

Methodology for Energy and Exergy Analysis of Steam Boilers

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Abstract

This paper presents a framework of thermodynamic, energy and exergy, analyses of industrial steam boilers. Mass, energy, and exergy analysis were used to develop a methodology for evaluating thermodynamic properties, energy and exergy input and output resources in industrial steam boilers. Determined methods make available an analytic procedure for exergetic analysis on steam boilers for appropriate applications. Chemical exergy of the material streams was considered to offer a more comprehensive detail on energy and exergy resource allocation and losses of the processes in a steam boiler.

Keywords: exergy, energy, steam boilers, chemical exergy, exergy destruction

LIST OF SYMBOLS

LPFO	low pour fuel oil	Chemical symbols	
AFR_{st}	stoichiometric air-fuel ratio (<i>kg of air/kg of fuel</i>)	C_xH_y	hydrocarbon (fossil fuel) molecules
AAF	actual air-fuel ratio (<i>kg of air/kg of fuel</i>)	C	carbon
\dot{m}_i	inlet mass flow rate, <i>kg/s</i>	H	hydrogen
\dot{m}_e	exit mass flow rate, <i>kg/s</i>	O	oxygen
\dot{Q}	heat transfer rate to the system, <i>kJ/s</i>	CO_2	carbon dioxide
\dot{I}	exergy destruction rate, <i>kJ/s</i>	H_2O	water
ϵ_i	inlet specific flow exergy of material streams, <i>kJ/s</i>	N_2	Nitrogen
ϵ_e	exit specific flow exergy of material streams, <i>kJ/s</i>	Ar	Argon
ϵ^{ph}	specific physical flow exergy, <i>kJ/kg</i>	Sub- and Superscripts	
ϵ^{ch}	specific chemical flow exergy, <i>kJ/kg</i>	a	air
h	specific enthalpy, <i>kJ/kg</i>	f	fuel
s	specific entropy, <i>kJ/kg K</i>	p	hot products
T	Temperature, $^{\circ}C, K$	w	feed water
P	Pressure, N/m^2	s	steam
$e_{x fuel}^{ch}$	molar chemical exergy of fuel, <i>kJ/kmol</i>	g	exhaust flue gas
$e_{xO_2}^{ch}$	molar chemical exergy of oxygen (O_2), <i>kJ/kmol</i>	$0a$	reference state of air
$e_{xCO_2}^{ch}$	molar chemical exergy of carbon dioxide (CO_2), <i>kJ/kmol</i>	0	reference state
$e_{xH_2O}^{ch}$	molar chemical exergy of water vapour (H_2O), <i>kJ/kmol</i>	atm	atmospheric
$\Delta\bar{g}$	the change in the standard Gibbs function, <i>kJ/kmol</i>	in	in
\bar{R}	molar or universal gas constant, <i>kJ/kmol K</i>	out	out
M	molar mass of chemical substance, <i>kg/kmol</i>	C	combustion unit
E_{in}	the energy input in the combustion unit, <i>kJ/s</i>	H	heat exchanging unit
HHV	high or gross heating value of fuel. <i>kJ/kg</i>	B	boiler
LHV	low or net heating value of fuel. <i>kJ/kg</i>	ph	physical

$Q_{H(loss)}$	Heat loss in heat exchanging unit, kJ/s	ch	chemical
Greek letters			
η	energy efficiency (%)		
ψ	exergy efficiency (%)		
ε	specific exergy (kJ/kg)		

1. Introduction

Steam boilers are closed vessels which are usually used to produce steam from water by combustion of fuel (Rajput, 2006). The steam may further be utilised, for many other production processes. Owing to its great significance in today's industrial world, it is imperative to fully understand how to effectively assess the energy resources utilization and outputs in steam boilers to ensure adequate energy management. The increasing energy demand from emerging economies versus the day-to-day decreasing storages of energy resources, the rising cost of fossil fuels and the considerable environmental impact connected with their exploitation are implications that policy makers cannot disregard. These would consequently result in energy-related problems to become more pronounced in the future (Tonon *et al.*, 2006). Therefore, the need for effective and efficient energy utilization in production systems cannot be overemphasised.

The impact of steam boilers on the environment, as regards competing for scarce energy resources as diesel, coal, natural gas, etc. for its operation with attended environmental degradation like air pollution, emission of green house gases, which continues to threaten quality of life and the ecosystem calls for closer attention. For a given environment, energy which is convertible into other forms of energy is called useful energy or exergy. Energy which is impossible to convert into other energy forms is called useless energy or anergy (Ayhan and Demirtas, 2001). Exergy analysis appears to be a significant tool in addressing the impact of energy resource utilization of steam boilers on the environment as raised in past work by Dincer *et al.* (2003) to further the goal of more efficient energy resource utilization of steam boilers; enabling locations, types, and true magnitudes of wastes and losses to be determined for steam boilers; revealing whether or not and how much it is possible to design more efficient steam boiler systems by reducing the inefficiencies in the existing systems; providing a sustainable development for steam boilers for sustainable supply of energy resources; and distinguishing the high-quality and low-quality energy resources of steam boilers.

This study presents a framework to evaluate thermodynamic properties and performance variables associated with material streams in boilers, such as, mass flow rate, temperature, enthalpy, entropy, energy and exergy transfer with chemical, heat and material interactions, efficiencies, and exergetic losses in steam boilers.

2. Method

2.1 Methodological Framework

The framework for the methodology of this study was classified into 2 major categories as shown in Figure 1. These include determination of operational variables and performance variables of steam boilers (Osemene, 2008, Ohijeagbon, 2012).

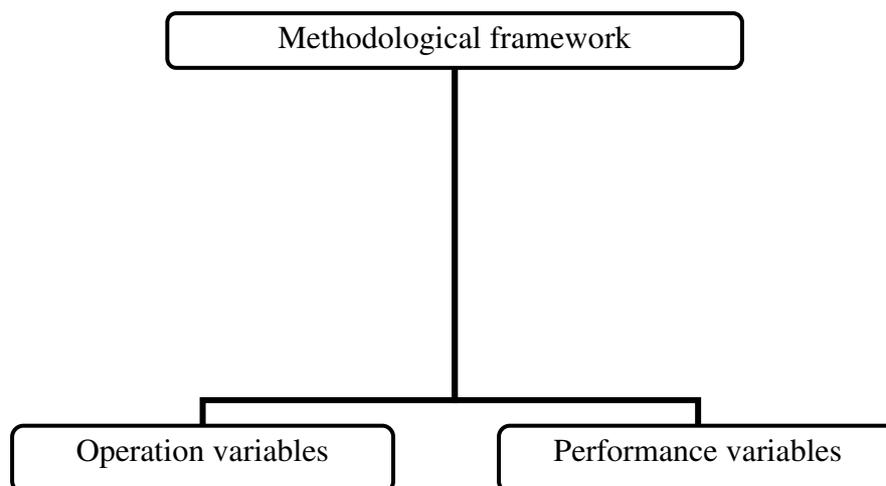


Figure 1: Methodological framework

2.1.2 Operation variables

These are parameters concerned with the functioning of the boilers. They indicate measurable (direct operational variables) and computable (indirect operational variables) properties which describe the generic thermodynamic activities taking place in a boiler. Overviews of these properties are outlined in Figure 2.

(i) Measurable properties

These are usually monitored and recorded directly from inbuilt or attached boiler measurement indicators over a specified period of time. An inventory data collection process is normally used to comprehensively collect boiler information.

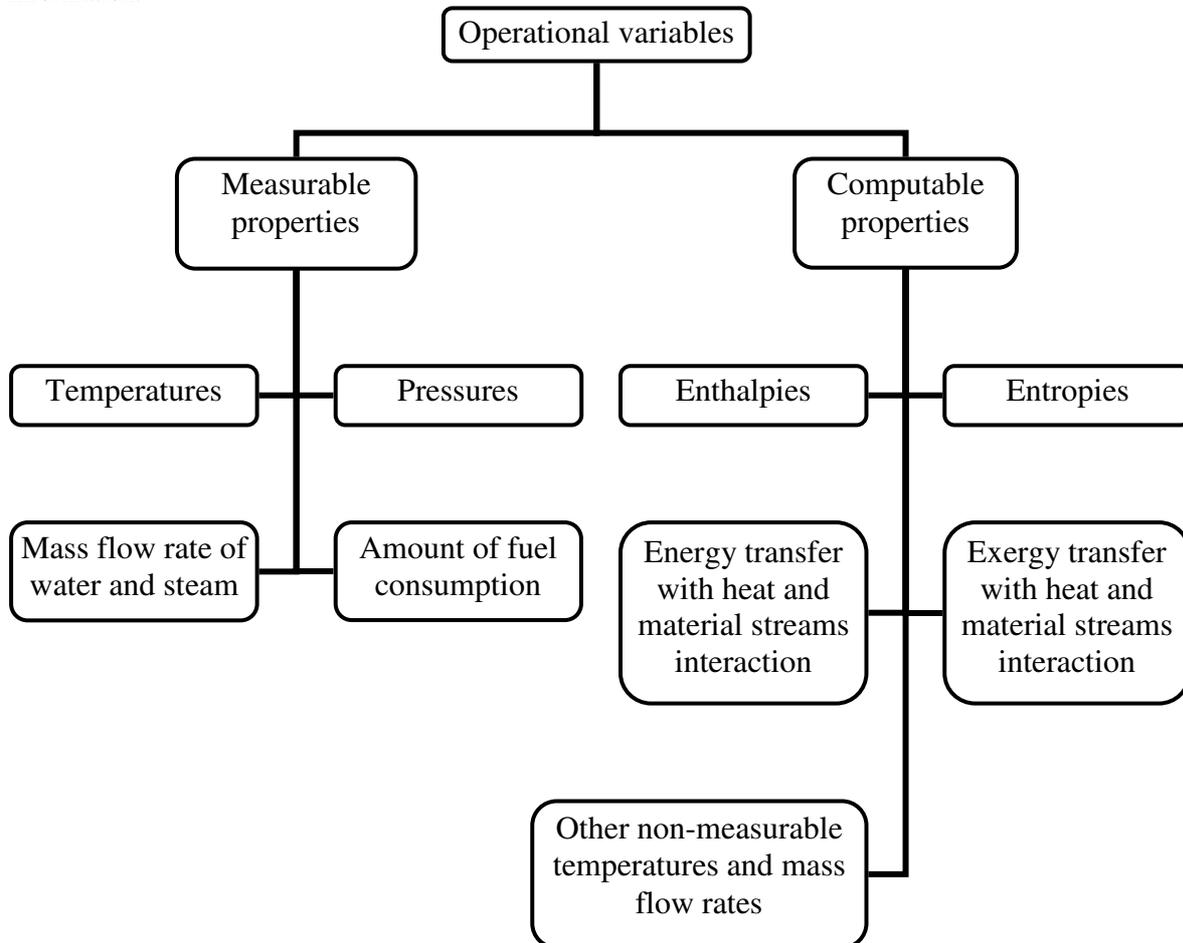


Figure 2: Operational variables framework

(ii) Computable properties

These properties are those that are not usually read directly from indicators, and as such would have to be computed through the use of appropriate energy tables or charts; thermodynamic formulae, such as conservation of mass and energy, and exergy balance equations.

2.1.3 Performance variables

These are parameters concerned with the performance of the boilers. Hence, they serve as indices to ascertain and analyse various performance levels of the steam boilers. They include variations of energy and exergy values and efficiencies of steam boilers in relation with input and output resources; and the magnitudes and types of irreversibility (exergy losses) and the locations they occur in steam boilers. Methods for computing various performance variables are enumerated in the theoretical framework.

2.2 Standard Environmental Reference State

Most analyses often involve the use of the natural environment-subsystem model described in Table 1 (Dincer and Rosen, 2007). A distinguishing difference between exergy and other thermodynamic properties is that the reference state for exergy is determined by the surroundings. In fact, exergy of matter will change if the state of the surroundings changes, even when no changes occur in the system itself. A temperature of 25°C (298.15 K), a pressure of 101.323 kPa and zero values for the height z_0 and velocity v_0 of the earth surface are typically taken as reference state (Jorge Luis Hau, 2005).

Table 1: A reference-environment model

Temperature: $T_0 = 298.15\text{ K}$														
Pressure: $P_0 = 1\text{ atm (1 bar)} = 101.325\text{ kPa}$														
Composition	(i) Atmospheric air saturated with H_2O at T_0 and P_0 having the following composition:													
	<table border="1"> <thead> <tr> <th>Air constituents</th> <th>Mole fraction</th> </tr> </thead> <tbody> <tr> <td>N_2</td> <td>0.7565</td> </tr> <tr> <td>O_2</td> <td>0.2035</td> </tr> <tr> <td>H_2O</td> <td>0.0303</td> </tr> <tr> <td>Ar</td> <td>0.0091</td> </tr> <tr> <td>CO_2</td> <td>0.0003</td> </tr> <tr> <td>H_2</td> <td>0.0001</td> </tr> </tbody> </table>	Air constituents	Mole fraction	N_2	0.7565	O_2	0.2035	H_2O	0.0303	Ar	0.0091	CO_2	0.0003	H_2
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(ii)	The following condensed phases at T_0 and P_0 :													
	Water (H_2O)													
	Limestone ($CaCO_3$)													
	Gypsum ($CaSO_4 \cdot 2H_2O$)													

Source: Adapted from Dincer and Rosen (2007)

2.3 Physical and Chemical Exergy

The total exergy transfer associated with material streams for a flow process comprises of the physical and chemical exergy (Cornelissen, 1997, Dincer and Rosen, 2007, Talens *et al.*, 2007, Chemical Exergy, 2011). The flow exergy of a substance is the theoretically obtainable work when the substance is brought into total equilibrium with the local environment. It can be split into chemical exergy and thermomechanical (physical) flow exergy which is represented by (Ertesvag, 2007):

$$\mathcal{E} = \mathcal{E}^{ph} + \mathcal{E}^{ch} \quad (1)$$

The specific physical flow exergy is expressed by:

$$\mathcal{E}^{ph} = h - h_0 - T_0(s - s_0) \quad (2)$$

where,

\mathcal{E} = specific flow exergy of material streams, kJ/kg

\mathcal{E}^{ph} = specific physical flow exergy, kJ/kg

\mathcal{E}^{ch} = specific chemical flow exergy, kJ/kg

h = specific enthalpy, kJ/kg

s = specific entropy, $kJ/kg\text{ K}$

$h_0 = h(T_0, P_0)$ = enthalpy at reference state

$s_0 = s(T_0, P_0)$ = entropy at reference state

T_0, P_0 = reference state temperature and pressure

2.4 Specifications of Selected Hydrocarbon Fuels

Every fuel has a unique composition and energy content described by its fuel specifications (Table 2). Knowing the fuel specifications is essential for determining combustion parameters such as combustion efficiency, minimum air requirements, CO_2 concentration and emissions factors (TSI Incorporated, 2004).

Table 2: Fuel specifications for selected fuels

Specifications	Natural Gas	Propane	No. 2 Oil (Diesel)	No. 6 Oil (LPFO)	Coal
%Carbon (C)	70.93	81.82	85.84	87.49	94.50
%Hydrogen (H)	23.47	18.18	12.46	9.92	5.20
Gross heating value (HHV) (Btu/lb)	21,869.00	21,669.00	19,512.00	18,300.00	13,388.00
(kJ/kg)	50,976.69	50,510.49	45,482.52	42,657.34	31,207.46
Net heating value (LHV) (Btu/lb)	19,693.00	19,937.00	18,357.00	17,381.00	12,903.00
(kJ/kg)	45,904.43	46,473.19	42,790.21	40,515.15	30,076.92
CO ₂ max	11.8.0	13.80	15.60	16.50	17.00
%Sulfur (S)	0	0	1.60	1.40	0.034
%Moisture (M)	0	0	0	0	0.12
%O ₂ [100 – (C+H+S+M)]	5.600	0	0.100	1.190	0.146

Source: TSI Incorporated (2004);

[Metric Equivalents: 1kJ/kg = 0.2388 kCal/kg = 0.429 Btu/lb]

3. Theoretical Framework

3.1 Air-fuel ratio determination for complete combustion

During the combustion of fossil fuels, hydrocarbon molecules (C_xH_y) are combined with oxygen to produce carbon dioxide (CO_2) and water (H_2O) in an exothermic reaction (Process Heating, 2010). The stoichiometric quantity of oxidizer is just that amount that is necessary to completely burn a quantity of fuel. The stoichiometric air-fuel ratio is calculated by balancing carbon (C), hydrogen (H), and oxygen (O) atoms in the combustion reaction.

Typical composition of low pour fuel oil LPFO (No. 6 fuel oil) and diesel (No. 2 fuel oil) given in Table 2, can be used to compute the amount of oxygen required, and other products released during the combustion of oil-fired boilers. Hence, the ultimate and proximate values of the products of combustion for complete combustion can then be determined.

Since air contained 23.3% O_2 by mass,

$$\therefore \text{Air required/kg of fuel} = \frac{O_2 \text{ required per kg of fuel}}{0.233} \quad (3)$$

Hence, the stoichiometric air-fuel ratio,

$$AFR_{st} = \frac{\text{Air required/kg of fuel}}{1} \text{ by mass (kg of air/kg of fuel)} \quad (4)$$

The actual air-fuel ratio (AAF) can be determined by (Process Heating, 2010),

$$AAF = (1 + EA) \times AFR_{st} \quad (5)$$

where, EA = excess air

Recommended excess air levels for fuel oil burners are: Register type, 15-20%; Multi-fuel burners and flat-flame type, 20-30% (Bureau of Energy Efficiency, 2010a).

Since air contained 76.7% of N_2 by mass,

$$\therefore N_2 \text{ supplied} = 0.767 \times AAF \text{ kg/kg of fuel} \quad (6)$$

Similarly,

$$O_2 \text{ supplied} = 0.233 \times AAF \text{ kg/kg of fuel} \quad (7)$$

$$\text{The excess air} = O_2 \text{ supplied} - O_2 \text{ required kg / kg of fuel} \quad (8)$$

That is,

$$O_2 \text{ contained in the products of combustion} = \text{The excess air kg/kg of fuel} \quad (9)$$

3.2 Carbon monoxide (CO) determination in combustion products

The excess air (EA) may be related with the measured or known quantities of oxygen (O_2) and carbon monoxide (CO) in the exhaust gas analysis by the following expressions (TSI Incorporated, 2004; Bureau of Energy Efficiency, 2010a; UNEP, 2010; Bureau of Energy Efficiency, 2010b):

$$\%EA = \frac{(\%O_2)_p}{21 - (\%O_2)_p} \times 100 \quad (10)$$

$$\%EA = \frac{(\%O_2)_p - \frac{(\%CO)_p}{2}}{21 - \left((\%O_2)_p - \frac{(\%CO)_p}{2} \right)} \times 100 \quad (11)$$

where,

$\%EA$ = percentage excess air

$(\%O_2)_p$ = percentage oxygen from proximate (volumetric) analysis

$(\%CO)_p$ = percentage carbon monoxide from proximate (volumetric) analysis

Equation (11) can be re-arranged and expressed in terms of percentage carbon monoxide as follows:

$$(\%CO)_p = \frac{2 \times (\%O_2)_p (1 + EA) - 2 \times 21 \times EA}{(1 + EA)} \quad (12)$$

3.3 The schematic of the boiler plants

The schematic diagrams shown in Figures 3 can be used to analyse the mass flow rate, energy and exergy balances and exergetic efficiencies of boilers (Saidur *et al.*, 2010). The schematic diagrams of the combustion and heat exchanging units respectively shown in Figures 3 may be separately analysed to establish the mass flow rate of the material streams in the boilers. Combustion of fuel takes place in the combustion unit of the boiler, while the heat carried by the hot flue gas from the combustion unit is used to transform liquid water to steam in the heat exchanging unit.

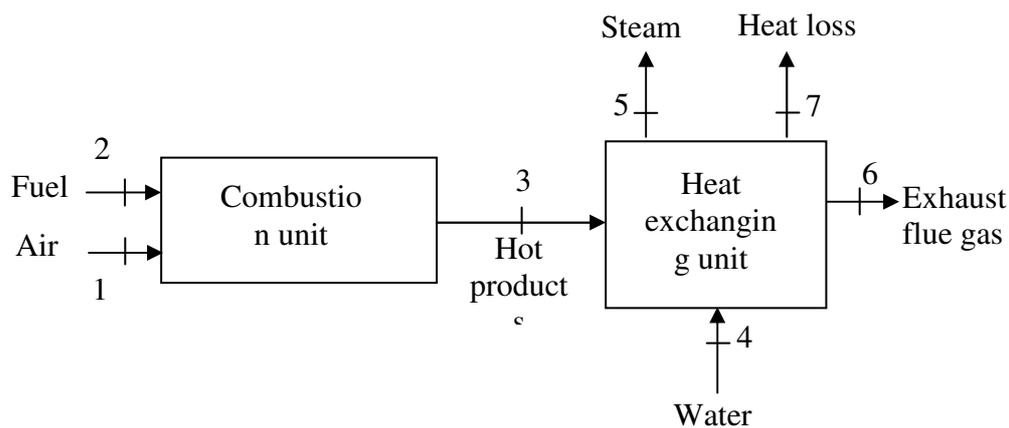


Figure 3: Schematic diagram of combustion and heat exchanging units in a boiler

3.4 Thermodynamic and exergetic analysis determination

An exergetic analysis involves mass, energy and exergy balance for each plant unit, and exergetic efficiency for each of them (Modesto and Nebra, 2009). The mass, energy and exergy balances at steady state for the material flows in a boiler system with negligible potential and kinetic energy changes can be expressed, respectively by equations (13) to (15) (Aljundi, 2009, Modesto and Nebra, 2009, Saidur *et al.*, 2010).

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (13)$$

$$\dot{Q} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \quad (14)$$

$$\dot{I} = \sum \dot{m}_i \varepsilon_i - \sum \dot{m}_e \varepsilon_e \quad (15)$$

The exergetic balance of a boiler can be determined using equations (13) to (15).

where,

\dot{m}_i = inlet mass flow rate, kg/s

\dot{m}_e = exit mass flow rate, kg/s

\dot{Q} = heat transfer rate to the system, kJ/s

\dot{I} = exergy destruction rate, kJ/s
 h_i = inlet enthalpy of material streams, kJ/kg
 h_e = exit enthalpy of material streams, kJ/kg
 \mathcal{E}_i = inlet specific flow exergy of material streams, kJ/kg
 \mathcal{E}_e = exit specific flow exergy of material streams, kJ/kg

1. Mass balance of material streams

Appropriate mass and energy balance as stated by equation (13) and equation (14) may be applied to a boiler system with the evaporation ratio and air fuel ratio and may be used to determine masses of substances of all material streams in the boiler, such as; air (\dot{m}_a), fuel (\dot{m}_f), hot products (\dot{m}_p), feed water (\dot{m}_w), steam (\dot{m}_s) and exhaust flue gases (\dot{m}_g) respectively.

hence,

$$\dot{m}_a + \dot{m}_f = \dot{m}_p \quad (16)$$

$$\dot{m}_p = \dot{m}_g \quad (17)$$

$$\dot{m}_w = \dot{m}_s \quad (18)$$

The mass flow rate of fuels and steam can be computed by

$$\dot{m} = q_m \times d / 3600 \quad (19)$$

where,

\dot{m} = mass rate of substance, kg/s

q_m = rate of material stream, $litres/hr$

d = relative density of substance

The evaporation ratio of a boiler is given by (Bureau of Energy Efficiency, 2010b);

$$\text{Evaporation ratio, } E_r = \frac{\text{Quantity of steam generation}}{\text{Quantity of fuel consumption}} \quad (20)$$

Equation (20) may simply be expressed as the quotient of mass flow rates of steam and fuel as shown in equation (21)

$$E_r = \frac{\dot{m}_s}{\dot{m}_f} \quad (21)$$

Computed mass flow rates of material streams of a boiler operation can be used to determine other thermodynamic properties of materials streams, such as enthalpy and entropy at different states.

2. Temperature, enthalpy and entropy of feed water and steam

The enthalpy and entropy of feed water may be determined at a saturation temperature of $100^\circ C$ or at other appropriate temperatures, while the saturation temperatures corresponding to their respective steam pressures may be obtained from saturated water and steam tables (Cengel and Boles, 2006). Superheated temperatures at the given steam pressures may be used where applicable for superheated steams.

3. Combustion temperatures

From an energy balance analysis of a combustion process, the combustion temperature can be calculated as follows (Process Heating, 2010),

$$T_c = T_{ca} + \frac{h_r}{[c_p \times (1 + AAF)]} \quad (22)$$

where,

T_c = combustion temperature

T_{ca} = temperature of the combustion air before entering the burner

h_r = heat of reaction ($h_r = LHV$, if exhaust gas streams is above $60^\circ C$, (Kitto and Stultz, 2005) c_p = specific heat of fuel at ambient temperature of products of combustion

To maintain satisfactory working conditions for personnel around a boiler, a cold face temperature or boiler room ambient temperature, T_{ar} of $57^\circ C$ ($135^\circ F$) or less is considered satisfactory (Kitto and Stultz, 2005).

The following data may be used to calculate the values of the combustion temperature, T_c for LPFO and diesel operated boilers:

$$T_{ca} = T_a$$

$$h_{r(LPFO)} = 40,515.15 \text{ kJ/kg}, h_{r(diesel)} = 42,790.21 \text{ kJ/kg}$$

$$AAF_{(LPFO)} = 16, AAF_{(diesel)} = 17$$

The specific heat of petroleum oils can be modeled as follows (Petroleum, 2011):

$$c_p = \frac{1}{\sqrt{d}} [1.6831 + 3.3913 \times 10^{-3} T_{ar}] \quad (23)$$

where,

d = relative density at 15 °C

c_p = specific heat, kJ/kg K

T_{ar} = ambient boiler room temperature

d = relative density = 0.95 for LPFO and 0.86 for diesel at 15 °C (Armstrong, 2010)

hence, the values of c_p were obtained as follows from equation (23);

$$c_{p(LPFO)} = 1.866 \text{ kJ/kg K}, c_{p(diesel)} = 1.9612 \text{ kJ/kg K}$$

Using the values of c_p obtained above, the values of $T_c = T_f$ can be obtained from equation (22) with their different combustion air temperature, T_{ca} .

4. Enthalpy and entropy of inlet air

The enthalpy and entropy of inlet air can be evaluated for inlet air temperature, T_a for different boilers operation from the ideal gas properties of air tables (Cengel and Boles, 2006).

5. Enthalpy of hot products

Applying the energy balance equation (14) to the combustion unit shown in Figure 3 and assuming heat was transferred adiabatically (Saidur *et al.*, 2010), the enthalpy of the hot products can be determined using

$$\dot{m}_f h_f + \dot{m}_a h_a = \dot{m}_p h_p \quad (24)$$

6. Temperature of exhaust flue gases

The steady-state efficiency of combustion is the ratio of the useful heat delivered to the process to the heat content of the fuel (Process Heating, 2010). The combustion efficiency is given by:

$$\eta_{comb} = \frac{[(1 + AAF) \times c_p \times (T_c - T_g)]}{HHV} \quad (25)$$

where,

c_p = specific heat of fuel at ambient temperature of products of combustion

HHV = Gross or high heating value of fuel

The benchmark combustion efficiency for various fuels, are given as: coal 90.3%, oil residual 89.6%, oil distillate 88.7%, natural Gas 85.7% (ETSAP, 2010). Hence,

$$\eta_{comb(LPFO)} = 89.6\%, \eta_{comb(diesel)} = 88.7\%$$

$$HHV_{(LPFO)} = 42,657.34 \text{ kJ/kg}, HHV_{(diesel)} = 45,482.52 \text{ kJ/kg} \text{ (Table 2),}$$

$$AAF_{(LPFO)} = 16, AAF_{(diesel)} = 17,$$

$$c_{p(LPFO)} = 1.866 \text{ kJ/kg } ^\circ\text{C}, c_{p(diesel)} = 1.9612 \text{ kJ/kg } ^\circ\text{C}$$

Equation (25) may be re-written as equation (26) and can be used to evaluate the exhaust flue gas temperatures

$$T_g = T_c - \frac{HHV \times \eta_{comb}}{(1 + AAF) \times c_p} \quad (26)$$

7. Enthalpy of exhaust flue gases

Enthalpies of most gases used in combustion calculations can be curve-fitted by the simple second order equation (Kitto and Stultz, 2005):

$$h = aT^2 + bT + c \quad (27)$$

where,

h = enthalpy in Btu/lb

T = temperature in degrees, °F

a, b and c are coefficients with the following values for T (0-500 °F) given as:

$$\begin{aligned} a &= 1.683 \times 10^{-5} \\ b &= 0.233 \\ c &= -18.03 \end{aligned}$$

Equation (27) can be used to evaluate the enthalpy of the exhaust flue gases. It should be noted that the constants a, b and c are stated only for the quoted temperature range given in $^{\circ}F$.

8. Entropy of combustion fuel gases

The entropy generated from a source can be expressed as follows (Cengel and Boles, 2006);

$$s_{gen} = \frac{q_{source}}{T_{source}} \quad (28)$$

where,

s_{gen} = entropy generated from the source, $kJ/kg K$

q_{source} = heat transfer from a source to a sink, kJ/kg

T_{source} = temperature of the source, $^{\circ}K$

A study of the thermodynamic processes taking place between the combustion and the heat exchanging units shows that: the entropy generated from the combustion unit is the entropy of the combustion fuel gas, s_f , the heat transfer from the combustion unit to the heat exchanging unit equals the energy value of the hot products, h_p and the temperature of the source is the combustion fuel temperature, T_f .

hence, equation (28) can be re-written as:

$$s_f = \frac{h_p}{T_f} \quad (29)$$

The entropy of the combustion fuel gases can be determined by equation (29).

9. Entropy of hot products

The entropy of the hot products can be determined by equation (30), where T_p is the temperature of the hot products

$$s_p = \frac{h_p}{T_p} \quad (30)$$

10. Entropy of exhaust flue gases

The change in entropy of an ideal gas can be expressed by (Cengel and Boles, 2006),

$$s_2 - s_1 = c_p \ln \frac{T_2}{T_1} - R \ln \frac{p_2}{p_1} \quad (31)$$

where, s_1 , T_1 and p_1 defines the reference state entropy, temperature and pressure, while s_2 , T_2 and p_2 defines the thermodynamic state entropy at a given temperature and pressure, and R is the specific gas constant.

At the exhaust of the boiler, the change in entropy of the exhaust flue gases can be determined by setting $s_2 = s_g$, $s_1 = s_a$, $T_2 = T_g$, $T_1 = T_a$, $p_2 = p_g = p_1 = p_a = p_{atm}$, in equation (31), in which

s_g = exhaust flue gas specific entropy

T_g = exhaust flue gas temperature

p_g = exhaust flue gas pressure

s_a = reference state entropy of air (at T_a and p_a)

T_a = reference state temperature of air

p_a = reference state pressure of air = 1 atm (Turns and Kraige, 2007)

p_{atm} = atmospheric pressure = 1 atm

$c_p = c_{pg} \cong c_{pa} \cong 1 \text{ kJ/kg K}$ (c_{pg} and c_{pa} are the specific heat of exhaust flue gas and air)

hence, equation (31) reduces to

$$s_g = s_a + c_p \ln \frac{T_g}{T_a} \quad (32)$$

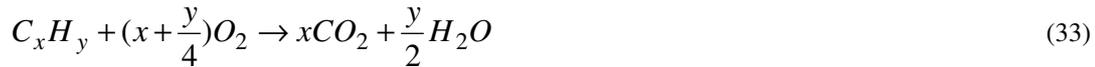
At $T_a = 200 \text{ K}$, $s_a = 1.29559 \text{ kJ/kg K}$ (Cengel and Boles, 2006)

The entropy of the exhaust flue gases can be determined by equation (32).

11. Chemical exergy of fuels

Complete combustion of a general hydrocarbon with atmospheric air is written as (Cengel and Boles,

2006, Roger and Mayhew, 1992),



Where x and y are constant coefficients that characterises the hydrocarbon and combustion process. Assuming no irreversibility, the molar chemical exergy of reactants and products can be developed as expressed by (Chemical Exergy, 2011).

$$e_{x\text{fuel}}^{ch} + (x + \frac{y}{4})e_{xO_2}^{ch} \rightarrow -\Delta\bar{g} + xe_{xCO_2}^{ch} + \frac{y}{2}e_{xH_2O}^{ch} \quad (34)$$

where,

$e_{x\text{fuel}}^{ch}$ = molar chemical exergy of fuel, $kJ/kmol$

$e_{xO_2}^{ch}$ = molar chemical exergy of oxygen (O_2), $kJ/kmol$

$e_{xCO_2}^{ch}$ = molar chemical exergy of carbon dioxide (CO_2), $kJ/kmol$

$e_{xH_2O}^{ch}$ = molar chemical exergy of water vapour (H_2O), $kJ/kmol$

$\Delta\bar{g}$ = the change in the standard Gibbs function, $kJ/kmol$

The chemical exergy of fuel can thus be obtained by (Chemical Exergy, 2011, Roger and Mayhew, 1992),

$$e_{x\text{fuel}}^{ch} = -\Delta\bar{g} + \bar{R}T_0 \ln \left[\frac{n_{O_2}^{(x+y/4)}}{n_{CO_2}^x n_{H_2O}^{y/2}} \right] \quad (35)$$

The mole fraction of oxygen (n_{O_2}), carbon dioxide (n_{CO_2}) and water (n_{H_2O}) in a standard environment are given in Table 1.

where,

$\bar{R} = 8.3144 \text{ kJ/kmol K}$ (molar or universal gas constant)

The standard Gibbs functions of formation of other components in equation (35) are given as follows (Roger and Mayhew, 1992):

$$\bar{g}_{CO_2} = -394,390 \text{ kJ/kmol}$$

$$\bar{g}_{H_2O(v)} = -228,590 \text{ kJ/kmol}$$

$$\bar{g}_{O_2} = 0$$

The change in standard Gibbs function can be determined by (Chemical Exergy, 2011, Roger and Mayhew, 1992),

$$\Delta\bar{g} = x\bar{g}_{CO_2} + \frac{y}{2}\bar{g}_{H_2O(v)} - (x + \frac{y}{4})\bar{g}_{O_2} \quad (36)$$

The specific chemical exergy was obtained by equation (37)

$$\epsilon^{ch} = \frac{e_x^{ch}}{M} \quad (37)$$

where, M = molar mass of chemical substance, $kg/kmol$

12. Chemical exergy of air

The chemical exergy of atmospheric air can be determined from equation (38) and the mole fractions of the elements in a standard environment presented in Table 1 with their respective chemical exergies given by Ertesvag (2007) as presented in Table 3.

$$e_{x(air)}^{ch} = \sum (n_i e_{x_i}^{ch})_{air} \quad (38)$$

Table 3: Chemical exergies of components of atmospheric air at reference conditions, 25^oC, 1 atm, 70% relative humidity

Components	Chemical exergies
Nitrogen, N_2	0.6681
Oxygen, O_2	3.9305
Carbon dioxide, CO_2	19.610
Argon, Ar	11.640
Water, H_2O (g)	9.474
Water, H_2O (liq)	0.8842
Hydrogen, H_2	236.098
Carbon monoxide, CO	274.87

Source: Ertesvag (2007)

The molar mass of air is given as $M_{air} = 28.96 \text{ kg/kmol}$ (Cengel and Boles, 2006).

13. Chemical exergy of LPFO and diesel fuels before combustion

The chemical exergy of LPFO and diesel fuels before combustion is equivalent to their respect Gross heating value (HHV) presented in Table 2.

14. Analysis of the combustion unit

Applying the energy balance equation (14) to the combustion unit as shown in Figure 3, the energy input in the combustion unit can be determined by

$$E_{in} = \dot{m}_f h_f + \dot{m}_a h_a \quad (39)$$

where, h_f and h_a are the specific enthalpies of combustion fuel and air.

The combustion efficiency of an adiabatic combustor is usually equal to unity (Saidur *et al.*, 2010), and may be represented by the first law efficiency given by

$$\eta_C = \frac{\dot{m}_p h_p}{\dot{m}_f \times HHV} \quad (40)$$

where, HHV = high or gross heating value of fuel

The combustion unit is assumed to operate in a steady-flow adiabatic process, whereby the change of mass and energy of the control volume is zero. It is also assumed that the kinetic and potential energies are negligible and that there is no work transfer involved. Applying the exergy balance equation (15) to the combustion unit, the exergy destruction in the combustion unit can be determined by

$$\dot{I}_C = \dot{m}_a [\epsilon_{a_1}^{ph} + \epsilon_{a_1}^{ch}] - \dot{m}_p \epsilon_{p_3}^{ph} + \dot{m}_f [\epsilon_{f_2}^{ph} + \epsilon_{f_2}^{ch} - \epsilon_{f_3}^{ch}] \quad (41)$$

where, $\epsilon_{a_1}^{ph}$, $\epsilon_{f_2}^{ph}$ and $\epsilon_{p_3}^{ph}$ are the specific physical exergies of air and fuel at inlet and that of hot products at exit, while $\epsilon_{a_1}^{ch}$, $\epsilon_{f_2}^{ch}$ (HHV), are the specific chemical exergies of air and the combustion fuel at inlet, and $\epsilon_{f_3}^{ch}$ is the specific chemical exergy of the combustion fuel at exit.

Using equations (1) and (2), equation (41) may be re-written as follows

$$\dot{I}_C = \dot{m}_a [(h_a - T_0 s_a) + \epsilon_{a_1}^{ch}] - \dot{m}_p (h_p - T_0 s_p) + \dot{m}_f [(h_f - T_0 s_f) + \epsilon_{f_2}^{ch} - \epsilon_{f_3}^{ch}] \quad (42)$$

where, h_p = specific enthalpies for hot products, s_f and s_a are the specific entropies of combustion fuel and air, and the reference state temperature, $T_0 = 25^\circ\text{C}$ (298.15 K). The specific chemical exergies can be determined using equations (35) to (37).

The exergy efficiency of the combustion unit can be determined by

$$\psi_C = \frac{\dot{m}_p \epsilon_{p_3}^{ph}}{\dot{m}_f [\epsilon_{f_2}^{ph} + \epsilon_{f_2}^{ch} - \epsilon_{f_3}^{ch}]} \quad (43)$$

Equation (43) may be re-written as

$$\psi_C = \frac{\dot{m}_p (h_p - T_0 s_p)}{\dot{m}_f [(h_f - T_0 s_f) + \epsilon_{f_2}^{ch} - \epsilon_{f_3}^{ch}]} \quad (44)$$

15. Analysis of the heat exchanging unit

Performing an energy balance on the heat exchanging unit as shown in Figure 3, and noting that $\dot{m}_p = \dot{m}_g$ and $\dot{m}_w = \dot{m}_s$, the heat loss can be determined by

$$Q_{H(loss)} = \dot{m}_p (h_p - h_g) - \dot{m}_w (h_s - h_w) \quad (45)$$

where, h_g , h_s and h_w are the specific enthalpies of exhaust flue gas, steam and feed water.

The first law efficiency of the heat exchanging unit can be determined by (Saidur *et al.*, 2010)

$$\eta_H = \frac{\dot{m}_w (h_s - h_w)}{\dot{m}_p (h_p - h_g)} \quad (46)$$

The exergy destruction in the heat exchanging unit can be determined by

$$\dot{I}_H = \dot{m}_p \epsilon_{p_3}^{ph} + \dot{m}_w [\epsilon_{w_4}^{ph} + \epsilon_{w_4}^{ch}] - \dot{m}_s [\epsilon_{s_5}^{ph} + \epsilon_{s_5}^{ch}] - \dot{m}_g [\epsilon_{g_6}^{ph} + \epsilon_{g_6}^{ch}] \quad (47)$$

where, $\epsilon_{p_3}^{ph}$, $\epsilon_{w_4}^{ph}$, $\epsilon_{s_5}^{ph}$ and $\epsilon_{g_6}^{ph}$, are the specific physical exergies of products of combustion, feed water, steam and exhaust flue gas, while $\epsilon_{w_4}^{ch}$, $\epsilon_{s_5}^{ch}$ and $\epsilon_{g_6}^{ch}$ are the chemical exergies of the feed water, steam and exhaust flue gases, The specific chemical exergies of steam and liquid water are respectively given as 526.33 kJ/kg (9474 kJ/kmol) and 49.12 kJ/kg (884.20 kJ/kmol) (Ertesvag, 2007, Szargut *et al.*, 2011, Talens, *et al.*, 2007). Equation (47) may be re-written as

$$\begin{aligned} \dot{I}_H = & \dot{m}_p (h_p - T_0 s_p) + \dot{m}_w [(h_w - T_0 s_w) + \epsilon_{w_4}^{ch}] \\ & - \dot{m}_s [(h_s - T_0 s_s) + \epsilon_{s_5}^{ch}] - \dot{m}_g [(h_g - T_0 s_g) + \epsilon_{g_6}^{ch}] \end{aligned} \quad (48)$$

where, s_g , s_s and s_w are the specific entropies of exhaust flue gas, steam and feed water.

The exergy efficiency of the heat exchanging unit can be determined by

$$\psi_H = \frac{\dot{m}_s [\epsilon_{s_5}^{ph} + \epsilon_{s_5}^{ch}] - \dot{m}_w [\epsilon_{w_4}^{ph} + \epsilon_{w_4}^{ch}]}{\dot{m}_p \epsilon_{p_3}^{ph} - \dot{m}_g [\epsilon_{g_6}^{ph} + \epsilon_{g_6}^{ch}]} \quad (49)$$

Equation (49) may be re-written as

$$\psi_H = \frac{\dot{m}_s [(h_s - T_0 s_s) + \epsilon_{s_5}^{ch}] - \dot{m}_w [(h_w - T_0 s_w) + \epsilon_{w_4}^{ch}]}{\dot{m}_p (h_p - T_0 s_p) - \dot{m}_g [(h_g - T_0 s_g) + \epsilon_{g_6}^{ch}]} \quad (50)$$

16. Analysis of the entire boiler

The overall boiler energy efficiency can be determined by (Saidur *et al.*, 2010)

$$\eta_B = \frac{\dot{m}_s (h_s - h_w)}{\dot{m}_f h_f} \quad (51)$$

The overall exergy destruction of the boiler was obtained as the sum of exergy destruction in the combustion chamber and the heat exchanger. That is,

$$\dot{I}_B = \dot{I}_C + \dot{I}_H \quad (52)$$

The overall boiler exergy efficiency can be determined as the rational efficiency of the entire boiler which is the ratio of the desired exergy output, $\dot{E}_{desired\ output}$ to the exergy used, \dot{E}_{used} (Cornelissen, 1997). The $\dot{E}_{desired\ output}$ was the net exergy for the transformation of water, while \dot{E}_{used} was the net energy input into the system. The exergy efficiency of the boiler can therefore be determined by

$$\psi_B = \frac{\dot{E}_{desired\ output}}{\dot{E}_{used}} \quad (53)$$

Equation (53) may be expressed as

$$\psi_B = \frac{\dot{m}_s [\epsilon_{s5}^{ph} - \epsilon_{w4}^{ph} + \epsilon_{s5}^{ch} - \epsilon_{w4}^{ch}]}{\dot{m}_f [\epsilon_{f2}^{ph} + \epsilon_{f2}^{ch} - \epsilon_{f3}^{ch}]} \quad (54)$$

$$\psi_B = \frac{\dot{m}_s [(h_s - T_0 s_s) - (h_w - T_0 s_w) + \epsilon_{s5}^{ch} - \epsilon_{w4}^{ch}]}{\dot{m}_f [(h_f - T_0 s_f) + \epsilon_{f2}^{ch} - \epsilon_{f3}^{ch}]} \quad (55)$$

4. Conclusion

The framework to evaluate thermodynamic properties and performance variables associated with material streams in steam boilers as presented in this study would afford researchers with a broad base of alternatives in analysing and determining vital parameters needed in an energy and exergy analysis of steam boilers. The framework offers advanced thermodynamic solutions based on first principles to determine mass flow rate, temperatures, enthalpies and entropies which could be used to obtain performance indices, resources allocation, areas and magnitude of energy losses and exergy destruction.

Instructors, researchers and advanced students of engineering, sciences and energy analysis are expected to find this material as a helpful tool to quickly understand fundamental concepts and approach required in energy and exergy analysis of industrial plants. A number of information that is not commonly contained in a single text or in a simplified manner has been elaborated in this methodology with worked examples presented in the appendix. Furthermore, the framework does not in any way place a limit on its users, on the contrary, users would interestingly discover a divergent and varied alternatives to tackling and solving problems related to energy and exergy analysis in diversified circumstances. Also, users could find the framework as a good starting point for modelling and simulation of energy and exergy related solutions of industrial plants and facilities.

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Appendix: Worked Examples

Preliminary computed mass flow rates of material streams in a boiler using previous mass balance equations are presented in Appendix Table 1. Some other properties, such as temperatures, enthalpies and entropies which may not be easily measured or determined directly from a boiler were therefore obtained using earlier derived thermodynamic, energy and exergy equations respectively as presented in Appendix Table 1.

Appendix Table 1: Computed thermodynamic properties of materials streams in a boiler using LPFO

Point	Substances	Mass flow rate (kg/s)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/kgK)
1	Air, \dot{m}_a ,	3.3744	80.63	354.53	1.8684
2	Fuel, \dot{m}_f	0.2109	1,084.82	40,515.15	2.0009
3	Hot products, \dot{m}_p	3.5853	275.73	2,716.92	4.9513
4	Feed water, \dot{m}_w	2.5308	100.00	419.10	1.3070
5	Steam, \dot{m}_s	2.5308	168.89	2,767.60	6.6759
6	Exhaust flue gas, \dot{m}_g	3.5853	152.95	231.00	2.0516

Source: Ohijeagbon (2012)

1. Combustion temperatures

Using equation (22) and the data stated as follows:

at $c_p = 1.866 \text{ kJ/kg K}$, $AAF = 16$, $T_{ca} = 80.63 \text{ }^\circ\text{C}$, $h_{r(LPFO)} = 40,515.15 \text{ kJ/kg}$

The combustion temperature of a boiler operation was calculated as

$$T_f = T_c = T_{ca} + \frac{h_r}{[c_p \times (1 + AAF)]} = 80.63 + \frac{40,515.15}{[1.866 \times (1 + 16)]} = 1,084.82 \text{ }^\circ\text{C}$$

2. Enthalpy of hot products

The enthalpy of the hot products can be determined using equation (24) and data from Appendix Table 1 as follows;

$$h_p = \frac{0.2109 \times 40,515.15 + 3.3744 \times 354.53}{3.5853} = 2,716.92 \text{ kJ/kg}$$

3. Temperature of exhaust flue gases

The benchmark combustion efficiency for various fuels, are give as: coal 90.3%, oil residual 89.6%, oil distillate 88.7%, natural Gas 85.7% (ETSAP, 2010). Hence,

$$\eta_{comb(LPFO)} = 89.6\%, HHV_{(LPFO)} = 42,657.34 \text{ kJ/kg}, AAF_{(LPFO)} = 16, c_{p(LPFO)} = 1.866 \text{ kJ/kg }^\circ\text{C}$$

The temperature of exhaust flue gases can be determined using equation (26) and data from Appendix Table 1 as follows;

$$T_g = 1,084.82 - \left[\frac{42,657.34 \times 0.896}{(1 + 16) \times 1.866} - 273 \right] = 152.95 \text{ }^\circ\text{C}$$

4. Enthalpy of exhaust flue gases

Equation (27) was used to evaluate the enthalpy of the exhaust flue gases from previously calculated data with the aid of the Microsoft excel spread sheet (inter-conversions were necessary) and is presented as shown in Appendix Table 1.

5. Entropy of combustion fuel gases

The entropy of combustion fuel gases can be determined using equation (28) and data from Appendix Table 1 as follows;

$$s_f = \frac{2,716.92}{1,357.82} = 2.0009 \text{ kJ/kgK}$$

6. Entropy of hot products

The entropy of hot products can be determined using equation (30) and data from Appendix Table 1 as follows;

$$s_p = \frac{2,716.92}{548.73} = 4.9513 \text{ kJ/kgK}$$

7. Entropy of exhaust flue gases

At $T_a = 200 \text{ K}$, $s_a = 1.29559 \text{ kJ/kg K}$ (Cengel and Boles, 2006)

The entropy of exhaust flue gases can be determined using equation (32) and data from Appendix Table 1 as follows;

$$s_g = 1.29559 + 1 \times \ln \left[\frac{(152.95 + 273)}{200} \right] = 2.0516 \text{ kJ/kg K}$$

8. Chemical exergy of air

The molar chemical exergy of atmospheric air can be determined using equation (38) and data from Tables 1 and 3 as follows;

$$\begin{aligned}
 e_{x(air)}^{ch} &= \sum \left(n_i e_{x_i}^{ch} \right)_{air} \\
 &= [0.7565(666.10) + 0.2035(3,930.50) + 0.0303(9,474.00) \\
 &\quad + 0.0091(11,640.00) + 0.0003(19,610.00) + 0.0001(236.098)] \\
 &= 1702.65 \text{ kJ / kmol}
 \end{aligned}$$

The molar mass of air is given as $M_{air} = 28.96 \text{ kg/kmol}$ (Cengel and Boles, 2006). Hence, the specific chemical exergy of atmospheric air can be determined using equation (37) as follows;

$$\epsilon_a^{ch} = \frac{1702.65}{28.96} = 58.79 \text{ kJ / kg}$$

9. Chemical exergy of LPFO before combustion

The chemical exergy of LPFO before combustion is equivalent to their respect Gross heating value (HHV) as shown in Table 2 as follows;

$$\epsilon_f^{ch} (LPFO) = 42,657.34 \text{ kJ / kg}$$

10. Chemical exergy of LPFO during combustion

The standard Gibbs functions of formation of other components in equation (36) are given as follows (Roger and Mayhew, 1992):

$$\bar{g}_{CO_2} = -394,390 \text{ kJ/kmol}$$

$$\bar{g}_{H_2O(v)} = -228,590 \text{ kJ/kmol}$$

$$\bar{g}_{O_2} = 0$$

The mole fraction of oxygen (n_{O_2}), carbon dioxide (n_{CO_2}) and water (n_{H_2O}) in a standard environment are obtained from Table 1 as follows:

$$n_{O_2} = 0.2035$$

$$n_{CO_2} = 0.0003$$

$$n_{H_2O} = 0.0303$$

Temperature, $T_0 = 298.15 \text{ K}$ for a standard reference environment (Table 1)

The molar mass of LPFO was estimated as 203.86 kg/kmol from properties and specifications of selected fuels, and their chemical formula which was estimated as $C_{14.88}H_{25.3}$ (TSI Incorporated, 2004, Cengel, 2006). The standard Gibbs functions of formation for LPFO can be determined by equation (36) as follows;

$$\therefore \Delta \bar{g} = 14.88 \times (-394,390) + \frac{25.3}{2} \times (-228,590) - (14.88 + \frac{25.3}{4}) \times 0$$

$$= -8,760,186.70 \text{ kJ / kmol}$$

The molar chemical exergy of LPFO can be determined using equation (35) as follows;

$$e_{x \text{ fuel}}^{ch} = -(-8,760,186.70) + 8.3144 \times 298.15 \times \ln \left[\frac{0.2035^{(14.88 + \frac{25.3}{4})}}{0.0003^{14.88} \times 0.0303^{(25.3/2)}} \right]$$

$$= 9,085,359.82 \text{ kJ / kmol}$$

The specific chemical exergy of LPFO can be determined using equation (37) as follows;

$$\epsilon_f^{ch} (LPFO) = \frac{e_{x(f)}^{ch}}{M_{f(LPFO)}} = \frac{9,085,359.82}{203.86} = 44,566.66 \text{ kJ / kg}$$

11. Chemical exergy of steam and liquid water

The specific chemical exergies of steam (ϵ_s^{ch}) and liquid water (ϵ_w^{ch}), are respectively given as 526.33 kJ/kg (9474 kJ/kmol) and 49.12 kJ/kg (884.20 kJ/kmol) (Ertesvag, 2007, Szargut *et al.*, 2011, Talens, *et al.*, 2007). $\epsilon_w^{ch} = 49.12 \text{ kJ / kg}$

$$\epsilon_s^{ch} = 526.33 \text{ kJ/kg}$$

12. Chemical exergy of exhaust flue gases

The chemical exergy of exhaust flue gases was determined from the mole fractions of the products of combustion presented in Appendix Table 2, their respective chemical exergies given by Ertesvag (2007) as shown in Table 3 and the associated carbon monoxide determined by equation (12) as follows;

$$(\%CO)_p = \frac{2 \times 3.668 \times (1 + 0.2) - 2 \times 21 \times 0.2}{(1 + 0.2)} = 0.336\%$$

Appendix Table 2: Ultimate and proximate analysis of the products of combustion for complete combustion of LPFO

Product	Mass of Wet Flue Gas (kg/kg of Oil)	Mass of Dry Flue Gas (kg/kg of Oil)	Ultimate Analysis (%)		Proximate Analysis (%)	
			Wet	Dry	Wet	Dry
CO ₂	3.2080	3.2080	18.740	19.780	12.4840	13.6430
H ₂ O	0.8928	-	5.220	-	8.4940	-
SO ₂	0.0280	0.0280	0.164	0.173	0.0754	0.0823
O ₂	0.6263	0.6263	3.660	3.860	3.3570	3.6680
N ₂	12.3600	12.3600	72.220	76.190	75.590	82.6070
	17.1151	16.2223	100.00	100.00	100.00	100.00

Source: Ohijeagbon (2012)

Hence, the molar chemical exergy of exhaust flue gases was determined as follows;

$$\begin{aligned} e_{x(g)}^{ch} &= \frac{1}{100} \sum (n_i e_{x_i}^{ch})_g \\ &= \frac{1}{100} [12.4840(19,610) + 8.4940(9,474) + 0.0754(609,600.00) \\ &\quad + 3.3570(3,930.50) + 75.590(668.10) + 0.336(274.87)] \\ &= \frac{1}{100} [435035.9598] \\ &= 4,350.36 \text{ kJ / kmol} \end{aligned}$$

The molar mass of the exhaust gas from the combustion of LPFO was also determined from the mole fractions of the products of combustion and the respective molar masses of each constituent member contained in the gas as shown in Appendix Table 2.

The molar mass of the exhaust flue gases was determined as follows;

$$\begin{aligned}
 M_{g(LPFO)} &= \sum (n_i M_{i(g)})_{LPFO} \\
 &= \frac{1}{100} [12.4840(44) + 8.4940(18) + 0.0754(64) \\
 &\quad + 3.3570(32) + 75.590(28) + 0.336(28)] \\
 &= \frac{1}{100} [2940.3656] \\
 &= 29.40 \text{ kg / kmol}
 \end{aligned}$$

The specific chemical exergy of the exhaust flue gases can be determined using equation (37) as follows;

$$\therefore \varepsilon_{g6}^{ch} = \frac{e_{x(g)}^{ch}}{M_{g(LPFO)}} = \frac{4,350.36}{29.40} = 147.97 \text{ kJ / kg}$$

13. Computation of energy and exergy values and efficiencies

The energy and exergy values of the flow processes in the investigated boilers which include the physical and chemical exergies were computed using the theoretical procedures given by equations (39) to (55) and previously computed thermodynamic properties of materials streams data given by Appendix Table 1 and are presented in Appendix Table 3 to 5. These comprise of exergetic computations in the combustion unit, heat exchanging unit and the entire boiler accordingly. The method used for the energy and exergy assessment of the boilers are summarised in Appendix Table 3 to 5. These includes evaluation of energy input, energy efficiency, exergy destruction and efficiency of the combustion unit; heat loss, energy efficiency, exergy destruction and efficiency of the heat exchanging unit; energy efficiency, overall exergy destruction and efficiency of the entire boiler.

Appendix Table 3: Summary of exergetic parameters of combustion unit

Exergetic equations	Exergetic Values and Efficiencies
1. Energy input (kJ/s)	
$E_{in} = \dot{m}_f h_f + \dot{m}_a h_a$	9740.97
2. Adiabatic energy efficiency (%)	
$\eta_C = \frac{\dot{m}_p h_p}{\dot{m}_f \times HHV}$	100.00
3. Exergy destruction (kJ/s)	
$\dot{I}_C = \dot{m}_a [(h_a - T_0 s_a) + \varepsilon_{a1}^{ch}] - \dot{m}_p (h_p - T_0 s_p) + \dot{m}_f [(h_f - T_0 s_f) + \varepsilon_{f2}^{ch} - \varepsilon_{f3}^{ch}]$	3103.92
4. Exergy efficiency (%)	
$\psi_C = \frac{\dot{m}_p (h_p - T_0 s_p)}{\dot{m}_f [(h_f - T_0 s_f) + \varepsilon_{f2}^{ch} - \varepsilon_{f3}^{ch}]}$	55.35

Appendix Table 4: Summary of exergetic parameters of heat exchanging unit

Exergetic equations	Exergetic Values and Efficiencies
1. Heat loss (kJ/s)	
$Q_{H(loss)} = \dot{m}_p(h_p - h_g) - \dot{m}_w(h_s - h_w)$	2969.19
2. Energy efficiency (%)	
$\eta_H = \frac{\dot{m}_w(h_s - h_w)}{\dot{m}_p(h_p - h_g)}$	66.69
3. Exergy destruction (kJ/s)	
$\dot{I}_H = \dot{m}_p(h_p - T_0s_p) + \dot{m}_w[(h_w - T_0s_w) + \epsilon_{w4}^{ch}] - \dot{m}_s[(h_s - T_0s_s) + \epsilon_{s5}^{ch}] - \dot{m}_g[(h_g - T_0s_g) + \epsilon_{g6}^{ch}]$	2182.44
4. Exergy efficiency (%)	
$\psi_H = \frac{\dot{m}_s[(h_s - T_0s_s) + \epsilon_{s5}^{ch}] - \dot{m}_w[(h_w - T_0s_w) + \epsilon_{w4}^{ch}]}{\dot{m}_p(h_p - T_0s_p) - \dot{m}_g[(h_g - T_0s_g) + \epsilon_{g6}^{ch}]}$	58.69

Appendix Table 5: Summary of exergetic parameters of entire boiler

Exergetic equations	Exergetic Values and Efficiencies
1. Energy efficiency (%)	
$\eta_B = \frac{\dot{m}_s (h_s - h_w)}{\dot{m}_f h_f}$	69.56
2. Overall exergy destruction (kJ/s)	
$\dot{I}_B = \dot{I}_C + \dot{I}_H$	5286.35
3. Overall exergy efficiency (%)	
$\psi_B = \frac{\dot{m}_s [(h_s - T_0 s_s) - (h_w - T_0 s_w) + \epsilon_{s5}^{ch} - \epsilon_{w4}^{ch}]}{\dot{m}_f [(h_f - T_0 s_f) + \epsilon_{f2}^{ch} - \epsilon_{f3}^{ch}]}$	38.57

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