

THERMODYNAMIC ANALYSIS OF A FLUIDIZED BED COAL COMBUSTOR STEAM PLANT IN TEXTILE INDUSTRY

A. Tantekin^{1,*}, N. F. Özdi1

ABSTRACT

The examinations of first and second laws of thermodynamics are performed on a 6.5 MW power plant, established in Adana, Turkey. The equipment for the investigated plant can be aligned as a fluidized bed coal combustor (FBCC), a heat recovery steam generator (HRSG), an economizer (ECO), fans, pumps, a cyclone and a chimney. Whole parts of equipment are investigated separately and energetic and exergetic inspections are enforced for whole parts of the plant. The maximum exergy destruction rates in the plant are obtained for the FBCC, HRSG and ECO with 95%, 3% and 1% of the whole system, respectively. Higher excess air in the system induces heat losses, especially in the FBCC component by virtue of the rising in mass flow rate of the flue gas. This situation can be considered as one of the primary reasons of irreversibility. Additionally, higher excess air induces the decrement of combustion efficiency in FBCC. Therefore, this value and adverse effects on combustion efficiency can be decreased by reducing the flow rate of air.

Keywords: *Fluidized Bed, Exergy, Thermodynamic Analysis*

INTRODUCTION

In the rapidly developing world, the industrial sector is growing at the same pace. The lack of energy supply, accessibility and cost constraints have forced companies to search and improve themselves constantly for cost-effective improvements. Industries with high energy needs have begun to use fluidized bed systems to meet their required energy needs and to reduce fossil fuel burnout. The most important features of fluidized bed systems are fuel flexibility and low emissions. Fluidized bed boilers have been used in chemical industry for many processes in many years, but they are started to be used as fluidized bed coal combustor after 1970s. After that, it has taken an important place in the production of steam and electricity [1-10].

As the literature is examined in terms of thermodynamics point of view, thermodynamics analyses have been done to increase the system efficiency in energy generating systems. Ozdil and Pekdur [9] performed a thermodynamic analysis on a 14.25 MW cogeneration system in food industry. According to the outcomes, obtained from the analysis, the uttermost exergy destruction occurred in boiler with 36% of the whole system and it was followed by economizer and chimney with 34% and 25%, respectively. Moreover, they also investigated the relation between the pressure of steam in boiler and efficiency of the system. They observed that increment in steam pressure on boiler caused a decrement in exergy destruction and so an increment in efficiency on boiler. Ozdil et al. [6] implemented a thermodynamic analysis of an Organic Rankine Cycle in a regional power plant. They showed a relation among exergy efficiency and pinch point. Since the temperature of pinch point went downward, the efficiency of exergy went upward owing to minor exergy destruction rate. They accomplished that the efficiencies of energy and exergy were obtained as 9.96% and 47.22%, respectively for working condition as saturated liquid form in evaporator inlet. They examined the impact of water phase of evaporator inlet on exergy efficiency. The exergy efficiency for water mixture with 0.3 quality was figured out as 41.04%. However, the exergy efficiency for water mixture with 0.7 quality was figured out as 40.29%. Therefore, the exergy efficiency for saturated vapor form was figured out as 39.95%. Callak et al. [11] put into practice an exergy analysis by using of the real working data taken from FBCC and HRSG in a textile factory placed in Turkey. As a beginning, the basic exergy analysis was put into practice on the parts of the system. The exergy efficiencies of the parts were reckoned as 44.2% and 46.2% for FBCC and HRSG, respectively. Then, improved exergy analysis was carried out by dividing the exergy destructions of the parts into evitable and inevitable sections. The evitable exergy destruction rates of the FBCC and HRSG were designated as 2999 kW

This paper was recommended for publication in revised form by Regional Editor Şevket Özgür Atayılmaz

¹*Department of Engineering, Adana Science and Technology University, Adana, TURKEY*

^{*}*E-mail address: atantekin@adanabtu.edu.tr*

Manuscript Received 2 June 2017, Accepted 1 August 2017

and 760 kW, respectively. Moreover, after exemption of inevitable sections, the exergy efficiencies were qualified as 53.1% and 48.1% for FBCC and HRSG, respectively.

In this study, a rigorous and vigorous exergy examination has been fulfilled on a fluidized bed coal combustor steam plant within a textile factory. The evaluation of exergy effectiveness of the whole system parts have been implemented in separate sections. The diagram of Grassmann has been demonstrated by virtue of providing quantitative data related with the input and output of the exergy rate of the system.

SYSTEM DESCRIPTION

In the system, which is named fluidized bed coal combustor steam plant (FBCCSP), thermodynamic and exergoeconomic analyses are implemented. The whole system consisting of a FBCC, a HRSG, an ECO, a CYC, a VF, an AF, a CH and two Ps, has a 6.5 MW power. FBCCSP investigated in the scope of study is installed in Adana, city of Turkey. The diagrammatic representation of the examined FBCCSP is presented in Figure 1.

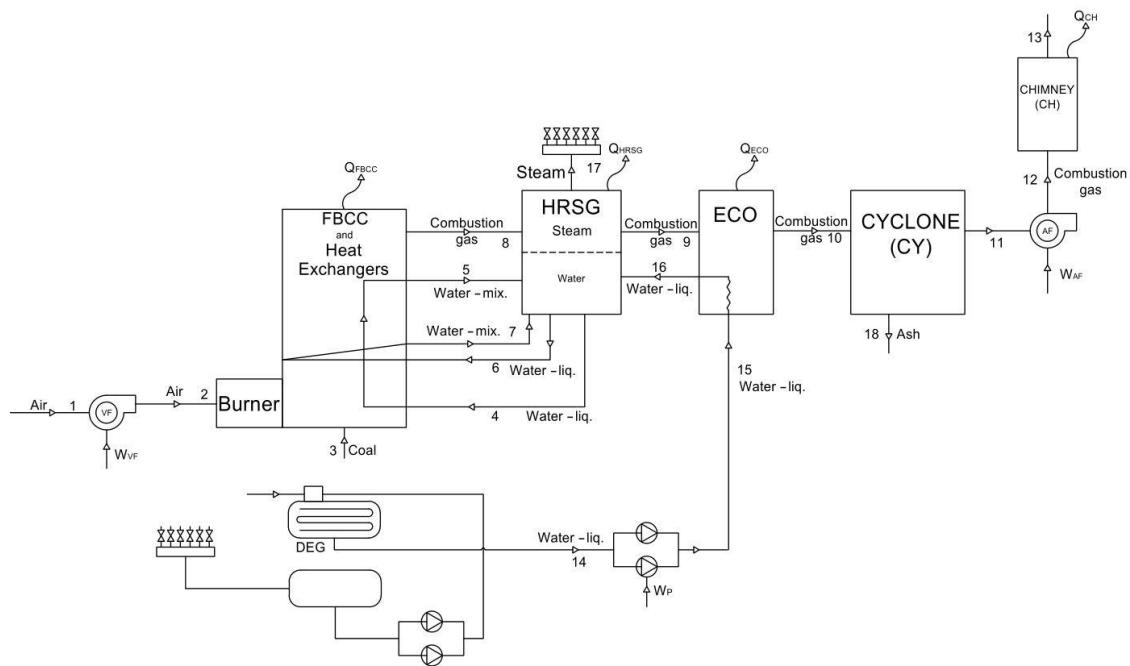


Figure 1. Schematic diagram of the power plant [10]

Besides, two ventilation fans, which are referred to as primary and secondary ventilation fans, are employed to provide combustion air for the system. The capacities of these primary and secondary fans are 8456 m³/h (45 kW) and 1845 m³/h (4 kW), respectively. Moreover, the system also includes two feed water pumps. First one supplies the water to the system and second one removes the combustion gas for aspiration. The capacities of these pumps and fans which are employed for the plant are 11 kW and 37 kW, respectively. The feed water in the system is pumped into the ECO, where it is preheated. Subsequently, this feed water reaches the HRSG which has steam and water. Water is transformed into steam by the help of heat exchangers, located in HRSG. In addition, the selected coal type for the operation of this FBCCSP is Şırnak Asphaltite. The required characteristics and components of the selected coal are given in the Table 1. The plant operating data are given in Table 2. The considered assumptions within this study are put in order as follows.

- i. The system is considered as steady state operation.
- ii. Vicissitudes in potential and kinetic energy are not taken into account.
- iii. Gases, flowing in the system, are taken into consideration according to the ideal gas principles.
- iv. The exergy of ash in the system is ignored owing to its relatively low impact.

Table 1. The content of the fuel

Moisture (w, %)	8.15
Ash (%)	36.67
Volatile Matter (%)	20.03
Sulphur (s, %)	5.36
Hydrogen (h, %)	4
Oxygen (o, %)	2
Nitrogen (n, %)	1
Carbon (c, %)	22.79
GCV/HHV (kcal/kg)	4637
LHV (kcal/kg)	4426

Table 2. Operating conditions of the power plant

Mass flow rate of coal	0.5 kg/s
Steam flow rate	1.2 kg/s
Steam pressure	750 kPa
Steam temperature	177 °C
Comb. gas flow rate	1.3 kg/s
Air flow rate	1.38 kg/s
Water flow rate	1.2 kg/s

ANALYSIS

The goal of present study is to practice an investigation of energetic and exergetic performance in belief that grasping and showing the methods of effectiveness enhancement of FBCC steam power plant. The relationship between balance equations of energy and exergy depends on the principle of thermodynamics laws.

The first law of thermodynamics generally relates to the conservation of energy. Energy can be converted one form to another form. The analysis of first law is employed with the help of mass and energy balance equations as can be shown in Eq. (1) and Eq. (2):

$$\text{Mass Input} = \text{Mass Output} (\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out}) \quad (1)$$

$$\text{Energy Input} - \text{Energy Output} = \text{Net Energy} (Q - W = \Sigma \dot{m}_{out}h_{out} - \Sigma \dot{m}_{in}h_{in}) \quad (2)$$

The diagrammatic representation of the parts in the examined system and all the inputs and outputs in these parts are given in Fig 2. For the calculations, the thermodynamic specifications of the water, steam and flue gases are obtained from the thermodynamic tables. Moreover, the thermodynamic specifications of the reference environment are assumed as $T_0 = 40^\circ\text{C}$, $P_0 = 101.3 \text{ kPa}$. The balance equation of energy for the FBCC, can be formed with the help of Eq. (3):

$$\dot{m}_2h_2 + \dot{m}_3h_3 + \dot{m}_4h_4 + \dot{m}_6h_6 = \dot{m}_5h_5 + \dot{m}_7h_7 + \dot{m}_8h_8 + Q_{loss,3} \quad (3)$$

The balance equation of energy for the HRSG, can be formed as Eq. (4):

$$\dot{m}_5h_5 + \dot{m}_7h_7 + \dot{m}_8h_8 + \dot{m}_{16}h_{16} = \dot{m}_4h_4 + \dot{m}_6h_6 + \dot{m}_9h_9 + \dot{m}_{17}h_{17} + Q_{loss,4} \quad (4)$$

The balance equation of energy for the ECO, can be formed as Eq. (5):

$$\dot{m}_9h_9 + \dot{m}_{15}h_{15} = \dot{m}_{10}h_{10} + \dot{m}_{16}h_{16} + Q_{loss,5} \quad (5)$$

Exergy balance equations can be seen as Eq. (6):

$$\text{Exergy Input} - \text{Exergy Output} - \text{Exergy Consumed} = \text{Net Exergy} \quad (6)$$

For calculation of physical exergy, the general physical exergy equation can be used, as Eq. (7):

$$\text{ex}^{\text{ph}} = (h - h_0) - T_0(s - s_0) \quad (7)$$

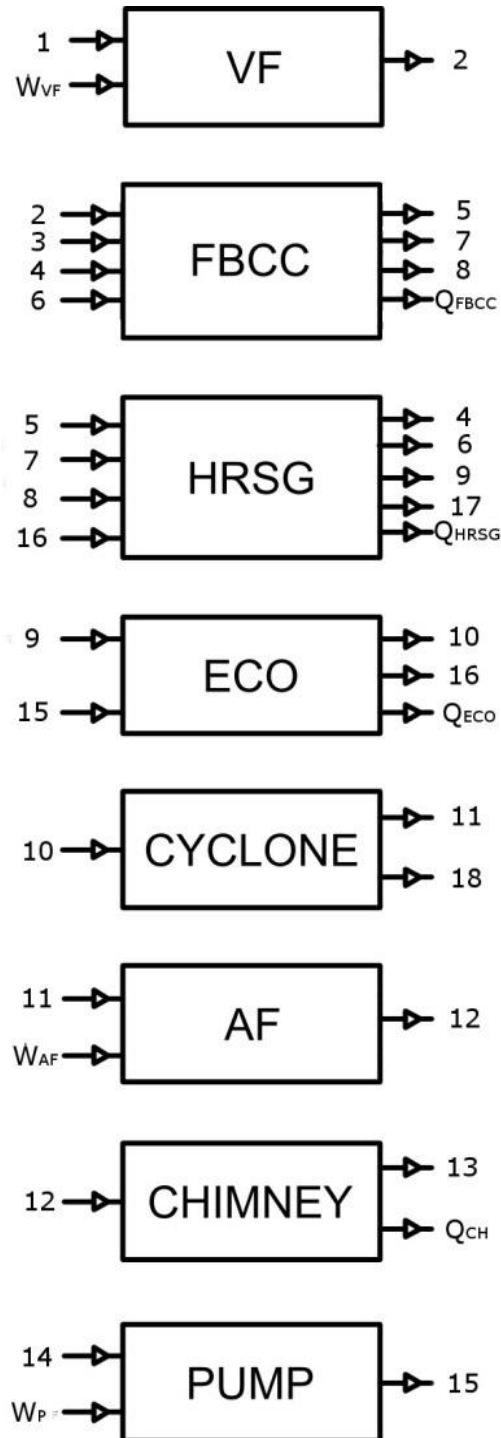


Figure 2. The diagrammatic representation of the parts [10]

The balance equation of exergy of the FBCC can be formed as Eq. (8):

$$\dot{m}_2ex_2 + \dot{m}_3ex_3 + \dot{m}_4ex_4 + \dot{m}_6ex_6 = \dot{m}_5ex_5 + \dot{m}_7ex_7 + \dot{m}_8ex_8 + Q_{loss,3} (1 - T_0/T_s) + \dot{E}_{XD} \quad (8)$$

The balance equation of exergy of the HRSG can be formed as Eq. (9):

$$\dot{m}_5ex_5 + \dot{m}_7ex_7 + \dot{m}_8ex_8 + \dot{m}_{16}ex_{16} = \dot{m}_4ex_4 + \dot{m}_6ex_6 + \dot{m}_9ex_9 + \dot{m}_{17}ex_{17} + Q_{loss,4} (1 - T_0/T_s) + \dot{E}_{XD} \quad (9)$$

The balance equation of exergy of the ECO can be formed as Eq. (10):

$$\dot{m}_9ex_9 + \dot{m}_{15}ex_{15} = \dot{m}_{10}ex_{10} + \dot{m}_{16}ex_{16} + Q_{loss,5} (1 - T_0/T_s) + \dot{E}_{XD} \quad (10)$$

RESULTS AND DISCUSSION

In the scope of this study, thermodynamic analyses have been carried out with the adherence to the thermodynamics laws in order to reveal the efficiency of the FBCCSP and to improve its effectiveness. Besides, energetic and exergetic efficiencies of the FBCC, HRSG and ECO have observed.

Depending on thermodynamic inspection, the destructions of exergy and the rates of energy and exergy efficiencies for base equipment of FBCCSP are demonstrated in Figures 3-4-5, respectively. Meanwhile the distribution of exergy destruction is revealed in Figure 6. Taking into consideration for balance equations, mentioned in the previous chapter, energy and exergy efficiencies and exergy destruction rates are computed and revealed in Table 3. As understood from Table 3, the exergy efficiencies of FBCC, HRSG, ECO, CY and CH are computed as 10.51%, 84.84%, 33.10%, 99.92%, and 99.99%, respectively. Figure 4 shows that energy efficiencies for major equipment are higher than 0.6 except FBCC part. The second law efficiency of the FBCCSP is 6.32% however the exergy destruction in the FBCCSP is observed as 7719.18 kW. As understood from Figure 3, the major exergy destruction among the equipment happens in FBCC part. The reasons of the irreversibility, happening in FBCC, can be represented as follows:

- i. The value of excess air, receiving into system, induces excessive heat loss which can be said as the first reason. The enhancement on the value of the excess air causes in the enhancement of the mass flow rate of the flue gases. By virtue of the enhancement in mass flow rate of flue gas, diminution of temperature of FBCC is observed. So heat losses from FBCC goes upward and efficiency of FBCC goes downward.
- ii. The second reason of the irreversibilities can be expounded as the chemical reaction happened in FBCC owing to combustion process. When the content of flue gas separated from the chimney is examined, it can be said that the combustion efficiency is poor due to high CO amount, unburned carbon content. Higher CO formation rather than CO₂, which is the result of an incomplete combustion. Namely, the combustion is inefficient due to the high excess air value. In other words, low combustion efficiency and heat losses due to high excess air ratio are other important reasons of the irreversibilities in FBCC.
- iii. The third reason of irreversibilities can be expounded as the coal type burned on FBCC. The exchange in the coal, employed into the FBCC, induces the alteration of the exergy efficiency in consequence of the diverse calorific value of coal. Since calorific value of coal rises, exergetic efficiency of FBCC also rises by virtue of the large internal energy of coal.

Table 3. The outcomes of exergetic analysis.

Components	Ex _D (kW)	η _{II} (%)
FBCC	7348.37	10.51
HRSG	229.31	84.84
ECO	55.66	33.10
CY	0.65	99.92
CH	0.11	99.99
VF+AF+P	85.07	10.70
FBCCSP	7719.18	6.32

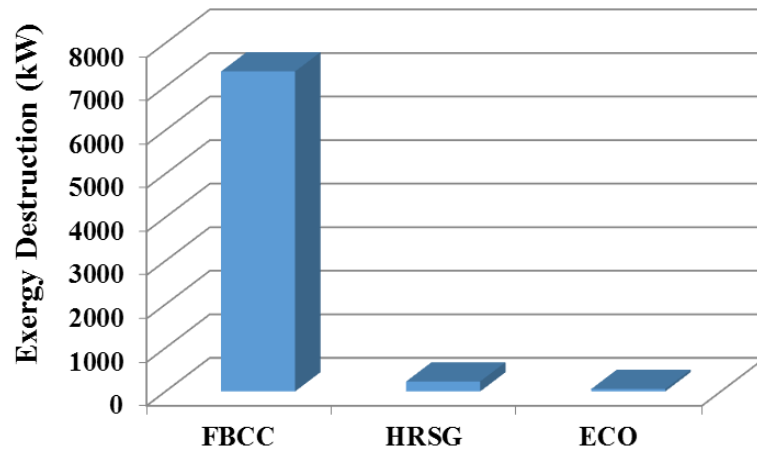


Figure 3. Exergy destruction rates for the major components

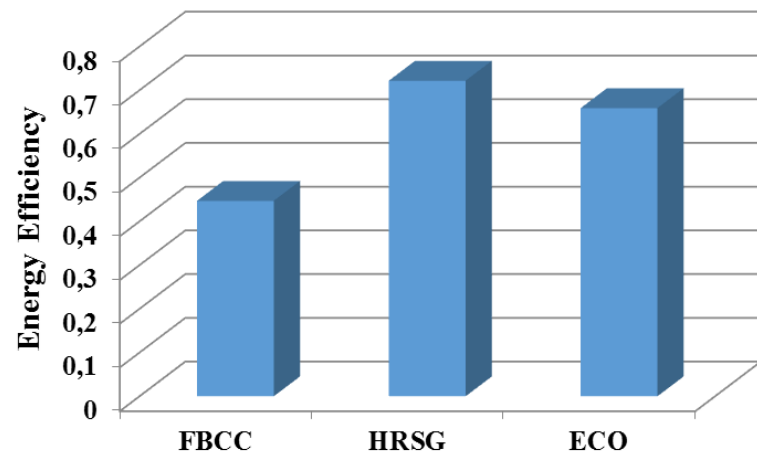


Figure 4. Energetic efficiency for the major components

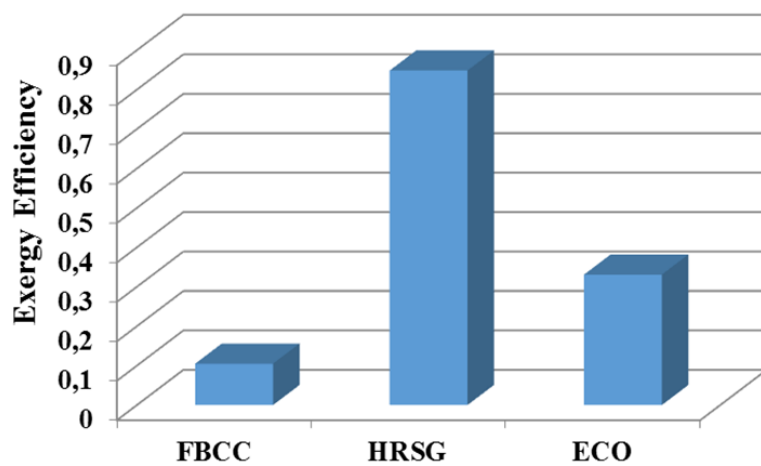


Figure 5. Exergetic efficiency for the major components

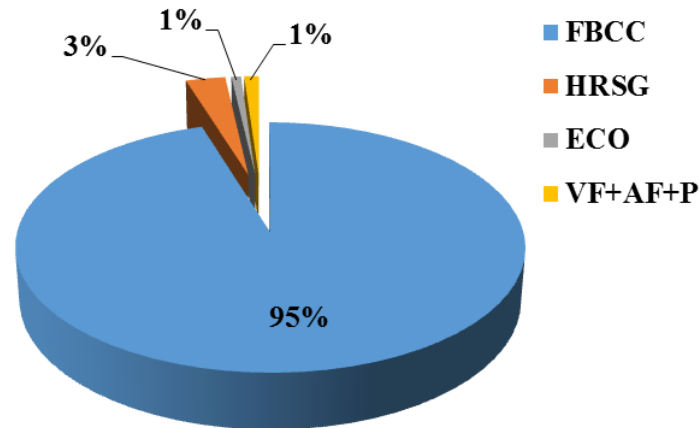


Figure 6. Dispersion of exergy destruction rates

CONCLUSION

In the scope of this study, thermodynamic analyses have been carried out for a fluidized bed coal combustion system that has produced steam. Thermodynamic examination has been applied in accordance with general thermodynamic laws, especially first and second laws. It is understood from the outcomes, the uttermost exergy destruction happens in the FBCC part with 7348.37 kW. Firstly, miscarriage calorific value of coal affects the effectivity of plant. Since the energy amount, obtained from the coal, is low owing to the low calorific value, the effectivity of the FBCC will decrease. In order to obtain better performance on FBCC, solid fuel, should be chosen, having enhanced calorific value. Furthermore, another reason of the inefficiency is that the amount of excess air is higher than the desired value. Elevated amount of excess air in the system directly affects the flow of the burned gas, which causes the temperature drop and the increase in heat losses on FBCC. The third reason, in conjunction with the second reason, is that the combustion efficiency in the system is low due to the high excess air content on the system. It is also seen that the unburnt carbon is found when the content of the combustion gas from the chimney. This unburnt carbon indicates that the combustion is not complete and the combustion efficiency is low. It can be said that the cause of the drop in combustion efficiency is the high amount of oxygen due to high excess air in FBCC.

ACKNOWLEDGMENTS

The authors are grateful to the financial support of Adana Science and Technology University Research Fund under project no: **MÜHDBF.MM.2015-10**.

NOMENCLATURE

ex	Specific exergy (kJ/kg)
$\dot{E}_x D$	Exergy Destruction (kW)
h	Specific enthalpy (kJ/kg)
LHV	Lower heating value of coal (kJ/kg)
\dot{m}	Mass flow rate (kg/s)
P	Pressure (Pa)
Q	Rate of heat transfer (W)
s	Specific entropy (kJ/kg K)
T	Temperature (K)
\dot{W}	Rate of work (W)
AF	Air fan
CH	Chimney
CY	Cyclone
ECO	Economizer
FBCC	Fluidized bed coal combustor
HRSG	Heat recovery steam generator

REFERENCES

- [1] Bejan, A., Tsatsaronis, G. and Moran, M. (1995) '*Thermal Design & Optimization*', A Wiley-Interscience Publication.
- [2] Dincer, I. and Rosen, M.A. (2007) '*Exergy, Energy, Environment and Sustainable Development*', Elsevier.
- [3] Kotas, T.J. (1995) '*The Exergy Method of Thermal Plant Analysis*', Krieger Publishing Company, London.
- [4] Kuzgunkaya, E.H. and Hepbasli, A. (2007) 'Exergetic performance assessment of a ground-source heat pump drying system', *Int. J. Energy Res.*, Vol. 31, pp.760–777.
- [5] Lee, U., Park, K., Jeong, Y.S., Lee, S. and Han, C. (2014) 'Design and analysis of a combined Rankine cycle for waste heat recovery of a coal power plant using LNG cryogenic exergy', *Ind. & Eng. Chem. Res.*, Vol. 53, pp.9812–9824.
- [6] Ozdil, N.F.T., Segmen, M.R. and Tantekin, A. (2015) 'Thermodynamic analysis of an organic Rankine cycle (ORC) based on industrial data', *Appl. Therm. Eng.*, Vol. 91, pp.43–52.
- [7] Ozdil, N.F.T. and Segmen, M.R. (2016) 'Investigation of the effect of the water phase in the evaporator inlet on economic performance for an Organic Rankine Cycle (ORC) based on industrial data', *Appl. Therm. Eng.*, Vol. 100, pp.1042–1051.
- [8] Ozdil, N.F.T. and Tantekin, A. (2016) 'Exergy and exergoeconomic assessments of an electricity production system in a running wastewater treatment plant', *Renew. Energy.*, Vol. 97, pp.390–398.
- [9] Ozdil, N.F.T. and Pekdur, A. (2016) 'Energy and exergy assessment of a cogeneration system in food industry: a case study', *Int. J. Exergy*, Vol. 20, pp.254–268.
- [10] Ozdil, N.F.T., Tantekin, A and Erbay, Z. (2016) 'Energy and exergy analyses of a fluidized bed coal combustor steam plant in textile industry', *Fuel*, Vol. 183, pp.441–448.
- [11] Callak M., Balkan F. and Hepbasli A. (2015) 'Avoidable and unavoidable exergy destructions of a fluidized bed coal combustor and a heat recovery steam generator', *Energy Convers Manage*, Vol. 98, pp.54-58.