loss and/or destruction in terms of fuel exergy input to the system for different components are shown in Fig.3.In Fig.3, percentage of exergy losses and/or destructions in different components are shown. It is noted that the maximum amunt of the exergy input is lost and destructed in gasifier, combustor and ethanol production processes due to chemical and thermal irreversibility.

4. Conclusion

Exergy analysis is an useful thermodynamic tool to identify the possible improvement of energy system. Polygeneration is an energy system for delivering multiple utilities. Exergy analysis of polygeneration shows different components for possible thermodynamic improvement. Significant amount of power, ethanol, heating and cooling can be obtained through this polygeneration. Results indicate that the critical components and processes of the polygeneration for exergy losses and destructions are gasification, ethanol production and combustion. This is due to irreversibility in chemical reactions and losses through ash.

Acknowledgements

The authors are grateful to the University Grants Commission (UGC) of India and Research Council of Norway (RCN) for financial support of INCP-2014/10086 project. Dr. Kuntal Jana gratefully acknowledges to the CSIR, India for Senior Research Fellowship during this work.

References

[1]BentsenNS, Felby C, ThorsenBJ, 2014,Agricultural residue production and potentials for energy and materials services,Progress in Energy and Combustion Science, 40,59-73

[2] Chen D, Chen X, Sun J, Zheng Z, Fu K,2016, Pyrolysis polygeneration of pine nut shell: Quality of pyrolysis products and study on the preparation of activated carbon from biochar, BioresourceTechnology, 216, 629–636

[3]Chicco G, Mancarella P, 2009, Distributed multi-generation: a comprehensive view, Renewable and Sustainable Energy Reviews, 13 (3), 535–551.

[4] Dincer I, Rosen MA, 2013. Exergy: Energy, Environment and Sustainable Development, Elsevier, Oxford, UK.

[5] Domalski EA, Jobe Jr TL, Milne TA, 1986, Thermodynamic data for biomass conversionand wastes incineration. A product of Solar Technical Information Program.United States: National Bureau of Standards.

[6]Gadde B, Menke C, Wassmann R, 2009, Rice straw as a renewable energy source in India, Thailand, and the Philippines: Overall potential and limitations for energy contribution and greenhouse gas mitigation, Biomass and Bioenergy, 33, 1532–1546.

[7] IEA, 2016. World Energy Outlook, International Energy Agency, Paris.

[8] Jana K, De S, 2015a, Techno-economic evaluation of a polygeneration – a casestudy for an Indian district, Bioresource Technology, 181, 163–173

[9] Jana K, De S, 2015b, Sustainable polygeneration design and assessment throughcombined thermodynamic, economic and environmental analysis, Energy, 91,540–555

[10] Jana., De S, 2015c, Polygeneration using agricultural waste: Thermodynamic and economic feasibility study, Renewable Energy, 74, 648-660

[11] JanaK, De S, 2017. Thermo-chemical ethanol production from agricultural waste through polygeneration: performance assessment through a case study. In: AgarwalAK, AgarwalRA, GuptaT, GurjarBR (Eds.), Biofuels, Springer, Singapore pp. 137-156(DOI: 10.1007/978-981-10-3791-7_8)

[12] Kotas TJ, 1985. The exergy method of thermal plant analysis,Butterworths, London, UK.

[13] Li Y, Zhang G, Yang Y, Zhai D, Zhang K, Xu G, 2014, Thermodynamic analysis of a coal-based polygeneration system with partial gasification, Energy, 72, 201-214

[14] Serra LA, Lozano MA, Ramos J, Ensinas AV, Nebra SA, 2009, Polygeneration andefficient use of natural resources, Energy, 34, 575-586.

[15] Trippe F, Frohling M, Schultmann F, Stahl R, HenrichE, 2011,Techno-economic assessment of gasification as a process step within biomass-to-liquid (BtL) fuel and chemicals production, Fuel Processing Technology, 92, 2169-2184

[16] Vidal M, Martín M,2015, Optimal coupling of a biomass based polygeneration system with aconcentrated solar power facility for the constant production of electricity over a year, Computers and Chemical Engineering, 72, 273–283