IMPROVING THE PERFORMANCE OF A HEATING SYSTEM THROUGH ENERGY MANAGEMENT BY USING EXERGY PARAMETERS

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Energy management systems are used to analyze the efficiency of energy systems and identify any problem areas to lower costs and save energy, typically using energy based performance measurements. Our aim was to use exergy parameters, instead, to see if more accurate information could be obtained about which energy saving application would result in greater energy savings. Exergy analysis is based on the second law of thermodynamics and focuses on the environment and the quality of the energy. Implementing an exergetic approach to analyze a steam heating system, we examined data related to exergy flows and exergy losses, and ultimately improved the performance of the system through this energy management model. The following seven energy saving applications were identified and ranked according to their improvement potentials: adjusting the air to fuel ratio (1), preventing steam leaks (2), installing an automatic blow down system (3), insulating the pipes (4), insulating valves and flanges (5), insulating fuel tank (6) and recovering heat loss from the waste condensate (7). The optimum ranking obtained through the exergy analysis was 3-1-2-5-7-6-4. A reduction of 15.918 kW in exergy consumption was achieved by installing an automatic blowdown system. This meant a total reduction of 1,779.03 kg/year in total fuel consumption, $1,458.81/year of cost reduction and the total cost reduction achieved was $1,829.25/year. Making improvements to the seven selected areas in the system, 38.4% of the energy loss was recovered while the recovery in the exergy consumption was 44.5%.

Keywords: *energy management; exergy analysis; exergy metrics; cost reduction.*

1. Introduction

When implementing any technique to save energy in a system, all types of energies involved are considered: the parts where temperature and pressure decrease are monitored and quantitative findings are measured and compared for evaluation in an effort to increase heat recovery rates, reduce waste heat rates, all the while keeping the costs as low as possible. However, energy management systems do not only lower costs and increase savings; they have a direct impact on people's quality of life as shown in AlFaris et al. [1]'s study on sustainability and energy management in schools, noting increased student and teacher satisfaction and comfort. It is important to consider energy management as a multi-faceted issue. Energy efficiency is only possible if an integrated energy management framework is put in place, as recommended by Schulze et al. [2] in their systematic review of energy management applications in industry. Evaluating energy consumption as part of such a framework requires accurate and detailed data.

To get the complete picture of a system, a thermodynamic investigation includes both energy and exergy analyses. While energy cannot be destroyed and the energy potential turns into other forms of energy, exergy can be destroyed and some cannot be recovered due to irreversibilities. Therefore, exergy analysis offers more advantages as a tool than energy analysis. By identifying the true magnitudes of losses, their causes and locations, the improvement potential of the overall system is more accurately indicated. Exergy analysis is necessary for effective energy management as explained in 1995 by Larson and Cortez [3] in their study on agricultural applications of evaporative cooling, refrigeration and milk processing. Many studies have been carried out in various areas such as power plants and solar collectors involving exergy analysis. One such study showing the importance of exergy analysis for energy systems was carried out by Yıldızhan [4], who found that the exergy consumption of harvested crops was more remarkable than their calculated energy consumption. This finding is parallel to the research done by Mitrovic et al. [5], who studied the performance of four thermal power plants from energetic and exergetic viewpoints. They found that exergy analysis results offered improved plant performance. Kanoglu et al. [6]'s investigation on power cycles and Pattanayak et al. [7]'s analysis of a combined cycle power plant also made use of both energy and exergy analyses. In the latter, exergy efficiencies of combustion chamber, steam generator and condenser were found to be 77.48%, 87.20% and 29% respectively. They suggested that by reducing the losses in bottoming cycle, the overall exergy efficiency can be improved. Rovira et al. [8] studied the subdivision of the solar field into different sectors reduced the exergy losses while heating the working fluid. Also the reduction of the average temperature of the heat transfer fluid resulted in a decrease in the exergy losses of the collectors. Finally, as an example of a heating system investigation, similar to our study, Kaya et al. [9] performed a study on energy saving and emission reduction for industrial boilers. The reason for efficiency losses was determined as: operating the boiler at the high air excessiveness coefficient, the air leakage in the rotary type air heaters and the heat losses of the surface. Total energy savings potential was found to be 2,029,692 kcal/h. 4861.7 tons of carbon dioxide emissions per year will be reduced.

In terms of the actual implementation of exergy analysis, an exergy management model was developed by Kilkis [10] which helped to reduce CO_2 emissions in built environments. Then, Hepbasli [11] was the first to propose a new exergy management system (ExMS) standard in the literature. In addition to energy parameters, he defined new exergy parameters while studying exergy consumption, exergy efficiency and exergy conservation for a case study. Hepbasli [12] recommended an exergy management structure in buildings. He proposed a new index named specific exergy utilization index (SExUI). This index can be calculated according to the energy source used like fuel, electricity, and so on.

Recent studies on thermodynamic analyses of energy systems mention the effectiveness of exergetic measures. Nami and Akrami [13] performed a work for a cogeneration system of power, steam and hydrogen production. By optimizing the exergy efficiency, hydrogen rate and sustainability index values, their calculated findings were 52.09%, 8.723 kg/hr and 2.162, respectively. Lingo Jr. and Roy [14] applied exergy management on a building for HVAC purpose. An air duct was configured and air was circulated between the shells of the wall. Thus the required heating load of the building was reduced. Di Somma et al. [15] studied energy districts to reduce both exergy losses and energy costs. A mixed integer optimization problem was defined to minimize exergy losses and energy costs to attain sustainability.

Within this context, the main objectives of this contribution are to (i) examine the performance of a steam heating system and its components, (ii) calculate energy and exergy losses from the heating system, (iii) assess the performance according to energy, exergy and cost metrics, (iv) compare the parameters calculated by energy and exergy analysis, (v) come up with a ranking of the problem areas for optimization, and (v) decide on improvements to invest in is a better approach by using exergetic parameters.

2. System definition

In this study, the heating system equipment of a building was investigated to obtain energy and cost savings in the heating system through an energy management. The problem areas were identified and waste energy was reduced at all of the problem areas analyzed, which were then remedied using Energy Saving Applications (ESA). The heating fluid in the system was steam. . The ESAs involved the steam boiler, fuel tank, pipes, valves, flanges and condensate tank. The possible improvement potentials were studied as rates of fuel and cost. The waste energy was in the form of heat. By reducing heat losses from the heating system equipment, the system efficiency was improved. Fig.1 illustrates the problem areas observed in the heating system.

Adjusting air to fuel ratio (ESA-1)

Pipes with steam leaks (ESA-2)

Automatic Blowdown System (ESA-3)

Uninsulated Valves and flanges (ESA-4)

Uninsulated Pipes (ESA-5)

Uninsulated Fuel Tank (ESA-6)

Heat recovery from waste condensate (ESA-7)

Fig. 1. Energy saving applications implemented on the heating system equipment

The seven selected ESAs were: adjusting air to fuel ratio (ESA-1), preventing steam leaks (ESA-2), installation of automatic blowdown control system (ESA-3), insulation of valves and flanges (ESA-4), insulation of the pipes (ESA-5), insulation of the fuel tank (ESA-6) and heat recovery from the waste condensate (ESA-7).

3. Analyses

3.1. Energy and exergy analyses

When the energy carrier flows in a pipe or in a similar closed container that is surrounded by air, heat transfer occurs from the hot surface to the air surrounding the flat surface by convection. The heat transfer coefficient may be taken as 5.8 W/m^{2}K, when air flow speed is approximately zero [16].

From the fuel tank (FT), pipes (P), valves and flanges (VF), the heat loss occurs because of the heat transfer from the equipment. The formulations used to calculate heat energy rates are presented in Tab. 1.

Table 1. Heat energy equations for energy saving applications

ESA (i)	**Heat Energy Relations**	**Reference**
FG	$\dot{m}_{FG} = [(1+\lambda).m_{da} + 1 - m_{wac}].\dot{m}_f$ $\dot{Q}_{FG} = \dot{m}_{FG}.(cp_{FG}\,.T_{FG}) + w.(1.9\,.T_{FG} + 2480)$	[17]
SL	$\dot{Q}_{SL} = \dot{m}_{SL}.[\mathrm{h}_{fg} + cp_s.\left(T_{sat} - T_{fw}\right)]$	[18]
BD	$\dot{Q}_{BD} = \dot{m}_s.r.\mathrm{h}_s$	[19]
P	$\dot{Q}_P = \alpha.A.(T_{sur} - T_0)$	[16]
VF	$\dot{Q}_{VF} = [L_V\,.no_V + L_F\,.no_F]\,.q_{VF}$	[20]
FT	$\dot{Q}_{FT,C} = \propto_c.A_{FT}.(T_{FT} - T_o)$ $\dot{Q}_{FT,Ra} = \sigma.\varepsilon.A_{FT}.T_{FT}{}^4$	[16]
WC	$\dot{Q}_{WC} = \dot{m}_{WC}.cp_{WC}.(T_{WC} - T_{fw})$	[21]

The exergy of heat transfer rate is expressed as follows:

$$\dot{Ex}_i = \dot{Q}_i.\left(1 - \frac{T_o}{T_i}\right) \tag{1}$$

For some of the ESA (the flue gas (FG), the steam leaks (SL), the condensate (WC) and steam blowdown (BD)), the heat was directly released into the environment, so that the heat loss was equal to the energy rate of the stream. The exergy of a stream is calculated by

$$ex = h_{out} - h_{in} - T_o(s_{out} - s_{in}) \tag{2}$$

If the energy carrier is assumed to be ideal gas, then the exergy rate relation can be constructed as

$$\dot{Ex_\iota} = \dot{m}_i \left[c_{p,i}(T_i - T_0) - T_0 \left(c_p . ln \frac{T_i}{T_0} + R . ln \frac{P_i}{P_0} \right) \right] \tag{3}$$

The exergy rate of the emitted radiation for an object is calculated by [16]

$$\dot{Ex}_{FT,Ra} = \dot{Q}_{FT,Ra} . \left(1 + \frac{1}{3} . \left(\frac{T_o}{T_{FT}} \right)^4 - \frac{4}{3} . \frac{T_o}{T_{FT}} \right) \tag{4}$$

The reduction of the fuel use rate by using the energy loss for the ith ESA is obtained from

$$\dot{m}_{R,e,i} = \frac{\dot{Q}_{R,i}}{LHV} \tag{5}$$

The reduction in fuel use by using the exergy loss rates for each ESA is calculated by

$$\dot{m}_{R,ex,i} = \frac{\dot{Ex}_{R,i}}{\varphi . LHV} \tag{6}$$

The cost saving per year for the ith ESA by the reduction of fuel consumption rates can be obtained by

$$\dot{C}_{e,i} = \dot{m}_{R,e,i} \, . \, c_f \tag{7}$$

$$C_{e,i} = \dot{C}_{e,i} . t \tag{8}$$

Similarly, the exergetic cost figures were calculated.

The air to fuel ratio in the boiler was so significant that an inappropriate ratio might result in high flue gas temperature, thus yielding high heat losses. In addition to the heat loss, low ratios might damage the boiler. Steam leaks were observed on pipes and joint points, indicating high heat losses. Steam plume lengths were used to obtain the resulting energy losses.

During the blowdown process, a controlled amount of hot water containing high dissolved concentrations should be discharged into the sewer. Inappropriate and uncontrolled action can lead to waste heat. It was observed that some of the pipes in the heating center did not have insulating material, which is crucial to prevent heat losses from the surface. Similarly some of the valves and flanges and the fuel tank were found as uninsulated. The last energy saving area was the waste condensate. Some of the condensate was transferred outside, which caused significant heat losses. The measured and given data for the heating systems are listed in Tab. 2.

Table 2. Measured and given data for the heating system

ESA (i)	Type of data	Measured or given value
1	Mass flow rate of fuel (kg/s)	0.0325
	Inlet temperature of the hot fluid (K)	348.15
	Outlet temperature of the steam (K)	393.15
	Operating pressure (kPa)	200
	Ambient temperature (K)	288.15
	Feed water temperature (K)	288.15
	Operating period in a year (hrs)	1440
	Mass flow rate of flue gas [kg/s]	0.0529

	Flue gas temperature before implementing ESA-1 [K]	473.15
	Flue gas temperature after implementing ESA-1 [K]	398.15
2	Steam plume length (type 1) [cm]	20
	Steam plume length (type 2) [cm]	30
3	Mass flow rate of steam (kg/s)	0.609
	Blowdown rate before implementing ESA-3 [%]	10
	Blowdown rate after implementing ESA-3 [%]	6
4	Surface temperature before implementing ESA-4 (K)	313.15
	Surface temperature after implementing ESA-4 (K)	298.15
	Length of the pipe [m]	5
5	Surface temperature before implementing ESA-5 (K)	358.15
	Surface temperature after implementing ESA-5 (K)	298.15
6	Surface temperature before implementing ESA-6 (K)	308.15
	Surface temperature after implementing ESA-6 (K)	288.15
	Diameter of the fuel tank (mm)	1250
	Length of the fuel tank (mm)	2740
	Surface area of the fuel tank (m^2)	12.7
	Emissivity rate of the fuel tank surface (-)	0.85
7	Temperature of the waste condense (K)	333.15
	Return rate of condensate before implementing ESA-7 (%)	60
	Return rate of condensate after implementing ESA-7 (%)	100
	Mass flow rate of waste condense (kg/h)	57

4. Results and discussion

Exergy metrics were used to measure the true magnitudes, causes, losses and identify the locations to be analyzed. Optimum improvement potentials were achieved for ESA-4, ESA-5 and ESA-1 by using exergy analysis results. By adjusting the air to fuel ratio (ESA-1), a 59% reduction in exergy loss rate was achieved. However, the reduction in energy loss rate was only 12%.

Conventionally, fuel savings are calculated according to the reduction in heat losses. The useful portion of the observed heat loss reduction is the exergy loss reduction. The reductions in exergy loss rates of each ESA highlighted the most urgent problem areas. The first ESA was installing an automatic blow down system. The second priority was adjusting the air to fuel ratio by using a flue gas analyzer. The resulting energy, exergy, fuel and cost saving rates are listed in Tab. 3.

Table 3. Calculated energy, exergy, fuel and cost savings for the implemented ESAs

ESA (i)	FG	SL	BD	P	VF	FT	WC
Energy Savings (kW)	5.459	5.869	65.820	0.174	3.146	2.772	3.309
Exergy Savings (kW)	1.712	1.452	15.918	0.0191	0.542	0.106	0.211
Fuel savings by energy analysis (kg/year)	634.517	682.172	7672.32	20.22	365.67	322.198	384.616
Fuel savings by exergy analysis (kg/year)	191.337	162.279	1779.038	2.135	60.575	11.847	23.582
Cost savings by energy analysis ($/year)	520.303	559.381	6291.302	16.58	299.849	264.202	315.385
Cost savings by exergy analysis ($/year)	156.896	133.068	1458.811	1.750	49.671	9.714	19.337

The total heat loss rate before the seven ESAs were applied had been 225.87 kW. This was reduced to 139.32 kW by implementing EMAs. On the other hand, the total exergy consumption rate had been 45.21 kWbefore it was decreased by 44.5% to 25.1 kW. The total fuel saved using energy analysis results was calculated as 10081.71 kg/year, compared to 2230.79 kg/year using exergy analysis. According to the energy analysis results, the greatest improvement in fuel consumption was for ESA-3 as 7672.32 kg/year. In fact it was only 1779.04 kg/year by taking into account the useful portion of energy. However, fuel saving rates for energy and exergy analyses were 7448.85 tons of oil equivalent (TOE) and 1727.22 TOE, respectively.

Efficiency improvement is a key objective in energy management applications. Although the improvements in energy efficiencies are found to be higher, the exergy based efficiency results could be said to be more reliable, since the energy efficiency results depend on the unavailable portion of energy from which the system cannot derive benefit due to irreversibilities. Improvements made by implementing each ESA to overall system efficiencies are can be seen in Tab. 4.

Table 4. Improvements in overall system efficiencies by implementing each ESA

		ESA-1	ESA-2	ESA-3	ESA-4	ESA-5	ESA-6	ESA-7
Energy Efficiency	**(%)**	0.37	0.4	4.54	0.0001	0.21	0.19	0.228
Exergy Efficiency	**(%)**	0.11	0.096	1.05	0.00001	0.036	0.007	0.014

For each ESA, the exergetic indices, specific exergy utilization and specific exergy cost were calculated. The results showed that the blowdown process needed to be addressed most urgently for as the amount of exergy consumption there indicated the greatest loss of the energy carrier (steam). The specific exergy utilization index for ESA-3 was found to be 87.87 MJ/m^2. The minimum specific exergy utilization index value obtained for ESA-4 was 0.23 MJ/m^2. The maximum specific exergy cost index was calculated as 1.17 \$/m2 for ESA-3. On the other hand, the minimum specific exergy cost index was obtained for ESA-4 as 0.003 \$/m^2. The findings related to the exergetic indices are given in Fig.2-3.

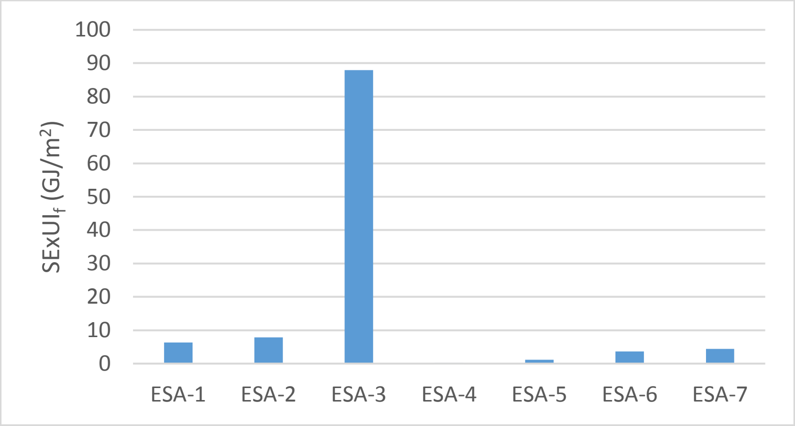

Fig. 2. Specific exergy utilization index values for the ESAs

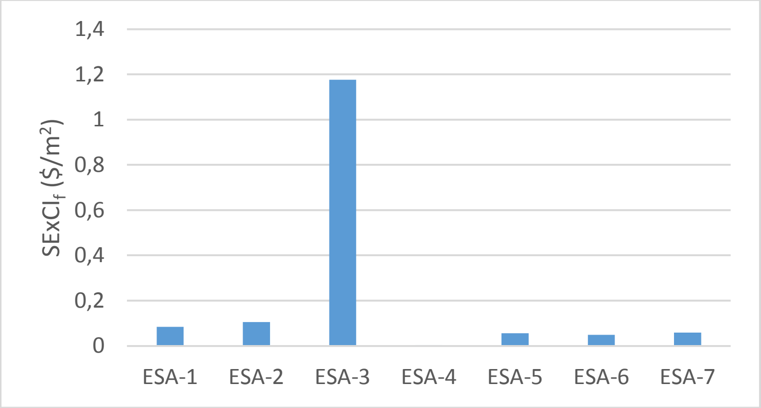

Fig. 3. Specific exergy cost index values for the ESAs

All seven ESAs are evaluated according to the improvement potential they offer through an analysis of energy and exergy parameters. The ESAs are then ranked to monitor and to demonstrate the advantages they offer based on the exergy analysis . Since some investment is required to improve the inefficiencies addressed by each ESA, in the event that there are insufficient funds, the improvements can be applied in order of ranking. The rankings were determined based on efficiency rates, fuel saving rates and fuel consumption rates and. by considering the maximum benefit offered to the overall system. Energy analysis is misleading, because it is a quantity based method, whereas exergy deals with useful energy and shows accurately where the most loss occurs. Going by the energy analysis results, the best ranking for the ESAs is 3-2-1-7-5-6-4. However, the decision to be made regarding the seven ESAs should take the true losses and ranking into account. The ranking best suggested by exergy analysis was 3-1-2-5-7-6-4. These rankings are presented in Tab. 5.

Table 5. The rankings obtained by energy and exergy analysis

	Energy Analysis	**Exergy Analysis**
Ranking	3-2-1-7-5-6-4	3-1-2-5-7-6-4

5. Conclusions

We analyzed a steam heating system to investigate the improvement potentials to reduce exergy consumption, fuel consumption and cost. We identified seven application areas to improve the heating system by using exergetic parameters. These application areas revealed a substantial amount of heat loss. Relatively simple solutions and investment suggestions were offered to reduce heat loss, fuel consumption and cost. Some conclusions drawn from the results of the study are as follows:

(a) The maximum amount of heat recovery was observed in ESA-3; i.e, 65.82 kW. The maximum reduction in exergy consumption and fuel consumption were found for ESA-3. The fuel savings by energy and exergy analysis were determined to be 7672.32 kg/year and 1779.04 kg/year, respectively.

(b) Total cost saving by using energy parameters was calculated as \$8,267 /year. Since exergy analysis depends on the quality of energy, the cost saving by exergy parameters was only \$1,829.25 /year.

(c) The maximum specific exergy utilization index and specific exergy cost index were calculated for ESA-3 as 87.87 MJ/m^2 and \$1.17 /m^2, respectively.

(d) The total fuel savings per year was calculated as 2,165.82 TOE by using exergy analysis.

(e) The exergy analysis parameters provided more accurate results. After resolving the seven problem areas, the energy use and exergy consumption of the overall system were reduced by 38.4% and 44.5%, respectively.

(f) While energy analysis suggested the best ranking of ESAs was 3-2-1-7-5-6-4, exergy analysis results revealed the best ranking as 3-1-2-5-7-6-4. The adjustment of air to fuel ratio and insulation of the pipes resulted in better improvements in exergy analysis.

(g) In this study, an exergetic approach was used to more accurately observe the impact of energy management. Future research is recommended on establishing standard exergetic parameters to evaluate energy management systems.

Nomenclature

A - area of heat transfer surface (m^2)
C - cost $(\$)$
c - unit fuel cost $(\$.\mathrm{kg}^{-1})$
cp - specific heat capacity (kJ.kg^{-1}.K^{-1})
$\dot{C}$ - cost rate $(\$.\mathrm{hr}^{-1})$
$\dot{E}x$ - exergy rate (kW)
h - specific enthalpy (kJ.kg^{-1})
L - equivalent pipe length (m)
m - mass (kg)
$\dot{m}$ - mass flow rate (kg.s^{-1})
no - number
$\dot{Q}$ - heat transfer rate (kW)
r - blowdown rate (%)
T - temperature (K)
t - operating hours (hrs/year)
w - humidity ratio (kg.kg^{-1})
α - heat transfer coefficient (W.m^{-2} .K^{-1})
σ - Stefan Boltzman constant (W.m^{-2} .K^{-4})
ε - emissivity factor
λ - excess air ratio

Subscript

BD - blowdown
c - convection
da - dry air
F - flange
FG - flue gas
FT - fuel tank
f - fuel
fg - latent heat
fw - feed water
o - ambient
Ra - radiation
s - steam
sat - saturation
SL - steam leak
sur - surface
V - valve
VF - valves and flanges
wac - water formed after combustion
WC - waste condensate

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