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Review of Thermal Characteristics of Diesel Fired Boiler for Steam Turbine Test Rig

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Abstract —*The economy and feasibility of a power plant is determined by the gross efficiency of the plant and plant load factor. A power plant is majorly demarcated into three parts namely Boiler Island, Turbine Island and BOP-Balance of Plant. The gross efficiency of plant is the function of efficiency of each component namely boiler, turbine, condenser, in-house power consuming unit (boiler feed pump) and other auxiliaries.*

This paper is a review on thermal characteristics namely thermal efficiency, heat distribution trend in the boiler and heat inertia of boiler which are critical in a power plant. The observation and data is collected from an experiment on an experimental steam turbine test rig established at Department of Mechanical Engineering of M. S. University. The heat distribution among the fluids is calculated, the amount of uncalculated heat lost in radiation, convection and leakage is determine and a comparison review is made on each part. The observed trend gives a clearer idea of the nature of the processes occurring inside the boiler.

Keywords*- Boiler, Direct Thermal Efficiency, Heat Balance Sheet, Heat Loss, High Speed Diesel Fuel, Separating and Throttling Calorimeter, Heat Inertia*

I. INTRODUCTION.

Thermal characteristics of a boiler play a vital role in determining the overall efficiency and thus the economy of boiler. The efficiency of boiler is directly related to the nature of combustion occurring inside the boiler. The conclusion derived in the report gives an idea of the nature of thermodynamic process occurring inside the boiler by discussing heat distribution trend, direct thermal efficiency of boiler and effect of heat inertia of boiler.

II. TEST RIG.

The test rig consists of an impulse type steam turbine with two nozzles, a boiler and a condenser unit. Suitable taps are provided in the main steam line from the boiler to sample the stream of steam and determine its quality and to measure its pressure and temperature. A separating and throttling type calorimeter is installed to measure state of the steam leaving the boiler.

Figure 2.1. Diesel test rig setup

III. BOILER.

Figure 3.1. Diesel fired boiler

The diesel fired boiler generating steam from the water and is supplied to the plant through an overhead and calibrated water tank. Cross section area of water tank (Aw) is measured. Change of the level (Δlw,1) in the tank for a given duration of time (tw,1) which is used to determine the mass flow rate of feed water going in to the steam boiler (mw,1) is recorded during study.

High Speed Diesel ($C_{12}H_{25}$) is supplied to the boiler through a separate fuel tank. Cross section area of fuel tank (A_f) is measured. Change in level of the fuel ($\Delta l_{f,1}$) in the tank during time ($t_{f,1}$) is used to determine the mass flow rate of fuel consumed at the boiler ($m_{f,1}$) is also recorded.

The air supplied for combustion in the boiler is supplied by the forced draft type air blower unit. Cross section area for air intake manifold is calculated ($A_{a,1}$). The measure of velocity of air entering at the suction of blower ($V_{a,1}$) was measured by a turbine type flow meter and recorded.

Temperature of combustion air ($T_{g,1}$) and barometric pressure reading for the laboratory ($P_{g,1}$) is measured at the start of the study. based on this mass of air taking part in the combustion process and entering at the combustion chamber of boiler can be estimated.

Sensible enthalpy of water stored in tank ($h_{w,1}$) and entering the boiler is estimated based on the temperature of water and inside the reservoirs. The diesel fired boiler generating steam from the water which is supplied to the plant through an overhead and calibrated water tank. Cross section area of water tank (A_w) is measured. Change of the level ($\Delta l_{w,1}$) in the tank for a given duration of time ($t_{w,1}$) which is used to determine the mass flow rate of feed water going in to the steam boiler ($m_{w,1}$).

High Speed Diesel ($C_{12}H_{25}$) is supplied to the boiler through fuel tank. Cross section area of fuel tank (A_f) is measured. Change in level of the fuel ($\Delta l_{f,1}$) in the tank during time ($t_{f,1}$) is used to determine the mass flow rate of fuel consumed at the boiler ($m_{f.1}$).

The air for combustion in the boiler is supplied by the forced draft type air blower. The measure of velocity of air entering at the suction of blower ($V_{a,1}$) can be measured by a turbine type flow meter. Cross section area for air intake manifold is calculated ($A_{a,1}$).

Temperature of combustion air ($T_{g,1}$) and barometric pressure ($P_{g,1}$) is measured based on which mass of air for combustion going at the boiler can be estimated.

Enthalpy of water in tank ($h_{w,1}$) is determined from condition of water inside the reservoirs.

IV. SEPARATING AND THROTTLING CALORIMETER.

Figure 4.1. Separating and throttling calorimeter

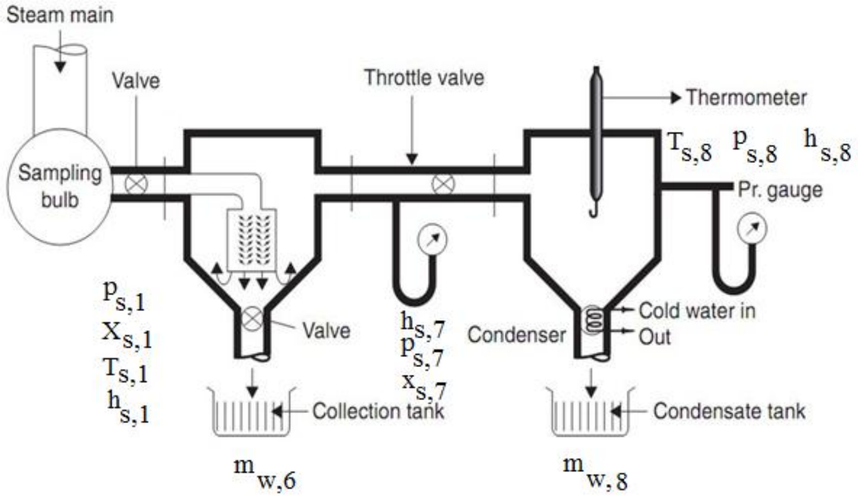

Figure 4.2. Schematic of separating and throttling calorimeter [1].

To determine overall performance of the steam power plant, determining the exact state of steam generated in the boiler is very essential. This is achieved by using calorimeter, separating and throttling calorimeter (S&TC) in the present case. The accuracy of measurement while measuring with only separating calorimeter is low, especially when handling steam with high moisture content, and therefore, this type of calorimeter only gives an approximate estimation of the dryness fraction of the steam. Unlike this, predictions using S&TC type calorimeter is highly accurate.

The steam at pressure ($P_{s,1}$) and temperature ($T_{s,1}$) with steam quality ($X_{s,1}$) is allowed to enter first in a separating type calorimeter. The steam is forced to make a sharp turn when it hits the perforated cup (or any other mechanism that produces the same effect that brings down to its instantaneous velocity to almost zero). These results in a vortex motion in the steam, due to this the tiny water particles are separated and drop down due to the centrifugal action. The droplets then remain inside the separator and are collected at the bottom (w,6) the quantity of which is recorded. The steam leaving the separating calorimeter would be of higher dryness fraction (X_7) compared to that it entered with. Pressure and temperature change during this process is considered as negligible. The steam then passes to a throttling valve. Relatively dry steam at enthalpy (h_7) is allowed to enter the throttling valve where steam is allowed to undergo a throttling process (i.e. ideally it is allowed to throttle against atmospheric pressure) this is achieved by allowing steam to pass from a very small orifice. The pressure ($P_{s,8}$) and temperature ($T_{s,8}$) after throttle is measured to determine the enthalpy of the steam (h_8). Balancing the enthalpy before and after throttling will enable to determine the dryness fraction of steam entering throttling process and the state of the steam can then be determined by considering the total mass of the moisture in the steam as mass of moisture collected at the separating stage and at obtained at entry of throttling stage.

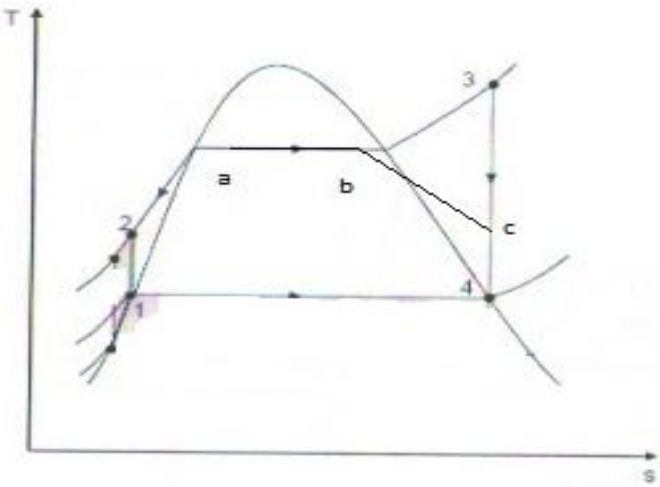

Figure 4.3. Process in S&TC on T-S chart

The process of S&TC is shown on the P-V diagram. Sate A, B and C are the state at the entry of separating calorimeter, exit of separating calorimeter and at the exit of throttling calorimeter respectively.

V. PAREMETERS: DESIGNATION AND DESCRIPTION.

Table 5.1. Important physical parameters at setup.

Parameter	Description	Remark/ Value
D_w	Diameter of water tank (mm)	1350 mm
L_f	Width of square fuel tank (mm)	735 mm
D_a	Diameter of air inlet duct for boiler (mm)	150 mm

Table 5.2. Inlet air parameters.

Parameter	Description	Remark/ Value
$P_{a,1}$	Barometric pressure of ambient air (bar)	1.013 bar
$T_{a,1}$	Temperature of ambient air (ºC)	32 ºC
$R_{a,1}$	Gas constant for air (J/kg k)	287.058 J/kg k
$\rho_{a,1}$	Density of air at boiler inlet (kg/m3)	1.156 kg/m^3
$A_{a,1}$	Cross section area of air duct at boiler inlet (m^2)	0.0086590 m^2
$V_{a,1}$	Velocity of air at entry of boiler (m/s)	
$m_{a,1}$	Mass flow rate of air at the inlet of boiler (kg/s)	
C_a	Specific heat of air (kJ/kg k)	1.005 kJ/kg k

Table 5.3. Feed water parameters.

Parameter	Description	Remark/ Value
$P_{w,1}$	Barometric pressure of feed water (bar)	
$T_{w,1}$	Temperature of water at feed water reservoir (ºC)	30 ºC
$t_{w,1}$	Time required to measure the change in the level of water tank (min)	
$\Delta L_{w,1}$	Change of water level at the boiler feed water tank (cm)	
$Q_{w,1}$	Volumetric flow rate of feed water (m^3/s)	
$m_{w,1}$	Mass flow rate of feed water (kg/s)	
$h_{w,1}$	Specific enthalpy of feed water in reservoir (kJ/kg)	

Table 5.4. Fuel parameters.

Parameter	Description	Remark/ Value
$P_{f,1}$	Barometric pressure of injecting fuel (bar)	
$\Delta L_{f,1}$	Change of fuel level at the boiler fuel feed tank (m)	
$t_{f,1}$	Time required to measure the change in the level of fuel tank (min)	Same as $t_{w,1}$
$Q_{f,1}$	Volumetric flow rate of fuel (m3/s)	
$m_{f,1}$	Mass flow rate of fuel (kg/s)	
GC	Gross calorific value of fuel (kJ/kg)	45,187 kJ/kg [2].
$\rho_{f,1}$	Density of fuel (kg/m^3)	840 kg/m^3 (average.) [3].

Table 5.5. Flue Gases and Moisture Parameters.

Parameter	Description	Remark/ Value
$m_{g,1}$	Mass flow rate of flue gases produced (kg/s)	
m_m	Mass flow rate of moisture content in flue gases (kg/s)	
$T_{g,1}$	Temperature of flue gases (ºC)	
$P_{g,1}$	Pressure of flue gases at exit (bar)	1.013 bar (as ambient)
P_m	Partial pressure of moisture in flue gases (bar)	0.28526 bar
C_m	Specific heat of moisture (kJ/kg k)	1.12J/kg k [4].
ΔH_g	Enthalpy change in flue gases (kJ)	
h_m	Specific enthalpy of moisture (kJ/kg)	
ΔH_m	Enthalpy carried by moisture (kJ)	

Table 5.6. Steam parameters.

Parameter	Description	Remark/ Value
$P_{s,1}$	Pressure of steam produced (bar)	
$T_{s,1}$	Temperature of steam produced (ºC)	
$h_{s,1}$	Specific enthalpy of steam at boiler outlet (kJ/kg)	
h_7	Specific enthalpy of steam before throttling (kJ/kg)	
h_8	Specific enthalpy of steam after throttling (kJ/kg)	
$m_{w,6}$	Mass of water collected at the separating calorimeter (kg/s)	
$m_{w,8}$	Mass of water collected at the throttling calorimeter (kg/s)	
$t_{s,1}$	Time required to conduct the operations of calorimeter (s)	
x_1	Dryness fraction of water leaving boiler (-)	
x_7	Dryness fraction of steam before throttling (-)	
ΔH_s	Enthalpy change from water to steam (kJ)	

VI. SAMPLE CALCULATION

6.1. Flow Rate Calculation.

Steam Consumption:
$m_{w,1} = (\Delta l_{w,1} \text{ x } A_w) / t_{w,1}$

Fuel Consumption:
$m_{f,1} = (\Delta l_{f,1} \text{ x } A_f) / t_{f,1}$

Mass Flow Rate of Air:
$P_{a,1}=\rho_{a,1} \text{ x } R_{a,1} \text{ x } T_{a,1}$
$\rho_{a,1}= P_{a,1} /(R_{a,1} \text{ x } T_{a,1})$
ma,1= $\rho_{a,1} \text{ x } A_{a,1} \text{ x } V_{a,1}$

6.2. Calorimeter Calculations.

Enthalpy of the steam before throttling:
$h_7 = h_{f7} + X_7 h_{fg7}$

Enthalpy of steam after throttling:
$h_8 = h_{f,8} + h_{fg,8} + Cp_s*(t_{sup,8} – t_{sat,8})$

Dryness fraction of steam before throttling (h_7) is calculated by equating above two equations.

Dryness fraction of steam is determined as:
$X_{s,1} =X_7 \text{ x } m_{w,8}/(m_{w,6}+m_{w,8})$ [1].

Enthalpy of generated steam ($h_{s,1}$) and that of feed water ($h_{w,1}$) is determined by steam table.

6.3. Direct Thermal Efficiency.

$\eta = [m_{w,1} \text{ x } (h_{s,1}-h_{w,1}) \text{ x } 100]/[m_{f,1}*GC]$ [5].

VII. CALCULATION TABLE

Table 7.1. Inlet air and feed water calculations.

INLET AIR			FEED WATER					
Sr. No.	$V_{a,1}$ (m/s)	$m_{a,1}$ (m/s)	$P_{w,1}$ (bar)	$T_{w,1}$ (°C)	$t_{w,1}$ (min)	$\Delta L_{w,1}$ (cm)	$Q_{w,1}$ (m^3/s)	$m_{w,1}$ (kg/s)
1	-	-	-	-	0.00	118.00	-	-
2	16.65	0.34027	7.00	30.00	4.00	113.00	0.000298326	0.298325875
3	18.60	0.38012	10.00	30.00	8.00	108.00	0.000298326	0.298325875
4	17.45	0.35662	11.25	30.00	12.00	102.00	0.000357991	0.35799105
5	16.55	0.33822	11.75	30.00	16.00	98.00	0.000238661	0.2386607
6	20.11	0.41098	12.50	30.00	20.00	93.00	0.000298326	0.298325875
7	17.25	0.35253	12.75	30.00	24.00	88.00	0.000298326	0.298325875
8	14.65	0.29939	14.00	30.00	28.00	84.00	0.000238661	0.2386607
9	19.67	0.40198	12.75	30.00	32.00	78.00	0.000357991	0.35799105
10	18.62	0.38053	12.50	30.00	36.00	73.00	0.000298326	0.298325875
11	11.45	0.23400	12.50	30.00	40.00	68.00	0.000298326	0.298325875
12	11.00	0.22480	12.00	30.00	44.00	63.00	0.000298326	0.298325875
13	18.55	0.37910	11.50	30.00	48.00	58.00	0.000298326	0.298325875
14	17.40	0.35559	11.00	30.00	52.00	53.00	0.000298326	0.298325875
15	17.55	0.35866	10.00	30.00	56.00	48.00	0.000298326	0.298325875
16	16.90	0.34538	8.50	30.00	60.00	43.00	0.000298326	0.298325875
17	15.55	0.31779	12.75	30.00	64.00	38.00	0.000298326	0.298325875

Table 7.2. Fuel and flue gases calculations.

	FUEL					FLUE GASES AND MOISTURE		
Sr. No.	$P_{f,1}$ (bar)	$T_{f,1}$ (°C)	$\Delta L_{f,1}$ (cm)	$Q_{f,1}$ (m^3/s)	$m_{f,1}$ (kg/s)	$M_{g,1}$ (kg/s)	M_m (kg/s)	$T_{g,1}$ (°C)
1	-	0	30	-	-	-	-	-
2	15	4	28.7	2.92622E-05	0.024580238	0.364846773	0.030467696	117
3	13	8	27.3	3.15131E-05	0.026471025	0.406588596	0.032811365	111
4	-	12	26	2.92622E-05	0.024580238	0.381195916	0.030467696	119
5	14.5	16	24.8	2.70113E-05	0.02268945	0.360912343	0.028124027	121
6	-	20	23.3	3.37641E-05	0.028361813	0.439338391	0.035155034	123
7	15	24	22.1	2.70113E-05	0.02268945	0.375217843	0.028124027	121
8	11	28	20.8	2.92622E-05	0.024580238	0.323973916	0.030467696	120
9	-	32	19.4	3.15131E-05	0.026471025	0.428455575	0.032811365	121
10	-	36	18	3.15131E-05	0.026471025	0.406997325	0.032811365	126
11	12	40	17.2	1.80075E-05	0.0151263	0.249123407	0.018749351	129
12	-	44	16.4	1.80075E-05	0.0151263	0.239927014	0.018749351	122
13	14.5	48	15	3.15131E-05	0.026471025	0.405566775	0.032811365	129
14	14.5	52	13.7	2.92622E-05	0.024580238	0.380174095	0.030467696	124
15	14.5	56	12.3	3.15131E-05	0.026471025	0.385130346	0.032811365	125
16	12.5	60	11.1	2.70113E-05	0.02268945	0.368065093	0.028124027	127
17	90	64	10	2.47603E-05	0.020798663	0.338585127	0.025780358	125

Table 7.3. Steam property calculations.

STEAM GENERATED					
$P_{s,1}$ (bar)	$T_{s,1}$ (°C)	X_1	T_{sat} (°C)	Nature of steam	$h_{s,1}$ (kJ/kg) [6].
-	-	-	-	-	-
6.867	164	0.9494	164.14	Wet	2656.2674
9.3195	183	-	176.809	Super heated	2786.5411
10.791	183	0.9577	183.178	Wet	2694.01
11.281	185	0.9654	185.14	Wet	2711.2728
11.772	187	0.9658	187.03	Wet	2713.8897

12.26	195	-	188.86	Super heated	2796.21
13.48	194	-	193.21	Super heated	2788.26
12.26	193	-	188.86	Super heated	2792.014
11.772	187	0.964 4	187.03	Wet	2711.0996
12.02	188	9471	188	Wet	2677.6903
11.28	185	-	185.15	Super heated	2780.7476
10.791	183.2	0.953	183.18	Wet	2684.5965
10.54	182	-	182.12	Super heated	2776.3495
9.3195	178	-	176.81	Super heated	2776.0474
7.848	174	-	169.57	Super heated	2775.803
7.5	170	0.955 1	188.88	Wet	2770

VIII. ENTHALPY CALCULATION

Table 8.1. Enthalpy used to convert water into steam.

$P_{w,1}$ (bar)	$T_{w,1}$ (°C)	$h_{w,1}$ (kJ/kg)	$h_{s,1}$ (kJ/kg)	$m_{w,1}$ (kg/s)	ΔH_s (kJ) [6].
7	30	126.379	2656.27	0.298325875	754.73
10	30	126.653	2786.54	0.298325875	793.51
11.25	30	126.767	2694.01	0.35799105	919.05
11.75	30	126.813	2711.27	0.2386607	616.81
12.5	30	126.88	2713.89	0.298325875	771.77
12.75	30	126.904	2796.21	0.298325875	796.32
14	30	127.017	2788.26	0.2386607	635.13
12.75	30	126.904	2792.01	0.35799105	954.09
12.5	30	126.88	2711.10	0.298325875	770.94
12.5	30	126.88	2677.69	0.298325875	760.97
12	30	126.835	2780.75	0.298325875	791.73
11.5	30	126.789	2684.60	0.298325875	763.06
11	30	126.744	2776.35	0.298325875	790.45
10	30	126.653	2776.05	0.298325875	790.38
8.5	30	126.516	2775.80	0.298325875	790.35
12.75	30	126.904	2770.00	0.298325875	788.50

Table 8.2. Enthalpy carried away by gases.

$T_{a,1}$ (°C)	$T_{g,1}$ (°C)	C_m (kJ/kg k)	C_a (kJ/kg k)	$m_{a,1}$(kg/s)	$m_{f,1}$(kg/s)	$m_{g,1}$(kg/s)	ΔH_g(kJ) [6].
32	117	1.12	1.005	0.340	0.025	0.365	36.867
32	111	1.12	1.005	0.380	0.026	0.407	38.323
32	119	1.12	1.005	0.357	0.025	0.381	39.337
32	121	1.12	1.005	0.338	0.023	0.361	38.034
32	123	1.12	1.005	0.411	0.028	0.439	47.306
32	121	1.12	1.005	0.353	0.023	0.375	39.512
32	120	1.12	1.005	0.299	0.025	0.324	33.914
32	121	1.12	1.005	0.402	0.026	0.428	45.136
32	126	1.12	1.005	0.381	0.026	0.407	45.198
32	129	1.12	1.005	0.234	0.015	0.249	28.468
32	122	1.12	1.005	0.225	0.015	0.240	25.554
32	129	1.12	1.005	0.379	0.026	0.406	46.405
32	124	1.12	1.005	0.356	0.025	0.380	41.363
32	125	1.12	1.005	0.359	0.026	0.385	42.384
32	127	1.12	1.005	0.345	0.023	0.368	41.246
32	125	1.12	1.005	0.318	0.021	0.339	37.182

Table 8.2. Enthalpy carried away by moisture in gases.

P_m (bar)	$T_{g,1}$ (°C)	h_m (kJ/kg)	m_m (kg/s)	ΔH_m (kJ) [6].
0.285	117	2388.21	0.0305	72.76
0.285	111	2382.18	0.0328	78.16
0.285	119	2390.22	0.0305	72.82
0.285	121	2392.22	0.0281	67.28
0.285	123	2394.23	0.0352	84.17
0.285	121	2392.22	0.0281	67.28
0.285	120	2391.22	0.0305	72.85
0.285	121	2392.22	0.0328	78.49
0.285	126	2397.24	0.0328	78.66
0.285	129	2400.26	0.0187	45.00
0.285	122	2393.23	0.0187	44.87
0.285	129	2400.26	0.0328	78.76
0.285	124	2395.24	0.0305	72.98
0.285	125	2396.24	0.0328	78.62
0.285	127	2398.25	0.0281	67.45
0.285	125	2396.24	0.0258	61.78

IX. RESULT TABLE AND HEAT DISTRIBUTION TREND

Table 9.1. Heat balance sheet.

Sr. No.	Gross enthalpy of fuel ΔH_{gross} (kJ) = $m_{f,1}$ x GC	Heat used to convert water to steam ΔH_s (kJ)	Heat carried away by flue gases ΔH_g (kJ)	Heat carried away by moisture ΔH_m (kJ)	Uncalculated heat loss ΔH_l (kJ)	Efficiency η (-)
1	1110.707	754.731	36.867	72.763	254.040	67.48
2	1196.146	793.513	38.323	78.163	281.197	66.61
3	1110.707	919.050	39.337	72.824	74.899	83.09
4	1025.268	616.809	38.034	67.279	298.904	60.41
5	1281.585	771.772	47.306	84.169	373.034	60.47
6	1025.268	796.323	39.512	67.279	117.911	77.99
7	1110.707	635.134	33.914	72.855	364.208	57.42
8	1196.146	954.086	45.136	78.492	113.482	80.09
9	1196.146	770.940	45.198	78.657	296.402	64.72
10	683.512	760.973	28.468	45.003	-153.760	111.80
11	683.512	791.731	25.554	44.871	-181.473	116.31
12	1196.146	763.060	46.405	78.756	302.976	64.06
13	1110.707	790.446	41.363	72.977	201.325	71.46
14	1196.146	790.383	42.384	78.624	279.806	66.35
15	1025.268	790.351	41.246	67.448	121.980	77.41
16	939.829	788.504	37.182	61.776	48.478	84.25

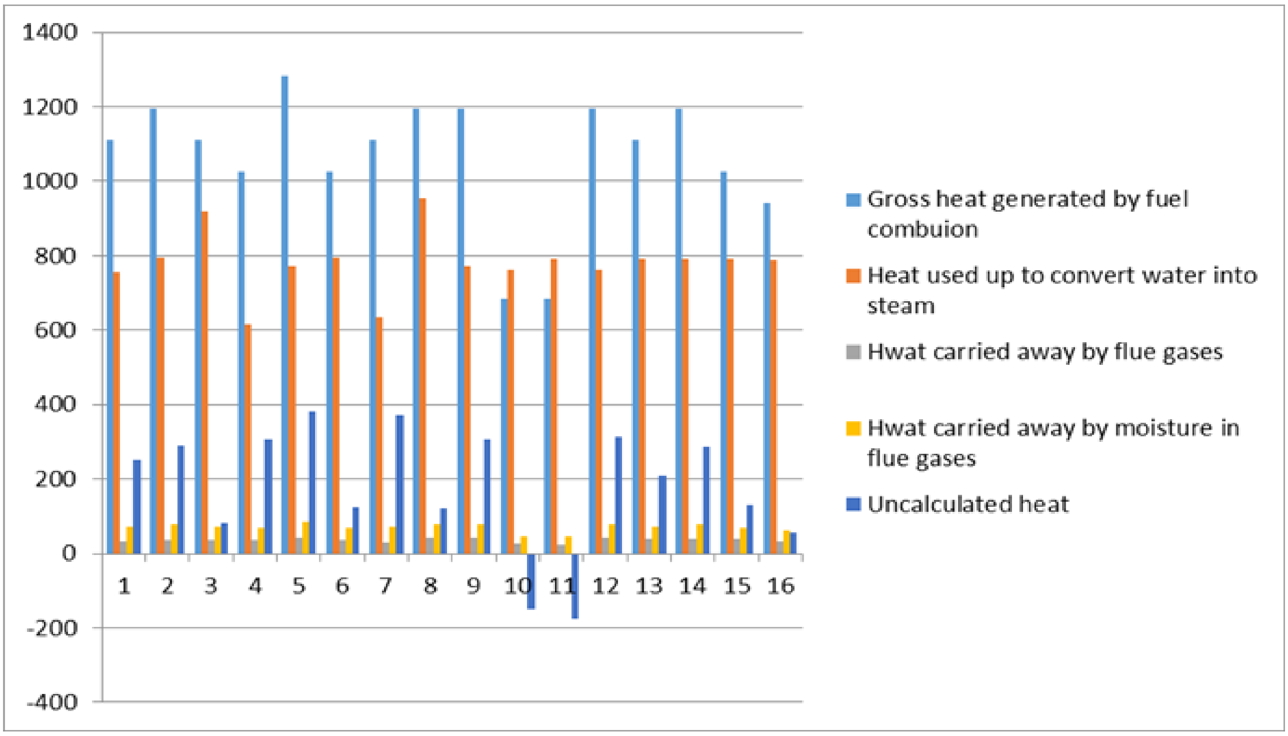

Figure 9.1. Heat distribution trend

Fig 9.1. Illustrates a typical heat distribution trend in a boiler. The gross heat generated by burning off the fuel is determined and the heat absorbed in major three parts is shown.

X. CONCLUSION

10.1. Limitation.

The power rig is not an actual power plant but is an experimental setup. It differs with actual power plant in some aspects and the repercussion of which are as follows:

10.1.1. Limitation due to sampling method.

Unlike sampling method used in actual power plant, there is no enough time given to completely wear off quenching effect of the pipeline and instruments used in sampling. Hence, the quality of steam measured is slightly differed from actual value.

10.1.2. Limitation due to type of fuel used.

The fuel used in experiment is High Speed Diesel (HSD) which has higher gross calorific value than actual fuel used viz. Furnace Oil (FO) or Light Diesel Oil (LDO). Hence, the atomization of fuel and the combustion efficiency slightly differs from commercially operating plants.

10.2. Findings.

10.2.1. Heat distribution trend and efficiency.

The heat used up in conversion of water into steam is, on average, 70%. Heat taken away by flue gases and moisture present in it is, on average, 10% collectively. The balance, 20% is uncalculated heat which is heat loss in boiler. The heat loss is majorly as heat loss by convection, heat loss by radiation and heat carried away by leaked fluid.

10.2.2. Heat inertia of boiler.

Observation 10th and 11th (marked red) shows negative uncalculated heat loss and efficiency more than 100% which implies that gross heat generated by burning of fuel is less than total heat distributed. Hence, the net heat distribution must reduce while it increases when the fuel supply is decreased. This is due to the heat inertia inside boiler. When the fuel supply is reduced which results in reduction in heat supplied, the heat energy already present in the furnace of boiler accounts for this instantaneous instability. As time progresses, the heat inertia is reduced by the continuous flow of fluids until the steady state is reached which tries to maintain equilibrium with the heat produced by burning of fuel.

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