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Heat and Mass Balance Calculations for Common Hazardous Waste Incinerator -Ship Scraping Waste

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Abstract— An estimate of heat and mass balance within a Hazardous Waste Incineration System is a very important part of designing and evaluating the performance of Incineration System. This study is focused on Heat and Mass Balance calculations to evaluate performance of existing hazardous waste incinerator for ship scraping waste, in terms of viz.: Theoretical Combustion Air requirement, Excess Air needed for actual combustion, Flue Gas composition and flow rates, Temperature in Secondary Combustion Chamber and at each stage, Residence time in Secondary combustion Chamber. Heat and mass balance are developed based on actual operating data and actual operating efficiency are evaluated in terms of temperature, residence time. The results of heat and mass balance indicates that 220 kg/h of incinerable hazardous ship scrap waste at fixed recipe needs 3565 kg/h combustion air and 24 kg/h of LDO as a fuel, with total heat capacity of 4582454 KJ/h to achieve temperature of 1150ºC in the secondary combustion chamber and detention time of 2.6 sec. Thus, it is the HW Incinerator in the study is designed and operated as per the guidelines of Central Pollution Control Board, India. The ttemperature and residence time achieved in the secondary combustion chamber are 1150ºC and 2.56 seconds respectively, which are well above the statutory requirement of 1100ºC, and 2 seconds.
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Index Terms— Incinerator, Hazardous Waste, Mass and Heat Balance,Calorific Value, Primary Combustion Chamber, Secondary Combustion Chamber, Ventury Scrubber, Pack Tower

1 INTRODUCTION

Incineration has been well recognized as one of the best demonstrated and available technologies for waste destruction. Incineration is an engineered process, with waste destruction being the ultimate goal. Its Function is to use direct either direct or indirect heat to break chemical structures of organic compounds, thus reducing the volume and toxicity of the remaining residuals.

From an engineering viewpoint, the basic objective of the incineration process is to efficiently; combust the material to an ash that is acceptable for land disposal while assuring that the exhaust gas products can likewise be dispersed without harm to the environment. Secondary objectives are to carry out the process with minimum energy usage and minimum system maintenance costs (2). Under normal conditions the incineration can dispose more than 99% of organic Waste(11).

An Estimation of mass and energy balance of an incinerator is an important consideration towards the design and operation of the incineration process (2). The mass and energy balance information enables the designer to calculate the amount of auxiliary fuel needed, amount of air needed for complete combustion, temperature profile across incineration system, the size and capacity of the incineration system, the flue gas composition at various stages of incineration viz. PM, SO_2, NOx, HCl, HF, Dioxins and Furans and control efficiencies required to control them in flue gases to meet the statutory norms. Conditions such as oxygen concentration, residence time, temperature and mixing turbulence are the governing factors for performance of incinerator.

This paper presents the results of Heat and Mass Balance carried out for Common Hazardous Waste Incineration Facility for Ship Scraping Waste". Every year on average 365 ships having a mean weight (2.10 · 106 ± 7.82 · 105 LDT) are scrapped. This industry generates a huge quantity of solid waste in the form of broken wood, rubber, insulation materials, paper, metals, glass and ceramics, plastics, leather, textiles, food waste, chemicals, paints, thermocol, sponge, ash, oil mixed sponges, miscellaneous combustible and non-combustible. The combustible solid waste quantity was around 83.0% of the total solid waste available at the yard.(12). The common incineration facility handles high CV combustible solid waste in the form of waste wood, plastic, insulation material, paper, glass wool, thermocol pieces (polyurethane foam material) sponge, oiled rope, cotton waste, rubber etc.

Common hazardous waste incineration facilities are designed based on assumptions regarding the availability of quantity and quality (characteristics) of waste. The actual operating waste recipe may differ considerably than the designed. An energy and mass balance procedure at actual plant operations recipe could be used to assess actual design adequacy/feasibility and identify weak points in terms of Conditions such as oxygen concentration, residence time, temperature , turbulence, flue gas compostion and thereby, identifying sensitive parameters.

2 METHODOLOGY

- A desk base study was carried out on available information of the site along with Incineration process details.
- Site visit and study the incineration system provided at the site with respect to capacity, type of waste charged, waste characteristics: i.e. Approximate and Proximate Analysis
- Carry out Mass balance of each component of the Inclination system w.r.t. the mass input to the mass output and the mass of remaining or generated from the system. This can be performed based on combustion reactions of Waste and Fuel with the Air.
- Perform energy balance of the system in accordance with the thermodynamics laws. The law of conservation of energy, which states that the total energy of an isolated system is constant. The energy cannot be created but can be transform from one form to another.
- Calculations for key parameters:
  - Theoretical Combustion Air
  - Excess Air needed fir actual combustion
  - Flue Gas composition and flow rates
  - Temperture in Secondary Combustion Chamber and at each stage
  - Residence time in Secondary combustion Chamber.

3 CASE STUDY

The mass and energy balance calculations for fixed bed common hazardous waste incinerator was conducted. The schemcatic of Incineration System is shown in Figure 1. The equipment details are presented at Table 1.

Table 1: Details of Incinerator

Capacity of Incineration System	The incinerator is designed for a capacity of 5 t/day (220 kg/h),
Type of unit	Dual chamber-static type
Pollution Control Systm	Venturi scrubber,Packed bed scrubber,ID fan ,HEPA Filter Chimney,On-line emission monitoring system
Primary Combustion Chamber:	
Temperature	Min.850^{0} C
Auxillary Fuel	90 kg/h LDO
Waste Blower	1 no. Of 4800 m3/h
Shell Volume:	11.40 m^3
Secondary Combustion Chamber:	
Temperature	Min.1100$\underline{+}$ 50 ^{0} C
Auxillary Fuel	24 kg/h LDO
Waste Blower	1 No. of 4800 m^3/h along with PC
Shell Volume:	11.40 m^3
Ventury Scrubber:	
Flue Gas Inside Temperature	1100± 50 ° C
Flue Gas Outside Temperature	80 - 90°C
Circulating Water Flow	10-12 m^3/hr.
Packed Bed Scrubber:	
Inlet Temp.:	80-90°C
Outlet Temp.	60-70°C
Water Circulating flow:	3 - 4.5 m^3/hr.

3.1 Mass & Heat Balance of Incineration System:

A mass and heat balance is an important part of designing and/or evaluating performance of Incineration system. The procedure entails mathematical evaluation of the input and output conditions of the Incinerator viz. excess air levels, temperatures, residence time and volumetric flow rates, based on design specifications and operating conditions.

Assumptions involved in incineration of combustible ship scrap waste:

1. Input temperature of waste, fuel and air is 30 °C.
2. Air contains 23% by weight O_2 and 77% by weight N_2.
3. Air contains 0.0132 kg H_2O/kg dry air at 60% relative humidity.
4. For any ideal gas 1 kg mole is equal to 22.1 m3 at 0°C and 101.3 kPa.
5. Latent heat of vaporization of water considered is 2460.3 KJ/kg.

Combustion Reactions :

The combustion reactions considered are as follows:

C	**+**	**O_2**	**+**	**$4N_2$**	→	**CO_2**	**+**	**$4N_2$**
12		32		4(28)		44		4(28)
1 Mole		1 Mole		4 Mole		1 Mole		4 Mole
$2H_2$		**O_2**		**$4N_2$**	→	**$2H_2O$**	**+**	**$4N_2$**
2		32		4(28)		2(18)		4(28)
1 Mole		0.5 Mole		2 Mole		1 Mole		2 Mole
S	**+**	**O_2**	**+**	**`$4N_2$**	→	**SO_2**	**+**	**$4N_2$**
32		32		4(28)		64		4(28)
1 Mole		1 Mole		4 Mole		1 Mole		4 Mole
C_2H_3Cl	**+**	**$2.5O_2$**		**`10N2**	→	**$2CO_2$**	**H_2O**	**HCl**
62.5		80		10(28)		2(44)	18	36.5
1 Mole		2.5 Mole		10 Mole		2 Mole	1 Mole	1 Mole

3.1.1 Mass Balance of the System

Mass balance of each component of the Inclination system is carried w.r.t. the mass input to the mass output and the mass of remaining or generated from the system. This is performed based on combustion reactions of Waste and Fuel with the Air.

3.1.1.1 Mass Input to Incinerator

Recipe for Incinerator

The ship breaking yards generate huge amount of Incinerble waste. Its quantity is around 83% of the total hazardous solid waste generated. It is in the form of insulation material, paper, thermocol pieces (polyurethane foam material), sponge, oiled rope, oiled soaked sand, cotton waste, rubber etc. These waste were analyzed individually, for Proximate and Approximate Analysis by standard ASTM Methods. These waste have CV's in the range from 4000-6000 Kcal/kg. A fixed recipe @ 4000 kcal/kg is considered for incineration and is presented below in Table No. 2.

Table 2: Recipe for Incinerator

Recipe for Incineration Considered	Composition (%)	GCV (kcal/kg)	C (%)	S (%)	H (%)	O (%)	Cl (%)	N (%)	Moisture (%)	Ash (%)
Plastic & Rubber	15	5977	70.3	1.5	10.7	12.3	--	2.5	0.33	2.3
Oil socked Sand	15	5399	67.8	1.1	1.2	10.2	0.8	0.1	8.00	10.8
PUFF &Thermocol	40	5137	58.7	0.7	3.1	16.1	1.9	1	6.24	12.3
Mis.	30	4000	55.1	0.2	2.8	15.0	0.5	4.1	11.80	10.5
Composition of Receipe	**4961.1**	**60.73**	**0.73**	**3.87**	**14.32**	**1.03**		**2.02**	**10.04**	

The Air Supply

The air is supplied to the incinerator by using blower of capacity 4800 m3/h, by two motors installed sideways of the incinerator. The one connected at right hand side is supplying the staved air thro the primary chamber, above and below the grate in the primary chamber. The excess air is supplied to the secondary chamber by the right hand side blower through the pipe closer to the exit of the chamber.

The Fuel Consumed

The diesel is used to heat up i.e. start up the incinerator before putting waste and for achieving secondary temp. The diesel is having CV of 10000 Kcal/kg. The density of diesel considered is 850 kg/m3.

3.1.1.2 Mass Output from Incinerator

Flue Gases:

Complete combustion of waste and fuel is assumed to be converted in to products viz. CO_2, H_2O, N_2, SO_2, and HCl. The mass concentration of flue gases constituent are estimated considering the removal efficiency of control equipment.

Bottom Ash

The mass flow rate of Ash was found to be 21 kg/h. The bottom ash generation was considered to be 5% of total ash generation

3.1.1.2 Heat Balance of the System:

The energy balance of the system is done in accordance with the thermodynamics laws. The law of conservation of energy, which states that the total energy of an isolated system is constant. The energy cannot be created but can be transform from one form to another.

4 RESULTS & DISCUSSIONS

The stagewise results of the mass and heat balance across incineration system are presented in Table 3 and Table 4 and block diagram is shown at Fig. 2. The overall results are discussed hereunder:

Table 3: Results of Heat and Mass Balance

Mass Balance for Primary Combustion Chamber:

Input	Quantity (kg/h)		Output	Quantity (kg/h)
Hazardous Waste	220	Primary Combustion Chamber	**Removed from Bottom**	
Air (50% Excess)	3025		Bottom Ash	21
Auxillary Fuel (LDO)	0		**To Secondary Combustion**	
			Mass	3223
			Particulates	1
TOTAL	**3245**		**TOTAL**	**3245**

Mass Balance for Secondary Combustion Chamber:

Input	Quantity (kg/h)		Output	Quantity (kg/h)
Mass from Primary	3224	Secondary Combustion Chamber	**To Ventury**	
Fuel (LDO)	24		Mass	3787
Air (20% Excess)	540		Particulates (	1.33
TOTAL	**3788**		**TOTAL**	**3788**

Mass Balance for Quench Tower:

Input	Quantity (kg/h)		Output	Quantity (kg/h)
Mass from Secondary	3789	Ventury Scrubber	To ETP	11712
Water + Caustic	11928		**To Packed Tower**	
			Mass	4005
TOTAL	**15717**		**TOTAL**	**15717**

Mass Balance for Packed Tower:

Input	Quantity (kg/h)		Output	Quantity (kg/h)
Mass from Venturi	4005	**Packed Tower**	To ETP	4213
Water	4200		**To HEPA Filter**	
			Mass	3992
TOTAL	**8205**		**TOTAL**	**8205**

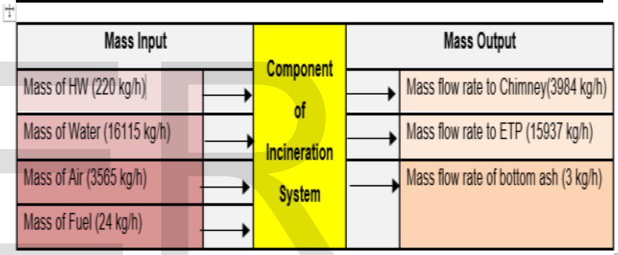
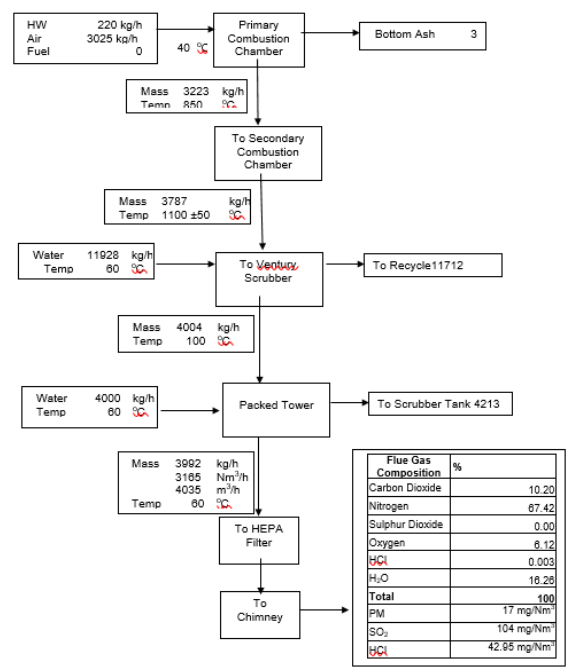


Fig. 2 Block Diagram of Mass Balance



The results of mass balance indicates that 220 kg/h of incinerable hazardous ship scrap waste at fixed recipe needs 3565 kg/h combustion air and 24 kg/h of LDO as a fuel in the secondary combustion chamber to achieve temperature of 1150^{o}C. The Flue gas consist of CO2-10.20 %, O2- 6.12 %, N2 -67.42 % by volume. To cool the combustion gases from secondary chamber from 1150^{o}C to 100^{o}C requires about 11915 kg/h water in the Ventury Scrubber. The scrubber water required for pack tower is 4200 kg/h.

The mass flow rate in the secondary combustion chamber works out to be 4.37 m^3/sec at 1150^{o}C temperature. The shell volume provided in the secondary combustion chamber is 11.40 m3. So the detention time achieved in the secondary chamber works out to be 2.6 sec.

Table 4: Results of Heat Balance

Heat Balance for Primary Combustion Chamber:

Heat Input	Quantity (kJ/h)		Heat Output (@ 850°C)	Quantity (kJ/h)
Heat in form of Waste	3620153	Primary Combustion Chamber	Radiation Loss @ 5%	181008
			Heat to Ash	2264
			Heat to Dry Combustion Products	2770424
			Heat to the moisture	490587
			Balance Energy carry forwarded to Secondary Chamber	175869
TOTAL	**3620153**		**TOTAL**	**3620153**

Heat Balance for Secondary Combustion Chamber:

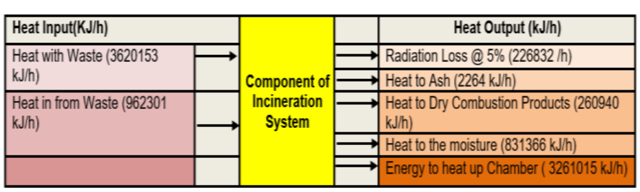
Heat Input	Quantity (kJ/h)		Heat Output (@ 1150°C)	Quantity (kJ/h)
Heat Capacity from Primary Chamber	175869	Secondary Combustion Chamber	Radiation Loss	45824
			Heat to Dry Combustion Products	1013570
Heat Capacity with Fuel	962301		Heat to Moisture	78777
TOTAL	**1138170**		**TOTAL**	**1138170**

Heat Balance for Ventury:

Heat Input	Quantity (kJ/h)		Heat Output	Quantity (kJ/h)
Heat to Dry Combustion Products	1013570	**Ventury Scrubber**	Heat with Dry Combustion Products	308468
			Heat Removed in Ventury	783878
Heat to Moisture	78777			
TOTAL	**1092347**		**TOTAL**	**1092347**

Heat Balance for Packed Tower:

Heat Input	Quantity (kJ/h)		Heat Output	Quantity (kJ/h)
Heat with Dry Combustion Products	308468	**Packed Tower**	Heat with Dry Combustion Products	260940
			Heat Removed in Packed Tower	47528
TOTAL	**308468**		**TOTAL**	**308468**



The results of heat balance indicates that combustion of 220 kg/h of incinerable HW of ship scraping waste at fixed recipe of 4000 kcal/kg generates 3620153 KJ/h heat and it further requires fuel in the secondary combustion chamber i.e. LDO @ 24 kg/h with heat capacity of 962301 KJ/h, to achieve temperature of 1150^{o}C.

This indicates that approximately 4582454 KJ/h heat capacity is required to incinerate 220 kg/h of incinerable HW of ship scraping waste at fixed recipe of 4000 kcal/kg. There works out to be 20830 KJ energy is required to incinerate a kg of waste. The heat loss to radiation is 5% , heat loss to ash is 0.05%, with dry flue gas is 6% and with scrubber water is 18%.

5 Conclusion

The results of heat and mass balance indicates that 220 kg/h of incinerable hazardous ship scrap waste at fixed recipe needs 3565 kg/h combustion air and 24 kg/h of LDO as a fuel, with total heat capacity of 4582454 KJ/h to achieve temperature of 1150^{o}C in the secondary combustion chamber and detention time of 2.6 sec. Thus, the HW Incinerator in the study is designed and operated as per the guidelines of Central Pollution control board, India. The temperature and residence time achieved in the secondary combustion chamber are 1150oC and 2.56 seconds respectively, which are well above the statutory requirement of 1100oC, and 2 seconds.

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ABBREVIATIONS:

CPCB	:	Central Pollution Control Board
CV	:	Calorific Value
GCV	:	Gross Calorific Value
HW	:	Hazardous Waste
LDO		Light Diesel Volume
PT	:	Pack Tower
PC	:	Primary Chamber
PCBs	:	Poly Chlorinated Benzens
VS	:	Ventury Scrubber
SC	:	Secondary Chamber

Figure 1: Schematic Block Diagram of Incineration System