Use of Energy and Exergy Analysis in Coal Fired Boiler

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***Abstract*— Overreliance on energy from coal is unsustainable because of their regional depletion and associated environmental impacts. Effective utilization of available energy and its management for minimizing irreversibility has made power plant engineers to look for efficient energy consumption & conversion. This study deals with the energy and exergy analysis of a 500 MW coal fired boiler in design and off design condition at constant pressure mode of operation. Locations and magnitude of exergy destruction is evaluated in the boiler and found that the major exergy destruction occurs at combustor followed by heat exchanger. The analyses have been performed by component wise modeling and simulation of the boiler and its heating surfaces. The results of energy and exergy efficiencies of boiler at design condition are found to be 85.54 % and 41.81 %, whereas at 80 % and 60% off design case energy efficiency increases to 85.77% and 85.71% respectively. The exergy efficiency at off design condition is 41.64% and 41.59% respectively.**

***Keywords*– Boiler Losses, Design, Off Design, Energy and Exergy**

I. INTRODUCTION

Since the energy sources in coal fired thermal power plants generally use boiler- steam turbine system to convert its chemical potential energy to electricity generation, one can only imagine the possible way of savings derivable from improving the efficiency of a steam boiler by just a small fraction. Boiler efficiency has a great influence on heating related energy savings. It is therefore important to maximize the heat transfer to the water and minimize the heat loss in the boiler. In order to optimize the boiler operation it is necessary to identify the areas to achieve the saving potential by minimizing the losses [1]. From second law analysis (entropy or exergy analysis) it is generally known that thermodynamic losses of boilers and furnaces are much higher than the thermal efficiencies. With thermal losses of around 5 % the thermodynamic losses (exergy losses) of a boiler can be 50 % or more. The combustion process is responsible for a significant part of these losses [2].

Growing concerns about energy savings have led to the development of analysis techniques based on second law of thermodynamics. Exergy is a combination property of a system and its environment because unlike energy it depends on the state of both the system and environment. The exergetic performance analysis has found as useful method in the design, evaluation and optimization of thermal power plants. This method can able to determine magnitudes, location and cause of irreversibility in the plant along with individual component efficiency. Hence, a combination of exergetic and energetic analysis can give complete depiction of system characteristics. Such type of comprehensive analysis will be a more convenient approach for the performance evaluation and determination of the steps towards improvement of performance of thermal systems [3], [4], [5].

Thermodynamic inefficiencies as well as reasonable comparison of each plant to others are identified and discussed for coal fired thermal power plants in Turkey by Hasan [6]. Energy and exergy analysis of a steam power plant in Jordan has been carried out by Aljundi [7]. Rashad and Maihy [8] presented energy and exergy analysis of Shobra El-Khima power plant in Cairo, Egypt at different load condition of the plant. Kwak et al. [9] presented exergetic and thermo-economic analyses for the 500 MW combined cycle plant by applying mass and energy conservation laws to each components. Quantitative balance of the exergies and exergy costs for each component and for the whole system was considered in the study. Khaliq et al. [10] used the second-law approach for the thermodynamic analysis of the reheat combined Brayton/Rankine power cycle. Sciubba et al. [11] presented a brief critical and analytical account of the development of the concept of exergy and of its applications.

Suryvanshee et al. [12] determines the exergy destruction of boiler system is 57 % in a 57 MW thermal power plant. Naterer analysed the coal fired thermal power plant with measured boiler and turbine losses [3]. Exergy losses and exergy losses of lignite fired thermal power plant at Neyveli was carried out by Ganapathy et al. [5] and the result revealed that maximum exergy loss of 42.73% occurs in combustor. Pradeep and Ibrahim [13] determines the irreversibilities in a boiler of 30 MW thermal power plant based on first and second law analysis R. Jyothu Naik [14] analyse the exergy destruction in a 4.5 MW biomass boiler and the result of the analysis indicate that the boiler produces the highest exergy destruction. Maghsoudi et al. [15] determines the energy and exergy analysis of 250 MW Shahid Rajaee Steam Power plant and the result revels that the exergy destruction in boiler is

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309.1 MW with exergy efficiency of 46.24 %. Sengupta et al. [16] presented the exergy analysis using the design data from a 210 MW coal fired thermal power plant. Vosough describes the useful concept of energy and exergy utilization in a boiler system and the energy and exergy efficiencies are found to be 89.21% and 45.48% [17].

An understanding of both energy and exergy efficiencies is essential for designing, analyzing, optimizing and improving energy systems through appropriate energy policies and strategies. If such policies and strategies are in place, numerous measures can be applied to improve the efficiency of industrial boilers [18]. Jamil [19] studied thermodynamics performance of Ghazlan power plant in Saudi Arabia where mixture of methane, ethane and propane were used as fuels. The study reveals that exergy efficiency in the boiler furnace was about18.88% and the total losses are high in the boiler especially in the heat exchanger as found to be 43.4%, also the study reveals that exergy efficiency in the furnace of Qurayyah power plant was about 16.88% and in the heat exchanger 25.19 % respectively. Gonzalez [20] studied the improvement of boiler performance by using economizer model.

This study deals with the energy and exergy analysis of a 500 MW coal fired boiler in design and off design condition at constant pressure mode of operation, in order to determine the magnitude and location of exergy efficiency and destruction in the boiler. For this objective a thermodynamic model for the boiler is prepared based on mass and energy balance equations.

II. COAL FIRED BOILER

Fig.1 shows the schematic diagram of the boiler. Design and off design parameters of the boiler is depicted in Table I. The boiler is a subcritical boiler of reheat type design and having forced circulation. Saturated steam produced leave drum and goes to three stages super heating, low temperature (LTSH), division panel (SHDP) and platen super hater (SHPL) respectively. Reheating of steam is done in one stage of reheater. Desuperheating is done two stages, first in super heating stage and second in reheating stage.

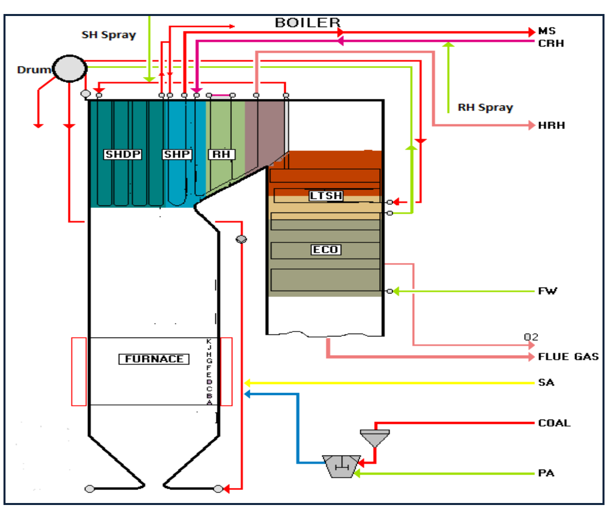

Fig. 1: Schematic diagram of boiler

III. ENERGY AND EXERGY ANALYSIS IN COAL FIRED BOILER

Energy analysis in the steam generator is calculated using indirect method as per ASME PTC-4-1 power test code steam generating units for evaluating energy efficiency of the boiler.

The flue gas temperatures across each heating surfaces are calculated by the thermodynamic model based on the measured flue gas temperature at economizer outlet and considering measured temperatures of water steam side across all heating surfaces. A combustion calculation is done for determining the flue gas composition and the adiabatic combustion temperature. Combustion efficiency is calculated by the model taking into account the flue gas analysis reports of unburnt carbon percentage in fly ash and bottom ash.

Mass and energy balance for flow process in a controlled volume system with negligible of potential and kinetic energy changes are:

TABLE I
MAIN PARAMETERS OF BOILER AT DIFFERENT LOAD

Description	**Unit**	**Design**	**80 % Load**	**60 % Load**
Gross load	MW	500	400	300
Main steam pressure	bar	173.28	170.64	168.58
Main steam temperature	°C	540	540	540
Main steam flow	Kg/s	415.333	331.083	250.028
Reheat steam pressure	bar	40.11	32.36	24.61
Reheat steam temperature	°C	540	540	540
Super heater spray flow	kg/s	2.5	15	21.667
Reheater spray flow	kg/s	0	0	0
Feed water temperature economizer inlet	°C	254	243	231
Feed water temperature economizer outlet	°C	359.47	356.67	354.28
Flue gas temperature economizer outlet	°C	325	318	295
Flue gas temperature airheater outlet	°C	125	119	118
Oxygen air heater Inlet	%	3.62	3.62	3.62
Unburnt carbon in fly ash	%	0.3	0.3	0.3
Unburnt carbon in bottom ash	%	0.7	0.7	0.7

Coal parameter (Ultimate analysis)

Carbon	%	29.76
Hydrogen	%	3.70
Nitrogen	%	2.38
Oxygen	%	8.66
Sulphur	%	0.5
Ash	%	40
Moisture	%	15
HHV (higher heating Value)	kcal/kg	3300

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$
$$\dot{Q} - \dot{W} = \sum \dot{m}_e\ h_e - \sum \dot{m}_i\ h_i \quad (2)$$

Where $\dot{m}$ is the mass flow rate, $\dot{Q}$ is the rate of energy transfer to the system as heat, $\dot{W}$ is the rate of work done by the system and the subscripts i and e denote inlets and outlets, respectively.

The energy efficiency of system and component is defined as the ratio of energy in products to total energy input to system or component. Mathematically,

$$\eta_I = \frac{\text{Energy in products}}{\text{Total energy input}} \quad (3)$$

Exergy is always evaluated with respect to a reference environment. The reference environment is in stable equilibrium, acts as an infinite system, and is a sink or source for heat and materials, and experience only internal reversible processes in which its intensive properties (i.e., temperature T_0, pressure P_0 remains constant). In this study the reference pressure and temperature are taken as P_0=1.013 bar and T_0 =33 ^{o}C respectively. The kinetic and the potential exergy are neglected. The exergy balance calculations have been established using methodology developed by Aljundi, Dincer and Rosen [7], [21], [22].

$$\dot{E}_D = \sum(1 - \frac{T_0}{T})\dot{Q} - \dot{W} + \sum_i \dot{E}_i - \sum_e \dot{E}_e \quad (4)$$

Where $\sum(1 - \frac{T_0}{T})\dot{Q}$ is the exergy transfer at temperature T, and the subscripts i and e denote inlets and outlets, respectively. $\dot{W}$ is the work rate excluding the flow work. The exergy transfer rates at inlets and outlets are denoted respectively as, $\dot{E}_i = \dot{m}_i e_i$ and $\dot{E}_e = \dot{m}_e e_e$.

$\dot{E}_D$ is the time rate of exergy destruction due to irreversibilities within the control volume. The exergy destruction rate is related to the entropy generation rate given by [22],

$$\dot{E}_D = T_0 \dot{S}_{gen} \quad (5)$$

$$\text{Totalexergy,} E = \dot{m}\ e = \dot{m}\ [h - h_0 - T_0(s - s_0)] \quad (6)$$

Where h and s denote the specific enthalpy and specific entropy respectively. e is specific exergy in kJ/kg . The subscript 0 denotes the restricted dead state.
Exergy balance for control volume is shown as [22]

$$\dot{E}_F = \dot{E}_P + \dot{E}_D + \dot{E}_L \quad (7)$$

Where $\dot{E}_F$ is the rate at which fuel is supplied and $\dot{E}_P$ is the product generated. $\dot{E}_D$ and $\dot{E}_L$ denotes the rate of exergy destruction and exergy loss respectively.

To define the exergetic efficiency both a product and a fuel for the system are identified. The product exergy represents the desired result produced by the system and the fuel exergy represents the resources expended to generate the product. The exergetic efficiency is the ratio between product exergy and fuel exergy [22], [23], [24].

$$\eta_{II} = \frac{\dot{E}_P}{\dot{E}_F} \quad (8)$$

TABLE II
ENERGY LOSS IN BOILER

Description	BMCR	100 % Load	80 % Load	60 % Load
Loss due to dry flue gas (%)	3.992	3.978	3.774	3.804
Loss due to hydrogen in fuel (%)	6.323	6.319	6.291	6.287
Loss due to moisture in fuel (%)	2.848	2.846	2.834	2.832
Loss due to moisture in air (%)	0.1	0.099	0.094	0.095
Loss due to unburnt carbon (%)	0.352	0.352	0.352	0.352
Radiation Loss (%)	0.112	0.119	0.142	0.177
Unaccounted losses (%)	0.751	0.75	0.742	0.742
Total Loss (%)	14.478	14.463	14.229	14.289
Boiler efficiency (%)	85.522	85.537	85.771	85.711

IV. RESULTS AND DISCUSSION

A detailed parametric study has been carried out, in order to account the performance of the boiler and its sub-systems. By employing mass and energy balances a first law analysis was performed across the boiler based on the parameters stated in Table I at design and off design conditions. Fig. 2 displays the relevant thermodynamic state for various components of boiler model. The total combustion air requirement is controlled to maintain the O_2 % (oxygen, 3.62%) at air heater inlet. Energy balance equation is solved taking fuel flow rate as m_f, air flow m_{sa} (secondary air), m_{pa} (primary air) and hot product mass flow as m_p.

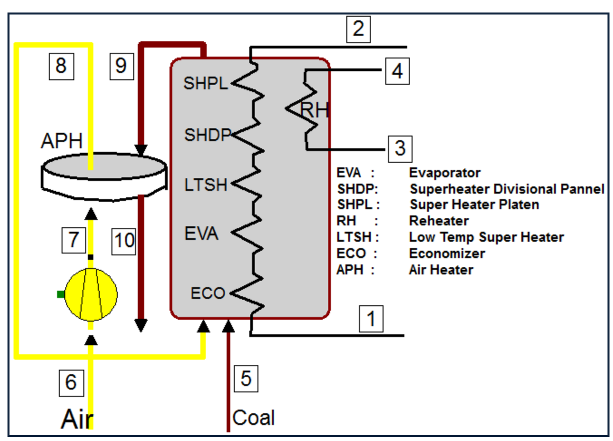

Fig. 2: Display of thermodynamic state of boiler model with arrangement

Boiler energy loss was evaluated based on indirect method (loss method) as per ASME PTC-4-1 power test code steam generating units. The loss percentage is expressed in Table II for different load condition. It was found that the maximum energy loss occurs due to hydrogen in fuel fallowed by loss due to dry flue gas. The fuel composition and the HHV of fuel have been kept constant for all loading condition. Unaccounted loss is provided in order to margin of safety and the radiation loss is derived based on ABMA radiation loss chart.

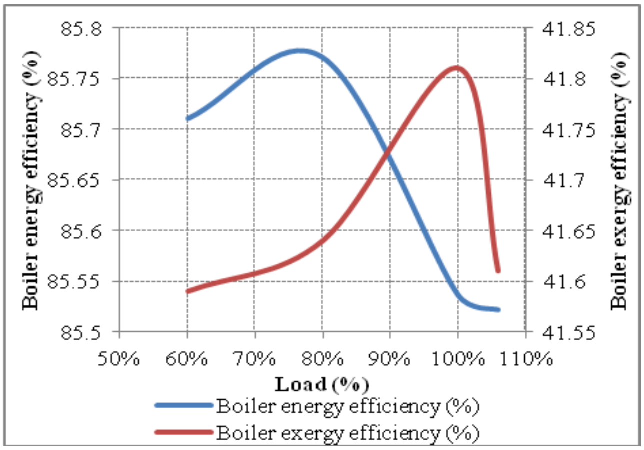

Fig. 3: Boiler energy and exergy efficiency

Thermodynamic properties and specific exergy on different streams for dead state condition of T_o= 33 ^oC and P_o= 1.013 bar, is depicted in Table III for design and off design condition. Exergy efficiency and exergy destruction are summarized in Table IV for all components of boiler. It is assumed that the combustor operates in steady flow process since there is no change of process with time at any point. It is also assumed that the kinetic and potential energies are negligible. Over all exergy destruction of boiler is found to be 609083.71 kW at 100 % design condition out of which combustor contributes the maximum destruction of 481148.99 kW. It may be stated that the combustion is not fully adiabatic and the combustion may not be completed.

Through simulation and calculation, exergy and energy efficiency of overall boiler for different load condition is shown in Fig. 3. Results shows that the energy efficiency of boiler increases in off design condition and is minimum of 85.522% at 106% load (BMCR) condition. Whereas the exergy efficiency is increases initially and is maximum at 100% load and further decreases when load reached 106%. The boiler energy efficiency (85.537%) and exergy efficiency (41.81%) at 100% load have led to very wide gaps between the total energy efficiencies and total exergy efficiencies.

To assure credible magnitude of heat exchange temperature difference and compliance with the second law the relevant temperature differences between the hot and cold fluid streams are monitored and the calculated relevant temperature-heat transfer (T-Q) diagram is presented in Fig. 4 for 100 % load condition and the corresponding values are shown in Table V for all off design conditions.

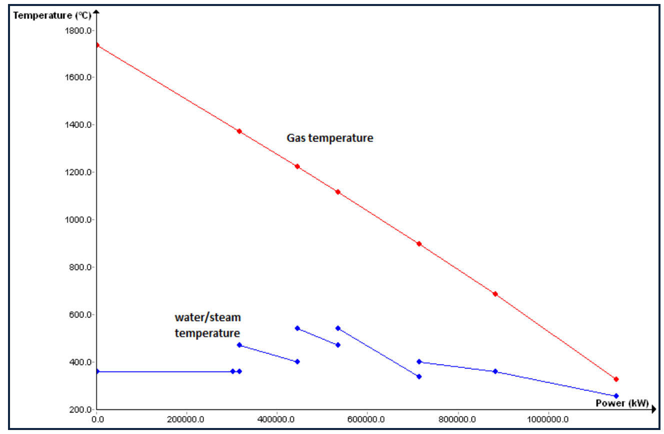

Fig. 4: Temperature-heat (T-Q) diagram of boiler (without air heater) at 100 % load

V. CONCLUSION

In this study an energy and exergy analysis of design and off design condition of a 500MW coal fired thermal power plant has been carried out based on mass, energy and exergy balance equation. The power plant boiler was simulated with data like pressure, temperature and mass flow in water steam side and the flue gas temperatures, flow etc is derived from the model simulation. The thermodynamic states of the plant components are shown in Table III. Exergy destruction, exergy and energy efficiency of the boiler components are presented in Table IV. It has been found that maximum exergy destruction occurs due to combustion process. Also there is significant exergy destruction occurs in the boiler pressure parts. It has also been found that exergy efficiency is lower than energy efficiency. The performance can be improved maintaining an optimum excess air level and also with change in ambient temperature.

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NOMENCLATURE

$\dot{W}$ Work done (kW)
$\dot{Q}$ Heat transfer (kW)
$\dot{m}$ Mass flow (kg/s)
s Specific entropy (kJ/kgK)
h Specific enthalpy (kJ/kg)
e Specific exergy (kJ/kg)
I Irreversibility (kJ/s)
E Exergy (kW)
η_{I} First law efficiency (%)
η_{II} Exergetic efficiency (%)
T temperature (^{o}C)
P pressure (bar)

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TABLE III
THERMODYNAMIC PROPERTIES AT EACH STREAM OF BOILER

Reference T_o= 33 °C and P_o= 1.013 bar

Design (100 % load case)

Stream	Physical State	T [°C]	P [bar]	m [kg/s]	h [kJ/kg]	s [kJ/kg°C]	e [kJ/kg]	Q [kW]
1	water	254	192.9	412.833	1105.32	2.794513	257.719	456311
2	steam	540	173.28	415.333	3397.18	6.398258	1446.29	1410961
3	steam	337	42.169	370.806	3054.93	6.499634	1073.01	1132784
4	steam	540	40.109	370.806	3537.23	7.205956	1339.07	1311626
5	coal	33	1.0199	96.9444	14153.2	0.67257	13947.3	1339427
6	air	33	1.013	521.111	33.7029	6.998861	5E-13	17563
7	air fan outlet	57.65	1.0302	364.778	58.9077	7.073165	2.45664	21488.2
8	hot air	311	1.0236	364.778	322.764	7.666107	84.7839	117737
9	flue gas airheater inlet	325	0.5079	614.15	357.297	7.606063	45.738	219434
10	flue gas airheater outlet	125	0.9962	614.15	133.413	6.966923	17.5264	81935.7

80 % Load case

Stream	Physical State	T [°C]	P [bar]	m [kg/s]	h [kJ/kg]	s [kJ/kg°C]	e [kJ/kg]	Q [kW]
1	water	243	184.76	316.083	1053.71	2.697492	235.815	456311
2	steam	540	170.64	331.083	3400.17	6.408235	1446.24	1125741
3	steam	329	34.029	299.472	3055.72	6.591943	1045.54	915103
4	steam	540	32.362	299.472	3544.76	7.311996	1314.13	1061557
5	coal	33	1.0199	79.4444	12711.9	0.67257	12506	1097639
6	air	33	1.013	426.389	33.7029	6.998861	5.2E-13	14370.5
7	air fan outlet	46.85	1.026	298.472	47.8637	7.040385	1.44816	14286
8	hot air	299	1.0221	298.472	309.988	7.644425	78.6454	92522.8
9	flue gas airheater inlet	318	0.7054	502.633	349.266	7.50208	69.383	175553
10	flue gas airheater outlet	119	1.0007	502.633	126.903	6.94864	16.4558	63785.7

60 % Load case

Stream	Physical State	T [°C]	P [bar]	m [kg/s]	h [kJ/kg]	s [kJ/kg°C]	e [kJ/kg]	Q [kW]
1	water	231	178.28	228.361	998.322	2.590445	213.2	227978
2	steam	540	168.58	250.028	3402.5	6.416064	1446.16	850719
3	steam	322	25.89	229.528	3059.82	6.716732	1011.43	702313
4	steam	540	24.615	229.528	3552.22	7.445219	1280.81	815334
5	coal	33	1.0199	61.6667	11344.7	0.67257	11138.8	852014
6	air	33	1.013	332.222	33.7029	6.998861	5.2E-13	11196.9
7	air fan outlet	53.34	1.0233	232.556	54.4983	7.061689	1.56064	12673.9
8	hot air	277	1.0211	232.556	286.65	7.603109	67.956	66661.9
9	flue gas airheater inlet	295	0.8455	391.405	322.851	7.408273	72.0748	126365
10	flue gas airheater outlet	118	1.0044	391.405	125.802	6.946242	16.4771	49239.6

BMCR condition								
Stream	Physical State	T [°C]	P [bar]	m [kg/s]	h [kJ/kg]	s [kJ/kg°C]	e [kJ/kg]	Q [kW]
1	water	255	196.82	451.389	1110.07	2.80261	259.997	501074
2	steam	540	174.56	451.389	3394.79	6.392333	1445.72	1532371
3	steam	339	44.032	406.884	3055.35	6.48215	1078.79	1243176
4	steam	540	41.874	406.884	3535.51	7.184469	1343.93	1438544
5	coal	33	1.0199	105.556	14718	0.67257	14512.1	1458402
6	air	33	1.013	567.5	33.7029	6.998861	5.2E-13	19126.4
7	air fan outlet	38.84	1.0318	397.25	39.667	7.012812	1.69304	15757.7
8	hot air	316	1.0241	397.25	328.098	7.675059	87.3765	130337
9	flue gas airheater inlet	344	0.4965	668.804	379.242	7.648438	54.7276	253638
10	flue gas airheater outlet	126	0.9933	668.804	134.5	6.970524	17.5287	89953.8

TABLE IV
ENERGY, EXERGY EFFICIENCY AND EXERGY DESTRUCTION OF BOILER AT DIFFERENT LOAD

	Energy efficiency (%)				Exergy efficiency (%)				Exergy destruction (kW)			
Components	BMCR	100 % Load	80 % Load	60 % Load	BMCR	100 % Load	80 % Load	60 % Load	BMCR	100 % Load	80 % Load	60 % Load
Combustion chamber	99.648	99.65	99.65	99.65	66.21	65.54	63.69	61.82	534388.76	481148.99	372984.93	271013.14
Heat exchanger	100	100	100	100	91.41	91.49	91.33	90.91	132755,93	119570.43	98191.35	78388.2
Heat recovery system	100	100	100	100	95.31	97.19	91.24	88.55	15583.5	8364.29	20813.76	20447.01
Over all boiler	85.52	85.54	85.77	85.71	41.61	41.81	41.64	41.59	549972.26	609083.71	491990.04	369848.35

TABLE V
FLUE GAS TEMPERATURE ACROSS HEATING SURFACES

Flue gas temperature (^oC)	BMCR	100 % Load	80 % Load	60 % Load
Combustion chamber out	1799.9	1738	1580.04	1423.01
SHDP inlet	1389	1374	1369	1373
SHPL inlet	1241.2	1224.80	1209.27	1198.24
RH inlet	1132.8	1116.13	1092.22	1070.02
LTSH inlet	914.51	898.05	873.24	852.22
ECON inlet	699.22	684.71	669.65	660.50
APH inlet	344	325	318	295