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DETERMINATION OF AVOIDABLE & UNAVIODABLE EXERGY DESTRUCTIONS OF FURNACE- AIR PREHEATER COUPLED SYSTEM IN A PETROCHEMICAL PLANT

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ABSTRACT

This study was performed with the intention of giving a deeper insight about the thermodynamic effectiveness of a thermal system. In this study, a fired heater (or furnace) existing in a petrochemical plant located in Aliağa, İzmir, Turkey were investigated from both first and second law point of view to identify the true magnitude of thermodynamic inefficiencies and reveal the true potential improvements for the system components. Hence, apart from the classical energy analysis, both conventional and advanced exergy analysis were applied to the system. The major source of inefficiencies within the system was enlightened by determining the exergy destructions and recommendation for possible modifications for improving thermodynamic efficiencies were stated. For each system component, amount of exergy destructions were determined and exergy efficiencies were calculated as 40.9% and 39.3% for fired heater (FH) and air preheater(APH), respectively in conventional exergy analysis. Besides, applying the advanced exergy analysis method it was seen that exergy efficiencies can be increased up to 52.4% and 85.8%, respectively.

INTRODUCTION

Shekarchian et. al [1] defined the furnaces as the largest energy consuming units in petroleum refining and petrochemical industries and the thermal efficiency of furnaces plays a crucial role in the plant's energy saving. So, it is really important to maximize the amount of heat transfered to the process fluid and minimize the heat losses from the furnace. Cengel et. al [2] stated that a significant amount of energy in the processes is lost via stack gas. Therefore, heat recovery units (like APH) have been widely used in petrochemical industry in order to reduce the high stack gas temperature and provide substantial energy savings.

The first law of thermodynamics is conventionally used with the purpose of energy utilization in the industrial systems. It determines the energy losses and effectiveness of the resources. However, it is inadequate when the quality aspect of energy use is taken into account. The exergy analysis, however is based on the second law. It is a more powerful thermodynamic method for assessing and improving the efficiency of processes, devices and systems, as well as for enhancing environmental and economic performance.

Dincer et. al [3] disscussed that exergy is a key concept which creates a linkage between the physical and engineering world and the environment and it helps to identify the true efficiency of engineering systems, which makes it a useful concept to find improvements.

Kanoglu et. al [4] indicated that energy and exergy efficiencies are essential for designing, analyzing, optimizing and improving energy systems through appropriate energy policies and strategies.

As it can be clearly seen from the references above, applying exergy based analysis on energy systems is significant for engineers and decision makers in order to save energy, optimize the resources, reduce to environmental pollution and enable sustainable development.

Shekarchian et. al [1] performed a study in order to analyze economic benefits of incorporating both heat recovery and air preheating techniques into the existing different fired heater units in a petroleum refinery. In addition to energy analysis, second law efficiency and the rate of irreversibilities in the system were also analyzed via an exergy analysis. It was seen from the study that both analyses were satisfying that heat recovery enhanced both first law and second law efficiency from 63.4% to 71.7% and from 49.4% to 54.8%, respectively. In addition, heat recovery and air preheating methods leads to a substantial fuel reduction (7.4%) while simultaneously decreasing the heat loss and irreversibilies of the unit.

Kelly et. al [5] mentioned that a conventional exergy analysis identifies the system components with the highest exergy destruction and the processes that cause them. Efficiencies within a system's component can then be improved by reducing the exergy being destroyed within the component.

Saidur et. al [6] also investigated a process heating system consisting of a boiler, a combustion chamber and a heat exchanger from second law point of view. They found that the combustion chamber and the heat exchangers are the main contributors for exergy destruction in a boiler with exergetic efficiencies of 45 % and 48 %, respectively. They also stated that the method of heat recovery from flue gas is one of the effective ways to save energy in a boiler.

Regulagadda et.al [7] carried out a study about second law analysis of a thermal power plant along with a parametric study that investigates the effects of different parameters like temperature and pressure on the system performance. They concluded that the maximum exergy destruction occurred in combustor unit and efforts at improving plant's performance should be directed to improving combustor efficiency.

Doseva et.al [8] conducted a second law study about a cogeneration system which is driven by biogas internal combustion engines located in Varna Wastewater treatment plant and stated that it would be helpful to know what part of the exergy destruction within system components can be avoided by technological improvement.

Conventional exergy analysis is used to evaluate the performance of an individual unit at certain operating conditions however it cannot consider the actual achievable best performance of the unit.

Such limitations in conventional exergy analysis may be considerably decreased by applying advanced or detailed exergy analysis. Tsatsaronis et. al [9] introduced advanced exergy analysis by splitting exergy destructions into avoidable and unavoidable parts and with the aid of a cogeneration plant example, he proved the advantages of dividing exergy destruction into avoidable and unavoidable parts by exergoeconomic analysis.

Morosuk and Tsatsaronis [10] explanied how to calulate the amount of unavoidable exergy destruction in an advanced exergy analysis and they applied their approach to a simple gas-turbine system that reveals the potential improvement and interaction among the system's components.

Wang et. al [11] applied both conventional and advanced exergy analyses to a supercritical coal-fired power plant. Their results showed that boiler in the system has a large amount of exergy destruction. But it's concluded in the study that, this unit has also the largest amount of avoidable exergy destruction.

Vuckovic et.al [12] also accomplished a study on conventional and advanced exergy analysis and exergoeconomic performance evaluation of an industrial plant. They found that although more than 97% of exergy destruction was caused by steam boiler, 92.3% of this exergy destruction in steam boiler can be avoided.

Petrakopouolu et. al [13] investigated a combined cycle power plant using both conventional and advanced exergy analyses. In the study, it was seen that the largest exergy destruction was occured in the combustion chamber and almost 68% of total exergy destruction cannot be avoided. Similar to the results obtained in conventional analysis, the advanced exergy analysis ranks the improvement priority of the combustion chamber first.

Vuckovic et. al [14] applied advanced exergy analysis and evaluated exergoeconomic performancefor a real complex industrial plant. They concluded that more than 80% of total exergy destruction of the overall system comes from the boiler and 83.5% of this destruction cannot be avoided.

As seen from the literature survey, there are numerious studies related with the design, simulation, energy analysis and performance evaluation of boilers. Since,it's one of the most energy consuming unit, investigating the boilers true thermodynamic efficiencies and propounding comments about its best achiveable performance via conventional and advanced exergy analyses gained much interest in recent years. Nevertheless, -to the best of the autor's knowledge- the studies investigating the performance assesment and exergetic analysis of individual industrial furnaces are very limited especially based on the actual operating data.

In this study, both conventional and advanced exergy analysis were performed on an existing furnace-air preheater units to reveal thermodynamic inefficiencies within this coupled system. By the help of conventional exergy analysis, the components with the highest exergy destruction and irreversibility were determined. Moreover, true improvement potential of each unit in the system were determined by splitting exergy destructions into avoidable and unavoidable parts via advanced exergy anaylsis. Also, a new expression for modified exergetic efficieny was presented and used in calculations.

CONVENTIONAL AND ADVANCED EXERGY ANALYSES

Bejan [15] expressed that exergy is the maximum theoretical work that can be extracted from a resource relative to its environment. In other words, it is a measure of the departure of the state of the system from that of the environment. Hence, it is very crucial to determine the environmental (reference) conditions in the exergy studies when investigating the exergetic efficiencies of the system's compounds. In this study, environmental conditions were taken as T_o = 293K and P_o = 1 bar.

The control volume exergy balance at the steady state for the *k*-th component of the energy system can be written as follows:

$$\dot{E}x_{F,k} = \dot{E}x_{P,k} + \dot{E}x_{D,k} + \dot{E}x_{L,k} \quad (1)$$

where $\dot{E}x_{F,k}$, $\dot{E}_{xP,k}$ are the fuel and product exergy rates, $\dot{E}x_{D,k}$ is the rate of exergy destructed in the component due to irreversibilites and provides a thermodynamic measurement of the system inefficiencies. If all the boundaries of a system is set to reference conditions as in this study, then the term of $\dot{E}_{L,k}$ can be eliminated. The exergetic efficiency is a common measure for assesing the thermodynamic perfomance of a system component in an industrial plant and is defined as:

$$\varepsilon = \frac{E\dot{x}_{P,k}}{\dot{E}x_{F,k}} = 1 - \frac{\dot{E}x_{D,k}}{\dot{E}x_{F,k}} = \frac{1}{1+\left(\frac{\dot{E}x_{D,k}}{E\dot{x}_{P,k}}\right)} \quad (2)$$

In advanced exergy analysis, the destruction of the exergy is split into two parts:

$$\dot{E}x_{D,k} = \dot{E}x^{AV}_{D,k} + \dot{E}x^{UN}_{D,k} \quad (3)$$

Tsatsaronis et. al [9] defined that $\dot{E}x^{UN}_{D,k}$ is the unavoidable part of the exergy destruction in kth component which cannot be eliminated even if ideal conditions (highest efficiency with minimum losses) are provided for the component with the best technology available. Whereas, $\dot{E}x^{AV}_{D,k}$ respresents the avoidable exergy destruction which is found by substracting the unavoidable part of destruction from the total exergy destruction.

Process Description

This study includes both conventional and advanced exergy analysis of an industrial furnace and air preheater units in a petrochemical plant in İzmir. The furnace has a capacity of 42 Gcal/h and used to vaporize the hydrocarbon process fluids. Natural gas is used as fuel for combustion with 20% excess air. The flue gas that exits the furnace stack at 408 °C is fed to the air preheater unit. Because flue gas from the furnace is at very high temperature, significant amount of energy is lost with it. Recovering this high-energy flue gas via an APH increase the temperature of fresh combustion air entering the furnace and eventually decreases the amount of fuel used for combustion. So, this can directly increase the thermal efficiency of the furnace. The flow diagram of the system is shown in Figure 1.

Conventional Exergy Analysis

Firstly, conventional exergy analysis was performed for the system. In order to obtain the conventional exergetic efficiencies of each unit; exergy rates of each stream were computed by using Eq.(4):

$$\dot{E}x = \dot{E}x^{PH} + \dot{E}x^{PT} + \dot{E}x^{KN} + \dot{E}x^{CH} \quad (4)$$

If $\dot{E}x^{PT}$ and $\dot{E}x^{KN}$ exergy changes are negligible as in this study, total exergy rate of each stream can be represented by the sum of the $\dot{E}x^{PH}$ and $\dot{E}x^{CH}$ where;

$$\dot{E}x^{PH} = (h - h_o) - T_o\,(s - s_o) \quad (5)$$

$$Ex^{CH} = \sum x_k e^{CH} + RT_0 \sum x_k \ln(x_k) \quad (6)$$

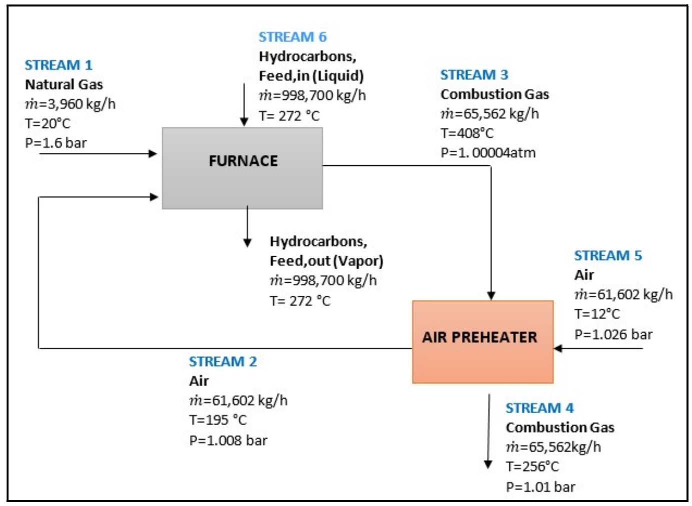

Figure 1. Furnace and Air Preheater

Operational data and the calculated total exergies of streams are given in Table 1 and Table 2.

As mentioned before, exergetic efficiency of a unit can be defined as the ratio of the product exergy rate over fuel exergy rate. The conventional exergetic efficiency of furnace can be defined as:

$$\varepsilon_{Furnace}\,(\%) = \frac{E\dot{x}_3 + \Delta Ex_{feed}}{E\dot{x}_1 + E\dot{x}_2} \times 100 \quad (7)$$

In this equation exergy change of feed stream (hydrocarbon mixture), ΔEx_{feed}, was calculated as 19.09 MW by the following equation:

$$\Delta Ex = \dot{m}_{feed}\left[(h_{vapor} - h_{liquid}) - T_0(S_{vapor} - S_{liquid})\right] \quad (8)$$

The conventional exergetic efficiency of APH unit is defined as:

$$\varepsilon_{APH}\,(\%) = \frac{E\dot{x}_2 - E\dot{x}_5}{E\dot{x}_4 - E\dot{x}_3} \times 100 \quad (9)$$

Conventional exergy efficiencies of the units are given in Table 3.

Advanced Exergy Analysis

To split the total exergy destruction into avoidable and unavoidable parts, unavoidable conditions should be well identified. Exergy rates of fuel and product of the unit will change when unavoidable (best) conditions are taken into account. The unavoidable conditions refer to best and unapproachable working conditions associated with the technical and economics limits of today's technology. The unavoidable operation conditions are better than real (actual) conditions, however they are still not the ideal conditions.

As Cziesla et. al [16] mentioned for heat exchangers, entropy generation, hence exergy destruction, can be minimized by assuming no pressure drop, no heat loss and temperature difference, as low as possible. These are the unavoidable conditions for APH unit in this study. For furnaces, however, unavoidable working conditions can be achieved when adiabatic combustion takes places with reactant and product temperatures, as high as possible.

To calculate the unvoidable exergy destruction of *k-th* component in a system, with an actual product exergy, $\dot{E}x_{P,k}$, the following equation is used:

$$\dot{E}x_{D,k}^{UN} = \dot{E}x_{P,k}\left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,best,k}}\right)^{UN} \quad (10)$$

where the ratio $\left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,best,k}}\right)^{UN}$ represents the unavoidable exergy destruction per unit of product exergy. According to these specifications, assumptions for unavoidable conditions of two system units were summarized in the Table 4.

Acıkkalp et. al [17] pointed that in order to compute unavoidable exergy destruction rates, each unit should be considered as in isolation and separated from the system. In this manner, for the two units, unavoidable and avoidable exergy destructions for two units were calculated using Eq.(10) and are given in Table 5. Modified exergetic efficiency (ε^*) was defined by eliminating all avoidable irreverbilities from the fuel exergy, Eq. (11). Then calculated modified exergy efficiencies for two units are given in Table 6.

$$\varepsilon^* = \frac{\dot{E}x_{P,k}}{\dot{E}x_{F,k} - \dot{E}x_{D,k}^{AV}} = \frac{1}{1+\left(\frac{\dot{E}x_{D,k}}{\dot{E}x_{P,k}}\right)^{UN}} \quad (11)$$

Improvement potential rates

As Callak et. al [18] conducted in their study, determining "improvement potential rates" is crucial when analyzing different processes or sectors of the economy from second law point of view. The conventional improvement potential rates are calculated in the following equation:

$$IP_{con} = (1-\varepsilon_k)\dot{E}x_{D,k} \quad (12)$$

Rearraging this equation based on advanced exergy analysis gives:

$$IP_{adv} = (1-\varepsilon_k^*)\dot{E}x_{D,k}^{AV} \quad (13)$$

RESULTS and DISCUSSION

The main results obtained by applying energy, conventional and advanced exergy analyses of the FH-APH coupled system are shown through Tables 1-6 and Figures 2-4.

Energy analysis applied to the system showed that furnace was operating with 77.7 % thermal efficiency while air preheater had 94.6% thermal efficiency. These relatively high energetic efficiencies often lead to misunderstandings since they can not provide exact measure for energy usage. Instead, exergetic efficiencies do that.

Table 1.Operating Data of the System

Stream No	Fluid Type	$\dot{m}$(kg/h)	T(°C)	P (bar)
1	NG	3690	20	1.6000
2	Air	61602	195	1.0080
3	CG	65562	408	1.0004
4	CG	65562	256	1.0100
5	Air	61602	12	1.0260
6	Aromatic	998700	272	1.3000

Table 2. Physical and Chemical Exergy Rates of Streams

Stream No	Fluid Type	$\dot{E}x^{PH}$ (MW)	$\dot{E}x^{CH}$ (MW)	$\dot{E}x_{total}$ (MW)
1	NG	0.01	54.17	54.18
2	Air	0.62	0.04	0.66
3	CG	2.72	0.67	3.39
4	CG	1.18	0.67	1.85
5	Air	0.01	0.04	0.05

Table 3. Conventional Exergy Efficiencies

Unit Name	$\dot{E}x_{F,k}$ (MW)	$\dot{E}x_{P,k}$ (MW)	$\dot{E}x_{D,k}$ (MW)	ε (%)
FH	54.83	22.48	32.35	40.9
APH	1.54	0.60	0.93	39.3

Table 4. Real and Best Conditions

Unit Name	Real Conditions	Best Conditions
FH	$Q \neq 0$ T_{fuel}= 20°C T_{air}= 12 °C $T_{flue\ gas}$= 408 °C	Q = 0 T_{fuel}= 577°C T_{air}= 527 °C $T_{flue\ gas}$= 957 °C
APH	ΔT_{min}= 213°C	ΔT_{min}= 10°C

Table 5. Total Exergy Rates With Best Conditions

Unit Name	Stream	Fluid Type	$\dot{E}x_{total}(MW)$
FH	1	NG	55.03
	2	Air	4.46
	3	CG	12.09
APH	2	Air	2.470
	3	CG	2.880
	4	CG	0.004
	5	Air	0.003

Table 6. Modified Exergy Efficiencies of the Units

Unit Name	$\dot{E}x_{D,k}$ (MW)	$\dot{E}x^{AV}_{D,k}$ (MW)	$\dot{E}x^{UN}_{D,k}$ (MW)	ε^* (%)
FH	32.35	20.39	11.96	52.4
APH	0.93	0.81	0.12	85.8

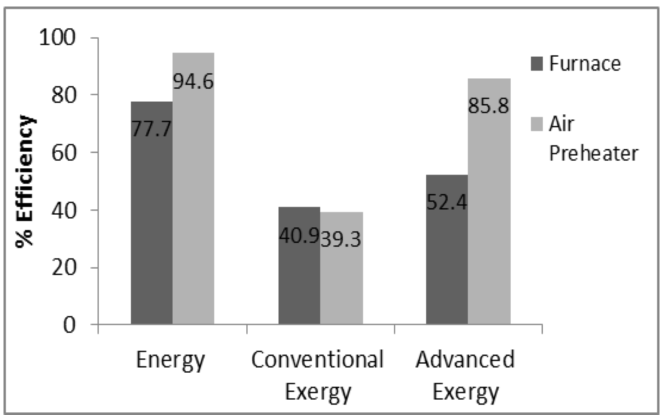

Figure 2. Energy and exergy efficiencies of the units

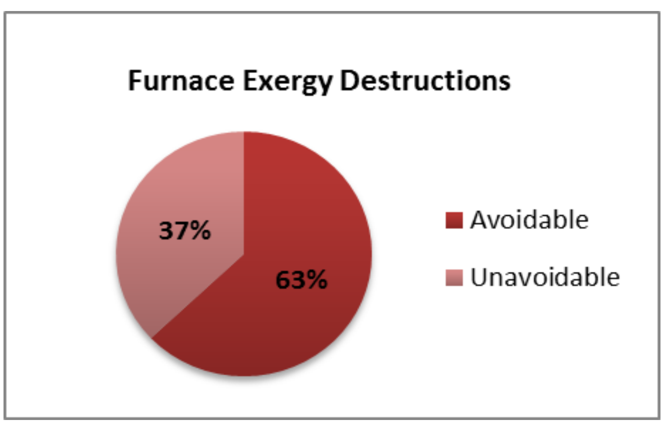

Figure 3. Parts of destructed exergy in furnace

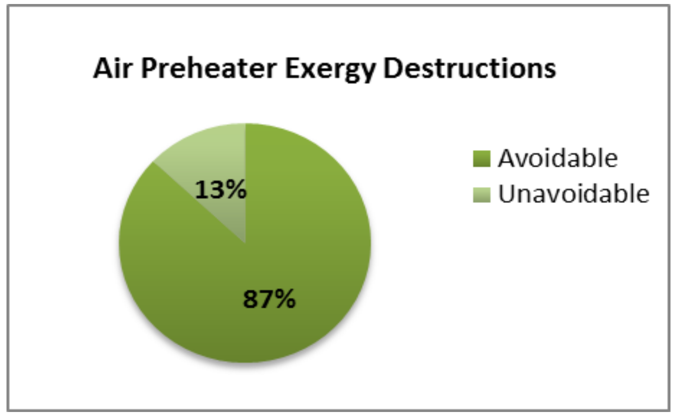

Figure 4. Parts of destructed exergy in air preheater

As it is seen in Table 3, the largest irreverbilities meaning, major exergy destruction (32.35 MW) was obtained in the furnace,.due to high entropy generation during fuel combustion and due to flue gas emissions.

Rosen and Dincer [19] and Rosen et. al [20] indicate that exergy is an effective measure of system deviation from environment. They relate exergy destruction with environmental sustainability and concluded that to reduce environmental impact (entropy generation), irreversibilities within the energy system must be minimized. In this study, furnace emits large amount of waste heat in the form of flue gas. This high temperature stack gas and particulates in the stack gas causes negative impact on environment due to large amount of exergy destruction. To achieve better environmental sustainability, utilization of fuel source, reducing the level of stack gas emission and decreasing the temperature of the stack gas should be the major priorities.

Exergy destruction in the furnace is also affected by the excess air and the air inlet temperature. The thermodynamic inefficiencies of combustion can be reduced by more effective preheating the combustion air by increasing the heat transfer area in the avaliable APH, and also avoiding from high air–fuel ratio for combustion.

Exergetic efficiency of APH was calculated as 39.3% with an exergy destruction of 0.93 MW.

The significant part of exergy destruction within a heat exchanger arises from heat transfer with finite temperature difference. Increasing temperature difference of fluids results in high entropy generation and exergy destruction in accordance with Gouy-Stodola theorem.

Using the best conditions in Table 4, the avoidable and unavoidable exergy destructions of the two units were calculated by Eq.(10) and shown in the Figure 3-4. Modified exergetic efficiency values were found as 52.4% and 85.8% for furnace and air preheater, respectively.

CONCLUSION

With the aid of conventional and advanced exergy analysis techniques, it follows from Table 3 that exergy destruction in the furnace (32.35 MW) was much higher than 0.93 MW in APH. Almost 97% of total exergy destruction arises from furnace irreversibilities as in Vuckovic and Regulagadda's study [14,7], because of highly irreversible combustion reaction and it results in high irreversibilities. It was determined by advanced exergy analysis that 63% of this destruction can be avoided (see Figure 3). Some modifications are given as:

- Enhancing heat transfer rate by adding extra heat transfer area by optimizing tube configurations in radiant and convection section of the furnace. With this modification, to transfer the same amount of heat, less temperature difference and hence, lower temperature combustion gases will be enough. This will lead us less amount of fuel consumption, finally.
- Preventing incomplete combustion, thus, improving combustion efficiency.
- Reducing waste heat, preventing leakage, providing better insulation.

In APH, it was found that 87% of total exergy destruction can be avoided and as it is seen in Figure 4 exergetic efficiency can be increased from 39.3% to 85.8% with suitable modifications such as:

- Adding extra tubes for increasing surface area,
- Decreasing fouling resistances

To accomplish increase in heat transfer rate in the air preheater, Saidur and Leong [21] conducted a study with the use of nanofluids to enhance heat transfer rate of the flue gases and achieved 2-8% energy saving with the related study. Hence, application of nanofluids can be a another powerful modification for the plant.

Nevertheless, 97% of total exergy destruction occurs in the furnace; so, enhancement of the system from exergy point of view should be especially focused on the furnace.

Finally, by using the results of the conventional exergy analysis, improvement potential rates are calculated as 19.1 MW and 0.56 MW for furnace and air preheater units, respectively. The advanced exergy analysis, the improvement potential rates are modified to much more realistic values due to tecnological, economical and physical limits, and calculated as 9.7 MW for furnace and 0.11 MW for aire preheater, respectively.

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NOMENCLATURE

$\dot{m}$: mass flow rate, [kg/h]
T: temperature, [°C]
P: pressure, [bar]
ε: efficiency, [-]
$\dot{E}x$:exergy flow rate, [MW]
h :specific entalphy, [kJ/kg]
s: specific entropy, [kJ/kgK]
R: universal gas constant, [-]
x: mol fraction, [-]
Q: heat flow rate, [kW]
NG:natural gas
CG:combustion gas

Subscripts
F: fuel
P: product
L: loss
D: destruction
o:reference state

Superscripts
AV: avoidable
UN: unavoidable
PH: physical
CH: chemical
PT: potential
KN: kinetic

REFERENCES

[1] Shekarchian M. ,Zarifi F., Moghavemmi M. Motasemi F., Mahlia T.M.I., Energy, Exergy, Environmental and Economic Analysis of Industrial Fired Heaters based on Heat Recovery and Preheating Techiniques, Energy Conversion and Management, 71 (2013), 51–61.

[2] Cengel,Y.A. and Boles,M.A., Thermodynamics & Engineering Approach, McGraw-Hill, Singapore, 2007.

[3] Dincer,I., Hussain, M.M., Al-Zaharna, I., Analysis of sectoral energy and exergy use of Saudi Arabia, International Journal of Energy Research, 28 (2004), 205-243.

[4] Kanoglu, M., Dincer I., Rosen M.A., Understanding energy and exergy efficiencies for improved energy management in power plants, Energy Policy, 35 (2007), 3967-3978.

[5] Kelly S., Tsatsaronis G., Morosuk T., Advanced exergetic analysis: approaches for splitting the exergy destruction into endogenous and exogenous parts, Energy, 34 (2009),384-91.

[6] Saidur R., Ahamed J.U., Masjuki H.H.,Energy, exergy and economic analysis of industrial boilers, Energy Policy, 38 (2010), 2188-2197.

[8] Doseva N., Chakyrova D., Energy and exergy analysis of cogeneration system with biogas engines, Journal of Thermal Engineering, 59 (2014), 391-401.

[7] Regulagadda P., Dincer I., Naterer G.F., Exergy analysis of a thermal power plant with measured boiler and turbine losses, App Therm Eng. 30 (2010), 970-976.

[9] Tsatsaronis G., Park M.H., On avoidable and unavoidable exergy destructions and ınvestment costs in thermal systems, Energy Conversion and Management, 43 (2002), 1259–1270.

[10] Morosuk T., Tsatsaronis G., Comperative evaluation of LNG-based cogeneration systems using advanced exergy analysis, Energy, 2011, 36: 3771-8.

[11] Wang L., Yang Y., Morosuk T., Tsatsaronis G., Advanced thermodynamic analysis and evaluation of a supercritical powerplant, Energies, 5 (2012), 1850-63.

[12] Vuckovıc G., Vukic M., Stojilljkovic M., Vukovic D., Avoidable and unavoidable exergy destruction and exergoeconomic evaluation of the thermal processes in a real industrial plant, Thermal Science, 2012, 16: 433-446.

[13] Petrakopoulou F., Tsatsaronis G., Morosuk T., Carassai A.,Conventional and advanced exergetic analyses applied to a combined cycle power plant, Energy, 41(2012), 146-52.

[14] Vuckovic G., Stojilljkovic M., Vukic M., Advanced exergy analysis and exergoeconomic performance evaluation of thermal processes in an existing industrial plant, Energy Conversion and Management, 85 (2014), 655-662.

[15] Bejan A.,Thermal Design and Optimization, John Wiley& Sons Inc, U.S.A, 1996.

[16] Cziesla F., Tsatsaronis G., Zengliang G., Avoidable thermodynamic inefficiencies and costs in an externally fired combined cycle power plant, Energy, 2006, 31: 1472-1489.

[17] Açıkkalp E., Aras H., Hepbasli A., Advanced exergy analysis of an electricity generating facility using natural gas, Energy Conv and Management, 2014, 82: 146-153.

[18] Callak M., Balkan F.,Hepbaslı A., Avoidable and unavoidable exergy destructions of a fluidized bed coal combustor and a heat recovery steam generator, Energy Conversion and Management, 98 (2015) 54-58.

[19] Dincer I., Rosen M.A., Exergy analysis of waste emissions, Int J Energ, Res, 1999, 23:1153-1163. edition,1056 pp. McGraw-Hill, New York.

[20] Rosen M.A., Dincer I., Kanoglu M., Role of exergy in increasing efficiency and sustainability and reducing environmental impact, Energy Policy, 36 (2008), 128-137.

[21] Leong K.Y., Saidur R., Mahlia T.M.I, Yau Y.H., Performance investigation of nanofluids as working fluid in an thermosyphon air preheater, International Communications in Heat and Mass Transfer, 39 (2012), 523-529.