Combustion optimization in PF Boilers

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Topics layout

1. Coal and Combustion process
2. Boiler losses and efficiency
3. Combustion measurement and optimization
4. Online diagnostic optimization
5. Advance Optimization techniques

Coal and its analysis

- Inhomogeneous organic fuel formed mainly from decomposed plant matter.
- Over 1200 coals have been classified.

- different coal types:
  (Peat)
  Lignite
  Bituminous coal
  Anthracite

Coal Analysis

Elemental Composition (C, H, O, S, N) / Proximate Analysis (Char, Ash, H_2O, VM)

C	65-95%
H	2-7%
O	<25%
S	<10%
N	1-2%
Char	20-70%
Ash	5-15%
H_2O	2-20%
VM	20-45%

Proximate analysis:
Determination of TM, FC, VM, Ash content and heat value

Used for characterizing the coal for its use

Ultimate analysis: Elemental analysis of carbon, Hydrogen, Nitrogen, Sulfur and other elements contained in fuel

It is derived from the proximate analysis of coal

Used in determining the quantity of air required for combustion and the volume and composition of the combustion gases for furnace design

Proximate to Ultimate analysis

	%C	=	0.97C+ 0.7(VM - 0.1A) - M(0.6-0.01M)
	%H	=	$0.036C + 0.086\ (VM - 0.1xA) - 0.0035M^2\ (1-0.02M)$
	$\%N_2$	=	2.10 -0.020 VM
where			
	C	=	% of fixed carbon
	A	=	% of ash
	VM	=	% of volatile matter
	M	=	% of moisture

Parameter	**Indian Coal**	**Indonesian Coal**	**South African Coal**
Moisture	5.98	9.43	8.5
Ash	38.63	13.99	17
Volatile matter	20.70	29.79	23.28
Fixed Carbon	34.69	46.79	51.22

Heat Value of coal

HHV: Higher heating value*:* the heat of vaporization of the water is released and becomes part of the heating value.

Lower heating value, LHV *:heating value in which the water remains a* vapor and does not yield its heat of vaporization.

Thus the energy difference between the two values is due to the heat of vaporization of water,

HHV = LHV + *hfg*

Coal rank Indian and Imported

Grade	Calorific Value Range (in kCal/kg)
A	Exceeding 6200
B	5600 – 6200
C	4940 – 5600
D	4200 – 4940
E	3360 – 4200
F	2400 – 3360
G	1300 – 2400

Table 1.4 GCV for Various Coals

Parameter	Lignite (Dry Basis)	Indian Coal	Indonesian Coal	South African Coal
GCV (kcal/kg)	4,500*	4,000	5,500	6,000

Effect of carbon content on Heat value

	Bituminous Coal (Sample I)	Bituminous Coal (Sample II)	Indonesian Coal
Moisture (%)	5.98	4.39	9.43
Mineral matter (%)	38.63	47.86	13.99
Carbon (%)	42.11	36.22	58.96
Hydrogen (%)	2.76	2.64	4.16
Nitrogen (%)	1.22	1.09	1.02
Sulphur (%)	0.41	0.55	0.56
Oxygen (%)	9.89	7.25	11.88
GCV (Kcal/kg)	4000	3500	5500

Indian and imported coals

Parameter	Indian Coal	Indonesian Coal	South African Coal
Moisture	5.98	9.43	8.5
Ash	38.63	13.99	17
Volatile matter	20.70	29.79	23.28
Fixed Carbon	34.69	46.79	51.22

Significance of Various elements of coal

Fixed carbon:

Solid fuel left after volatile matter is distilled off. It consists of mostly carbon.
•Gives a rough estimate of heating value of coal

Volatile Matter:

It is an index of the gaseous fuels present.
Volatile Matter
•Proportionately increases flame length, and helps in easier ignition of coal.
•Sets minimum limit on the furnace height and volume.
•Influences secondary air requirement and distribution aspects.
•Influences secondary oil support

Significance of Various Parameters in Proximate Analysis

Ash Content:

Ash is an impurity that will not burn.
•Reduces handling and burning capacity.
•Increases handling costs.
•Affects combustion efficiency and boiler efficiency
•Causes clinkering and slagging.

Moisture Content:

Moisture in coal must be transported, handled and stored. Since it replaces combustible matter, it decreases the heat content per kg of coal.

•Increases heat loss, due to evaporation and superheating of vapour

Typical analysis of Indian coal

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Sl. No.	Characteristics		Column-1 Design Coal	Range of 95% coal supplies: Column-2 Worst Coal	Range of 95% coal supplies: Column-3 Best Coal	Range of 5% coal supplies: Column-4
1.0	**Proximate Analysis (As received basis)**					
1.1	Total Moisture	(%)	14	15	12	10-17
1.2	Ash	(%)	40	46	32	30 - 50
1.3	Volatile Matter	(%)	22	19	24	24 - 17
1,4	Fixed Carbon	(%)	24	20	32	34 - 16
2.0	**Ultimate Analysis (As received basis)**					
2.1	Carbon	(%)	35	29.0	42	45.0 - 26.5
2.2	Hydrogen	(%)	2.3	1.88	3	3.50 - 1.75
2.3	Nitrogen	(%)	0.83	0.52	1	1.25 - 0.6
2.4	Oxygen	(%)	7.24	6.96	9.23	10.0 - 5.0
2.5	Sulphur	(%)	0.28	0.25	0.34	0.22 - 0.8
2.6	Carbonates	(%)	0.3	0.35	0.27	0.42 - 0.2
2.7	Phosphorous	(%)	0.05	0.04	0.06	0.07 - 0.03
2.8	Total Moisture	(%)	14	15	12	10 - 17
2.9	Ash	(%)	40	46	32	30 - 50
2.10	GCV (Kcal/Kg)	(%)	3300	2800	4200	4500 - 2600
2.11	Hard Grove Index		55	53	58	45 - 60
3.0	**Ash Analysis**			Range of 95% supplies		
3.1	Silica (SiO_2)	(%)	59.5	61.2 - 60.2		59.0 - 62
3.2	Alumina (Al_2O_3)		29.63	30 - 29		27.5 - 31.5
3.3	Iron Oxide (Fe_2O_3)	(%)	4.32	4.1 - 4.42		3.8 - 5.20
3.4	Titania (TiO_2)	(%)	1.72	1.60 - 1.75		1.5 - 1.8
3.5	Phosphoric Anhydride (%)		1.57	0.51 - 0.61		0.48 - 0.7
3.6	Lime (CaO)	(%)	1.53	1.50 - 1.62		1.46 - 1.82
3.7	Magnesia (MgO)	(%)	0.57	0.50 - 0.70		0.4 - 0.8
3.8	Sulphuric Anhydride	(%)	0.28	0.25 - 0.29		0.22 - 0.4
3.9	Alkalies (Na_2O+K_2O)	(%)	00.88	-		0.6 - 1.93
4.0	**Ash Fusion Range**					
4.1	Initial Deformation Temp.	°C	1100	1100 - 1200		>1050
4.2	Hemispherical Temp.	°C	>1400			>1450
4.3	Flow Temp.	°C	>1450			>1450

Boiler Losses and efficiency

Quick recap: Boiler losses

Dry gas loss: *sensible heat carried out of the stack* [5-6%]

Moisture loss: *loss due to vaporizing the moisture in* the fuel [2%]

Incomplete combustion loss: *loss due to combustion of* carbon that results in carbon monoxide (CO), instead of, carbon dioxide (CO_2) [0.2-0.5%]

Hydrogen Loss: Hydrogen in the fuel converts to H_2O [4%]

Unburned carbon loss: *loss due to carbon that does not* get combusted and ends up in the refuse (ash) [1%]

Moisture in the combustion air loss: *loss due to heating* up water vapor contained in the combustion air [0.2-0.25%]

Radiation loss: *heat lost from the external furnace* walls to the surrounding air [1%]

Total losses **[13-15%]**

Boiler Losses efficiency

LOAD	UNITS	500 MW	400MW	300MW	250MW
Evaporation	t/h	1498.5	1198.9	909.3	772.9
Fuel	--	-------- Guarantee Coal --------			
Higher Heating value	Kcal/Kg	--------- 3300 --------			
Ambient Temperature	Deg.C	---------- 13 -----------			
Relative Humidity	%	------------ 60 -----------			
Air moisture	Kg/kg of dry air	----------0.006 ----------			
Excess Air at AH inlet	%	------------ 20 -------------			
Gas temperature leaving AH (corrected)	Deg.C	115	113	112	111
Heat losses and Efficiency					
I) Heat losses due to flue gases - Dry gas loss	%	4.25	4.22	4.26	4.28
- Hydrogen in Fuel		3.96	3.95	3.95	3.95
- Moisture in Fuel		2.29	2.29	2.29	2.29
- Moisture in air		0.04	0.04	0.04	0.04
- Total heat loss due to flue gases		10.54	10.50	10.54	10.56
ii) Heat loss due to unburnt carbon in - Furnace bottom ash } - Fly ash } - Total heat loss due to unburnt carbon	%	1.20 1.20	1.20 1.20	1.20 1.20	1.20 1.20
iii) Sensible heat loss in - Furnace bottom ash - Economiser hopper - Air heater hopper - ESP hopper - Total sensible heat loss	%	0.416 0.033 0.006 0.142 0.597	0.416 0.031 0.006 0.139 0.592	0.416 0.029 0.006 0.138 0.589	0.416 0.027 0.006 0.136 0.585
iv) Heat loss due to radiation	%	0.115	0.139	0.177	0.206
v) Manufacturer's margin	%	0.100	0.100	0.100	0.100
vi) Unaccounted heat loss - Bottom radiation - Mill reject + co Total unaccounted heat loss	%	0.098 0.080 0.178	0.101 0.080 0.181	0.105 0.080 0.185	0.107 0.080 0.187
vii) Total heat losses (sum of Sl.nos. (i) to (vi))	%	12.73	12.71	12.79	12.84
vii) Heat credits	%	Not accounted as not permitted by specification			
viii) Steam generator efficiency	%	87.27	87.29	87.21	87.16

Cost of losses

Parameter	*Deviation*	*Effect on Heat Rate*
Excess Air (O2)	per %	7.4 Kcal/kWh
Exit Gas Temp	per ^{o}C	1.2 Kcal/kWh
Unburnt Carbon	per %	10-15 Kcal/kWh
Coal moisture	per %	2-3 Kcal/kWh
Boiler Efficiency	per %	25 Kcal/kWh

1 kcal reduction ~ 1.2 & 3 T/day saving in coal in 200/500 MW units @ 90% PLF & 3600 GCV; CO_2 reduction ~ almost 1.25 times coal saved

Operator Controllable Losses – Dry Flue Gas & Unburnt Carbon Loss

Combustion- a brief discussion

Combustion

Coal is a hydrocarbon with CHNOS as main elements

Fuel + Oxidizer ---Products of combustion + Energy

Primary combustion reaction

The combustion process: Fuel [C + H] + Air [$O_2 + N_2$] —Combustion→ Heat [$CO_2 + H_2O + N_2$]

Secondary combustion products : NOx, SOx, CO and unburnt fuel

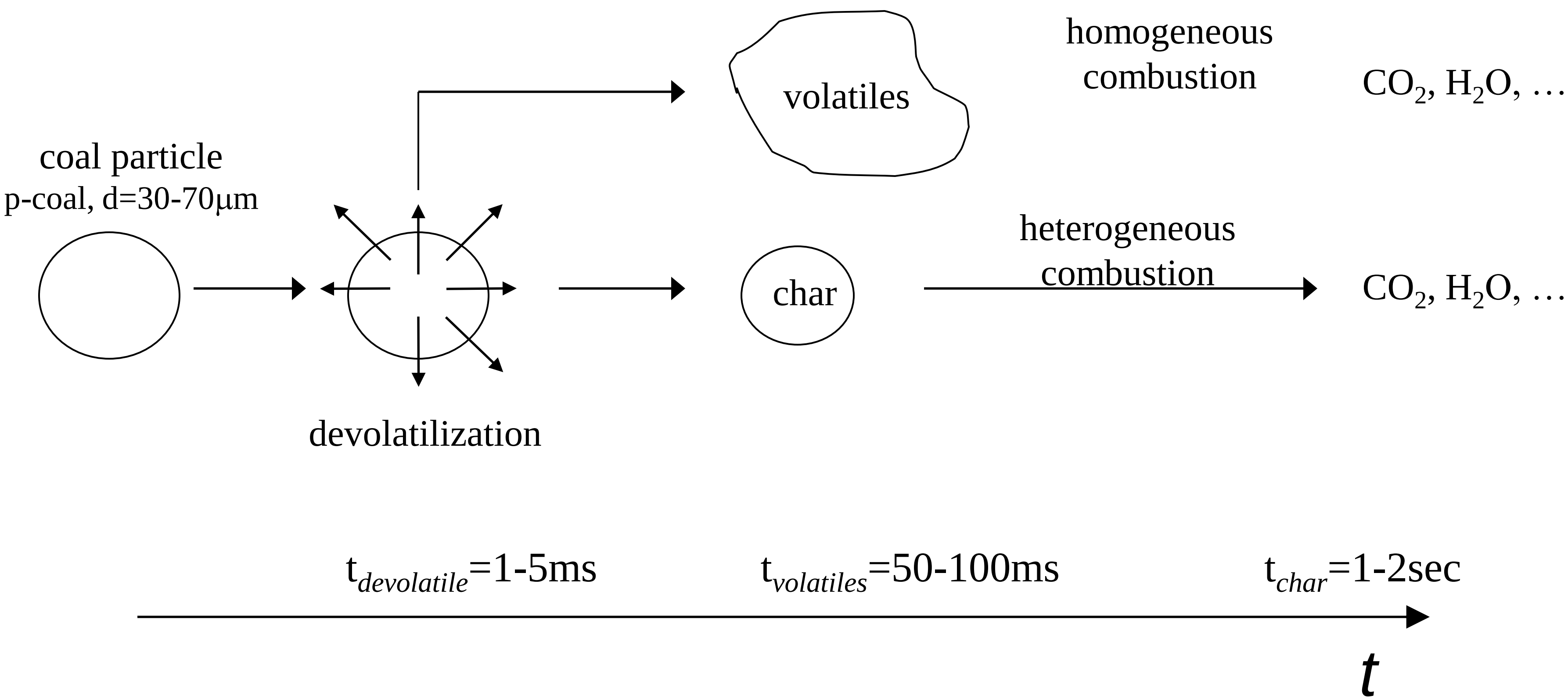
NOx and Sox (ppm) : air pollutants.

CO and unburnt fuel : a waste of available heat ,loss of efficiency

Combustion efficiency:

[Heat In Fuel-Heat carried away by flue gas from the stack] / [Heat in the fuel]

Process of coal combustion



Physical process of coal combustion

- Turbulent/swirling flow of air and coal.
- Turbulent/convective/molecular diffusion of gaseous reactants and products.
- Convective heat transfer through the gas and between the gas and coal particles.
- Radiatiion heat transfer between the gas and coal particles and between the coal/air mixture and the furnace walls

Requirements for complete combustion

four basic criteria :

1. Adequate quantity of air (oxygen) supplied to the fuel,

2. Oxygen and fuel thoroughly mixed,

3. Fuel-air mixture maintained at or above the ignition temperature,

and

4. Furnace volume large enough to give the mixture time for complete

combustion

Air for Combustion

Air contains **21% oxygen**, **78% nitrogen**, and 1% other constituents by Volume and 23% and 77% by weight.

Air required for one ton of Oxygen= 100/23=**4.32** tons of air/ton of O_2

From **Fuel analysis**

$C + O_2$ ---- CO_2: C=38% =32/12=2.67* 38= tons of O_2 per ton of C

Air required to burn carbon completely= 2.67*4.32*38=**438** tons of air/100 tons of fuel

$H_2 + 1/2O_2$ ---H_2O: H=2.3% = 32/4 =8 tons of O_2 per ton of H

Air required to burn Hydrogen completely =8*4.32*2.3=**78** tons of air/100 tons of fuel

$S + O_2$-----SO_2: S=0.2% = 32/32=1 tons of O_2 per ton of S

Air required to burn Sulfur completely =1*4.32*0.2=**0.8**tons of air/100 tons of fuel

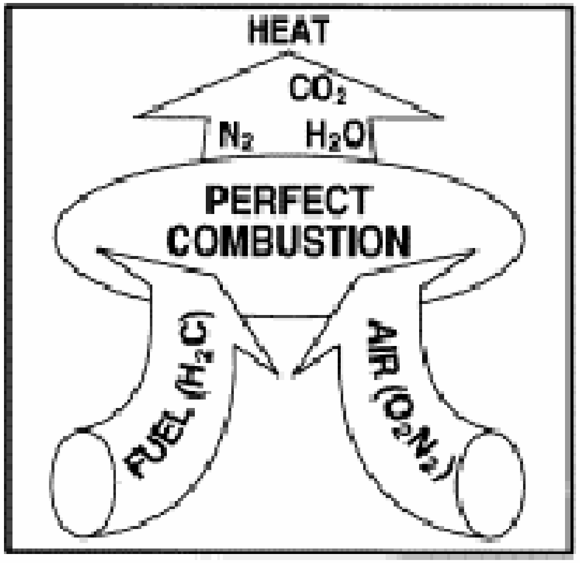
Remaining are Ash and Moisture which do not participate in combustion

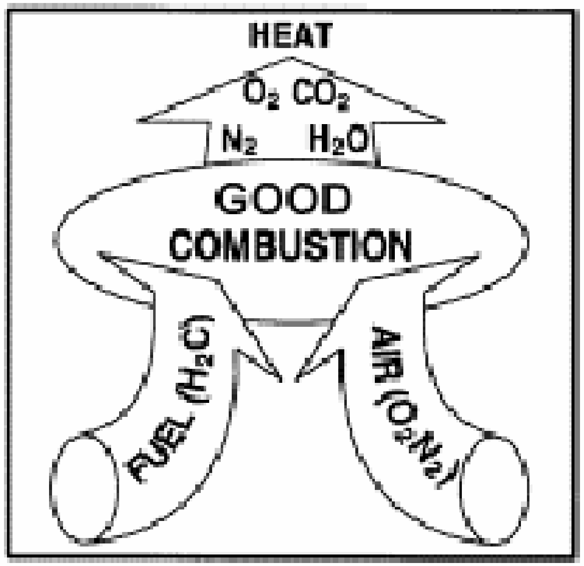
Nitrogen inert at normal combustion temperatures,unless the temperatures are very high.

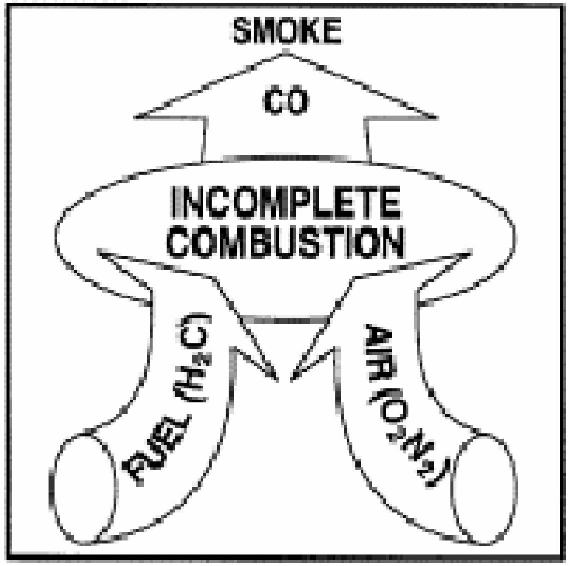
Total Air required for complete combustion is 517 tons per 100 tons of fuel(given)

Thumb rule= every ton of fuel=5 tons of air

Combustion-quality assessment





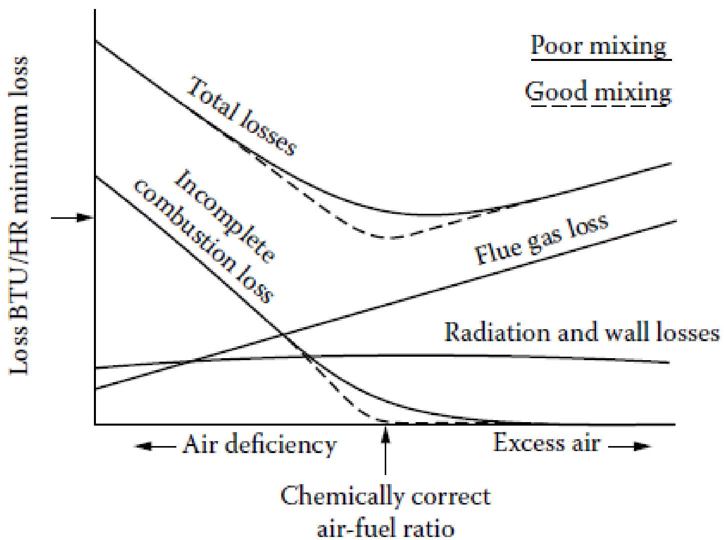


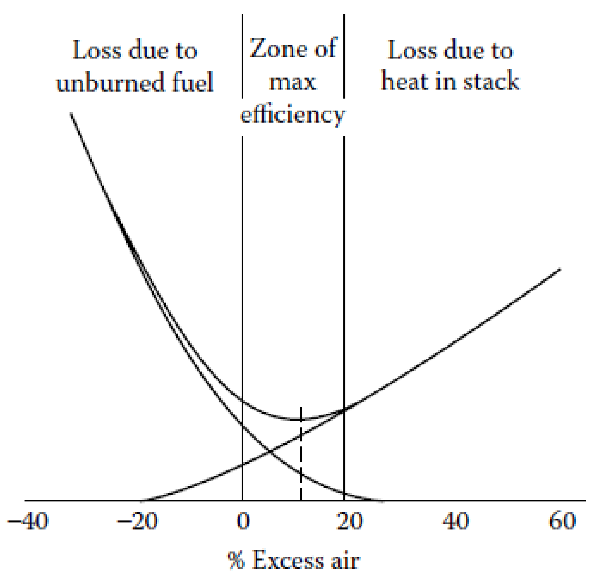
C	$+ O_2$	$\rightarrow$	CO_2	+ 8,084 kcals/kg of Carbon
2C	$+ O_2$	$\rightarrow$	2 CO	+ 2,430 kcals/kg of Carbon
$2H_2$	$+ O_2$	$\rightarrow$	$2H_2O$	+ 28,922 kcals/kg of Hydrogen
S	$+ O_2$	$\rightarrow$	SO_2	+ 2,224 kcals/kg of Sulphur

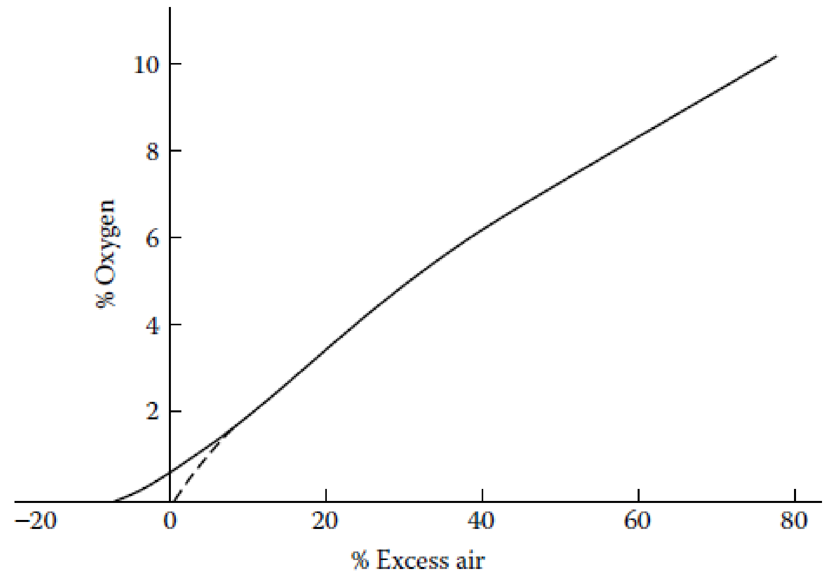
Each kilogram of CO formed means a loss of 5654 kCal of heat (8084 – 2430).

If every molecule of fuel came into contact with the right number of molecules of air, all the fuel would be combusted .(not practical) – **Excess air is required**

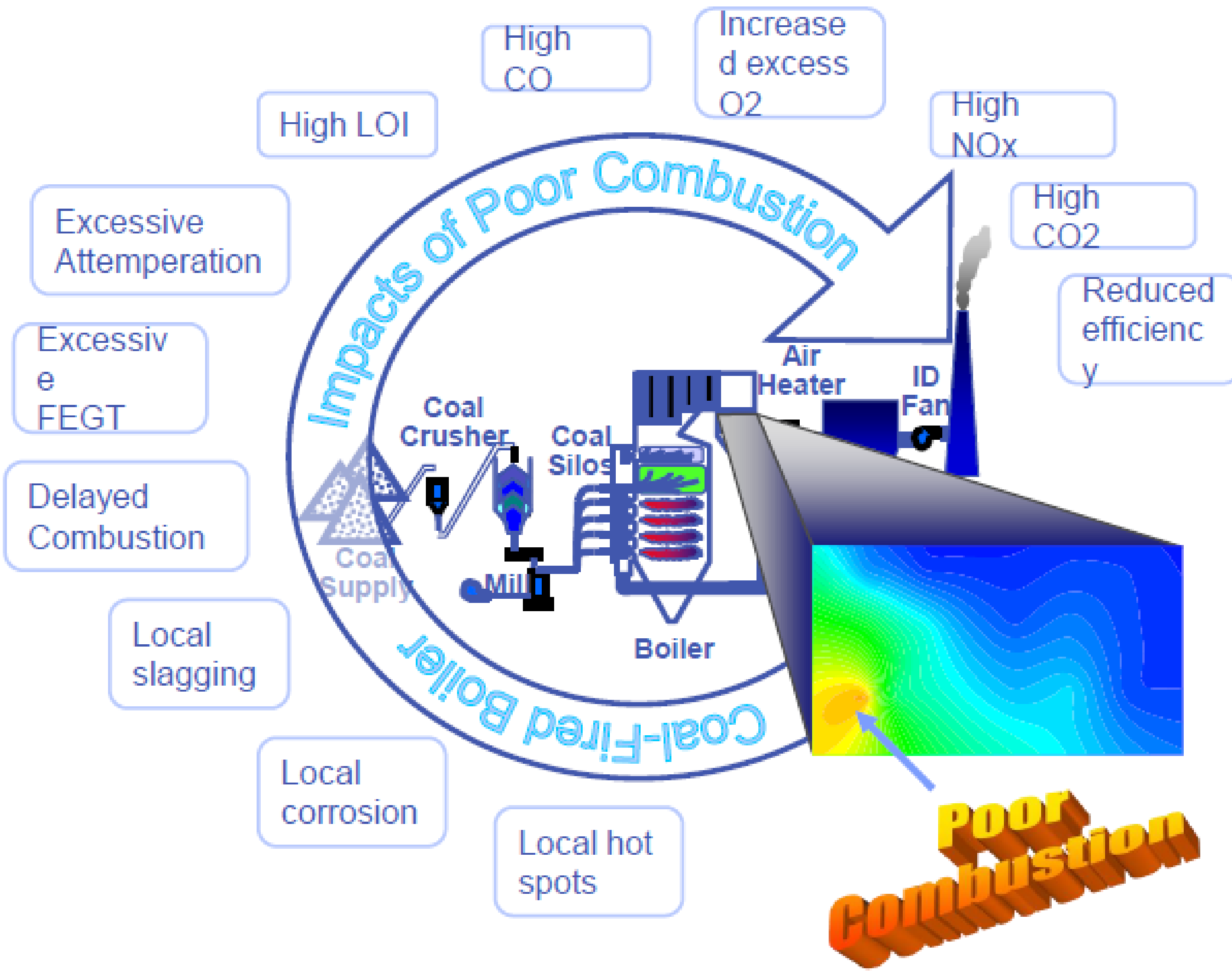
How much excess air







Impacts of poor combustion



Ref: GE Zonal System

Reasons for improper combustion

✓Significant quantities of air in-leakage or “tramp” air into the furnace

✓Improper turbulence

✓Improper fuel sizing

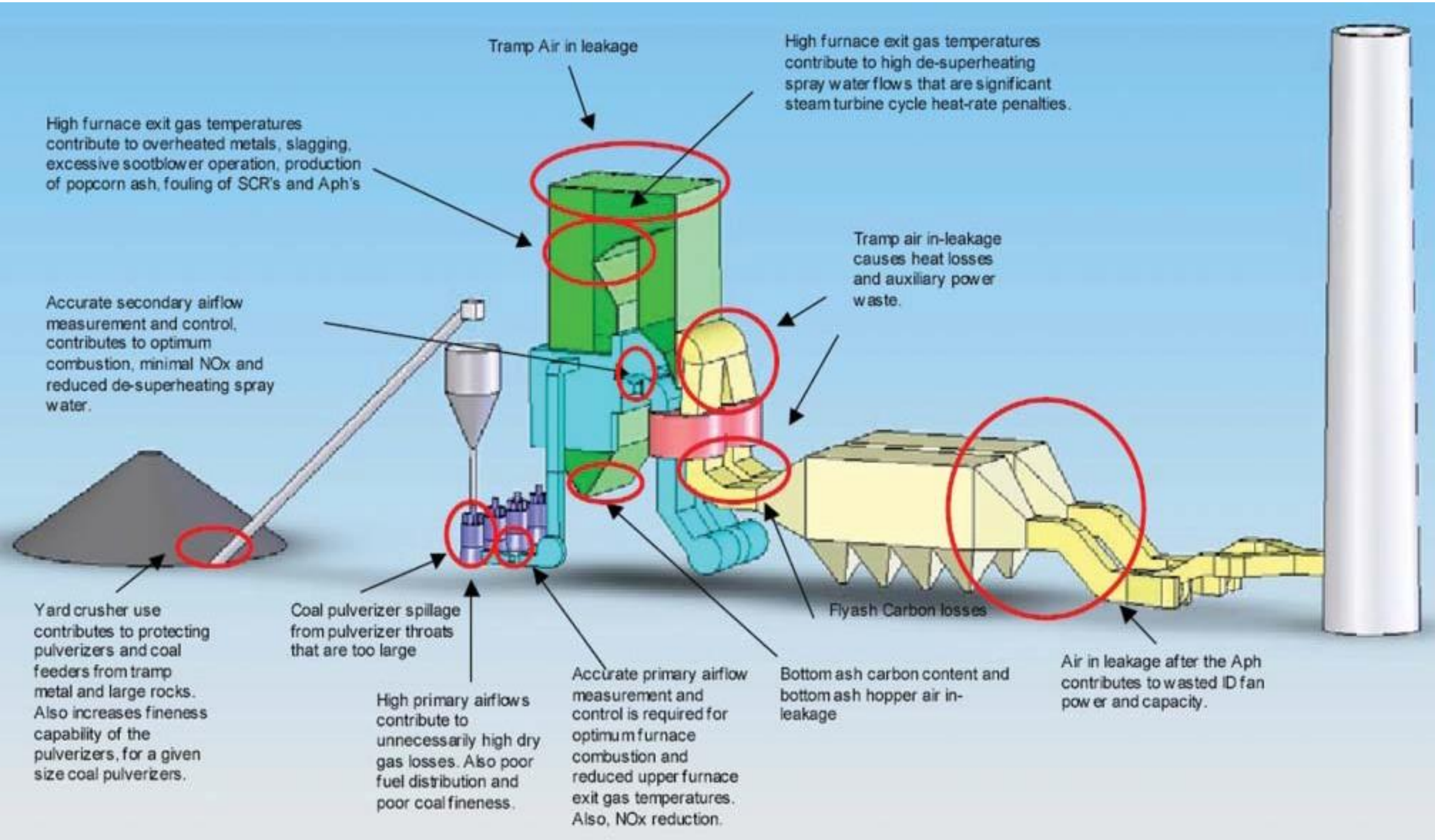
✓Inadequate fuel flows

✓Inadequate fuel velocities

✓Improper temperatures

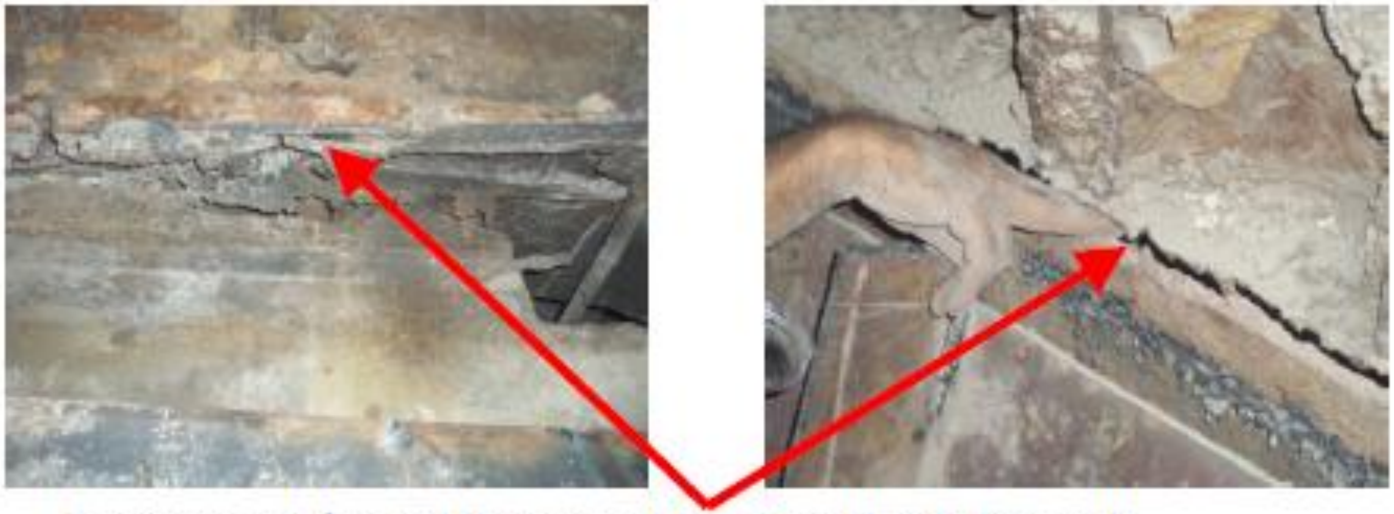
Consequences: significant loss of boiler efficiency, caused by high furnace exit gas temperatures.

Areas for Air ingress



Poor combustion cases

Locations of Air ingress



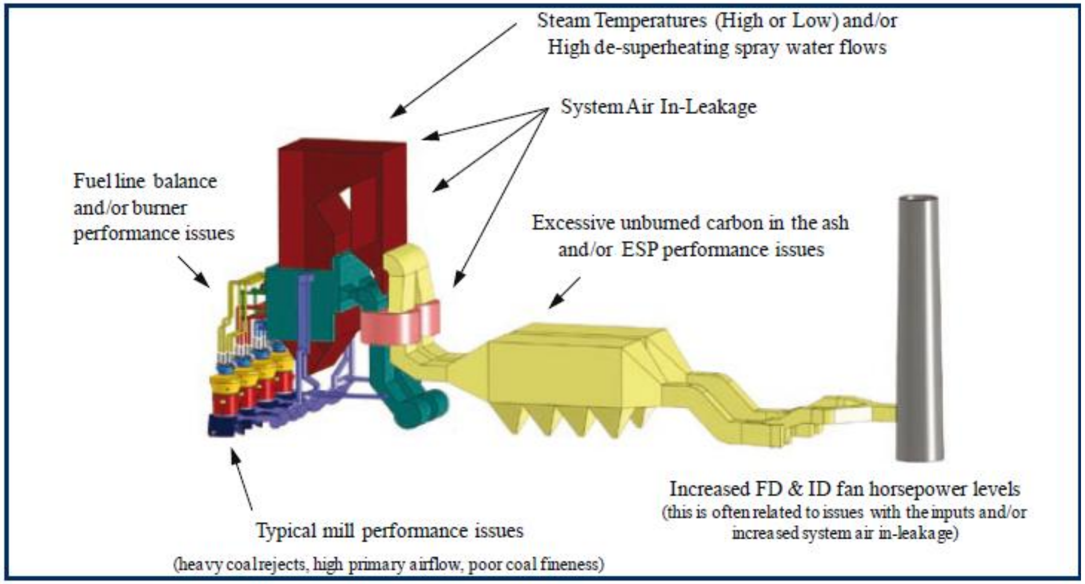
Large cracks in Bottom Hopper Seal Trough seal plates and trough connections to hoppers

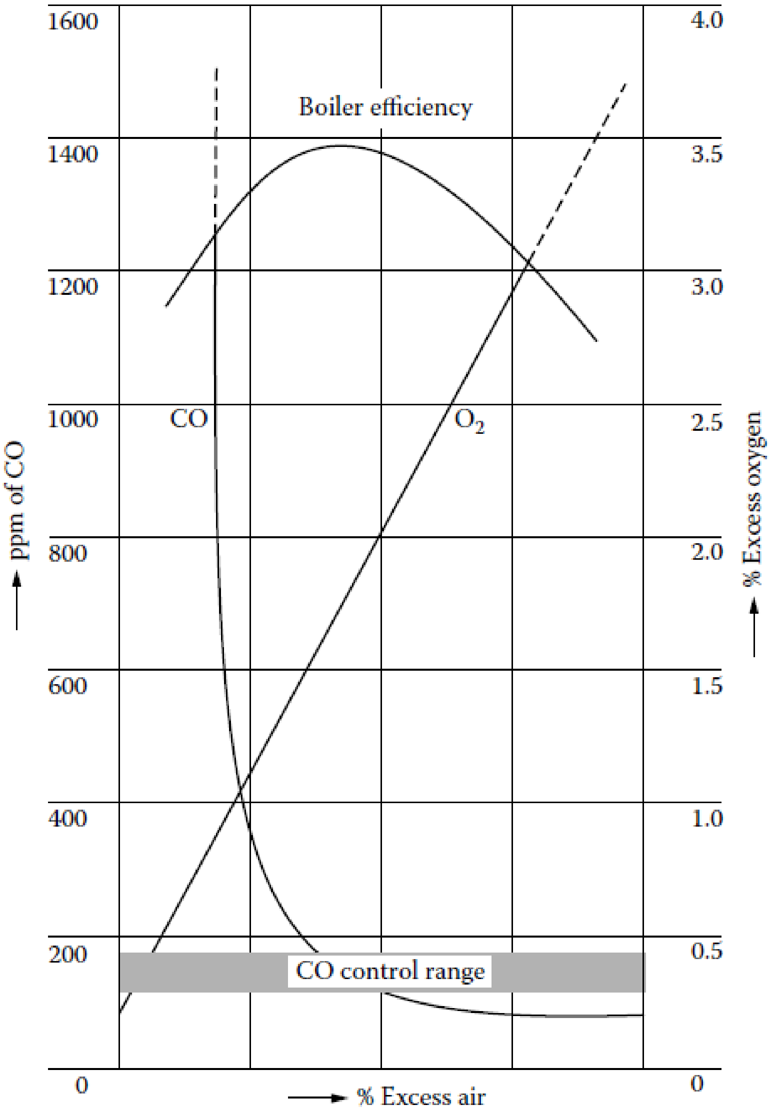
Need for combustion optimisation

Operating a boiler that is not optimised, or tuned, can

- ✓fallout of pulverised fuel, blocked pipes, or high mill pressure
- ✓erosion of mill, pipes and burner components
- ✓poor burner ignition, and flame instability and dislocation
- ✓incorrect primary and secondary air-to-fuel ratios
- ✓increased nitrous oxide production
- ✓increased levels of unburnt carbon
- ✓increased excess-air requirements
- ✓increased erosion between furnace and boiler exit
- ✓reduced boiler efficiency
- ✓localised furnace problems that can include inappropriate superheater and reheater temperature profiles,
- ✓ increased slagging and greater water-wall wastage.

What to Optimize?





Methods for Combustion optimization

- Diagnostic testing
- Sensor based
- Online Optimization
- Modeling based approach for combustion control
- Control loop tuning

Diagnostic testing

Diagnostic tests

Clean Airflow Tests

Dirty Airflow Tests

Iso kinetic Coal Sampling

Furnace Exit HVT Traverse

Air In-Leakage survey

Insulation survey

Furnace temperature survey

Flue Gas Flow Measurement

Boiler Efficiency Tests

AH Performance Tests

Boiler Tuning & Optimization

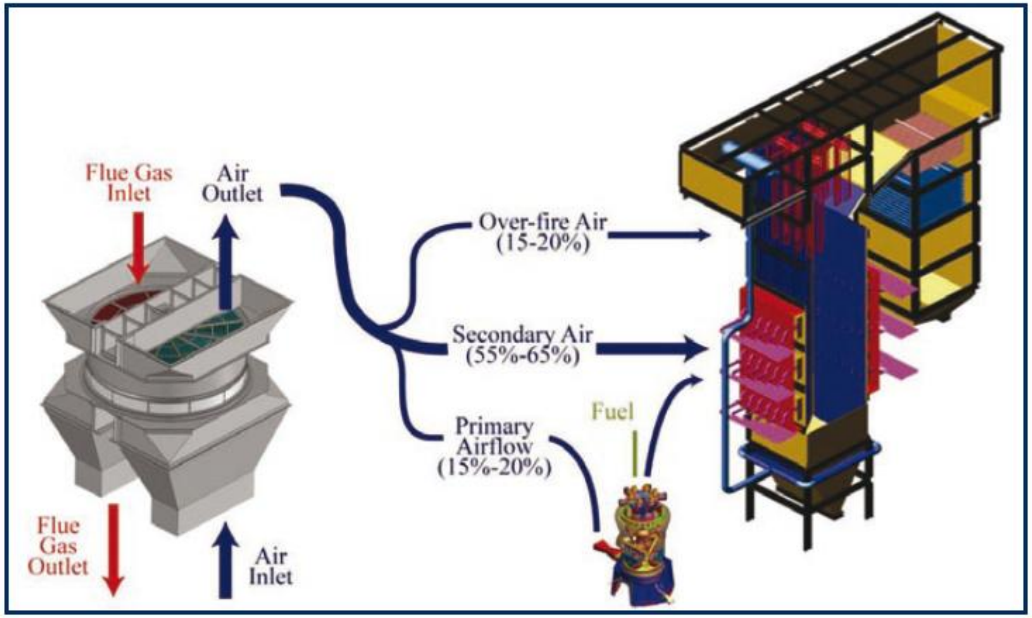
Combustion optimization based on Diagnostic testing

The fuel lines balanced to each burner by
• clean air test ± 2%or better;
•dirty air' test, ± 5% or better;
•balanced in fuel flow to ± 10 %or better.

For carbon burnout control : coal fineness to be

•75 %or more passing a 200 mesh.
•50 mesh particles shall be <0.1%.

• Secondary air distribution to burners should be within ±5-10 %.
• primary and secondary airflow shall be accurately measured and controlled to ± 3%accuracy



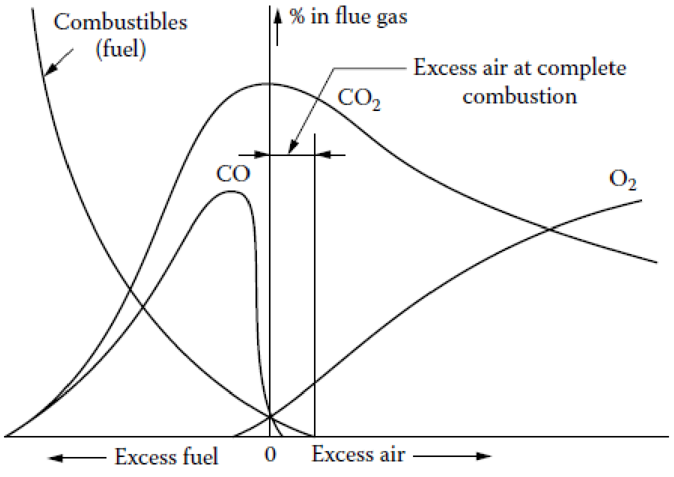
Sensor based diagnostic and optimization

CO2 sensing as combustion control

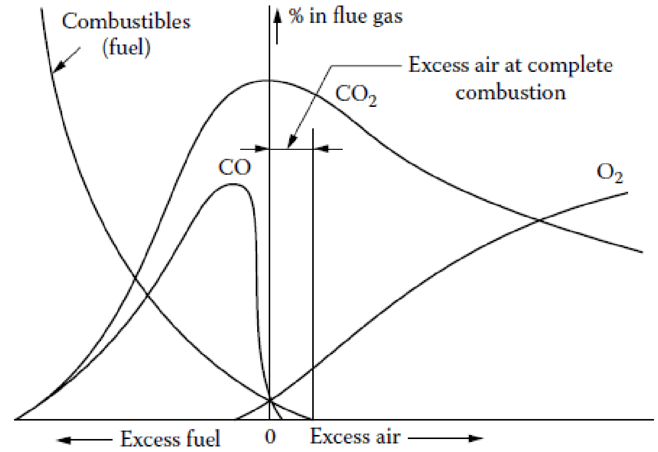
Rate of change of CO2is rather small at the point of optimum excess air.

In fact, the CO2 curve is at its maximum point when the combustion process is optimized.

CO2 is not a very sensitive measurement.



O2 sensing as combustion control



Excess O2: zirconium oxide probes.

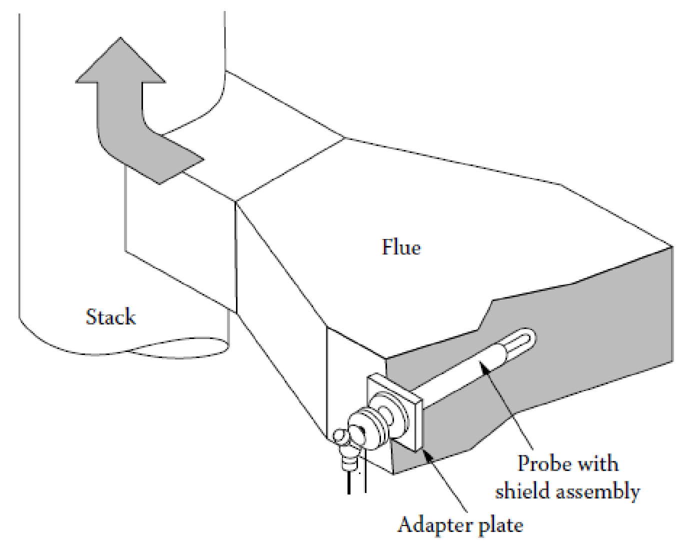
It uses the probe should be installed close to the combustion Zone ,

the gas temperature is below that of the electrically heated zirconium oxide detector.

The flow should be turbulent

probe cannot distinguish leakage from excess oxygen left over after combustion.

a relatively insensitive measurement.



CO as combustion control

CO is a direct measure of the completeness of combustion ,

unaffected by air infiltration,

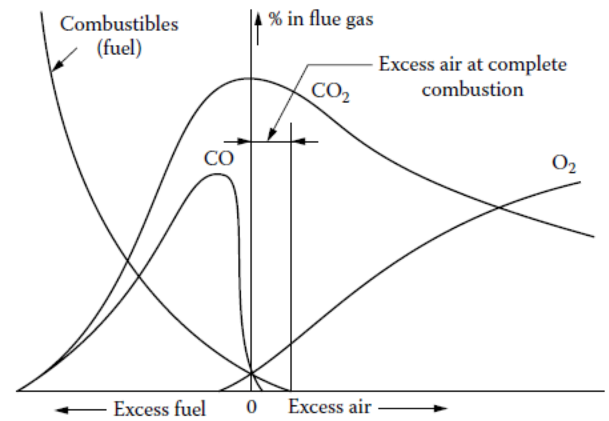
optimum boiler efficiency :when the losses due to incomplete combustion *equal the effects of* excess air heat loss.

Theoretically, CO should be zero whenever there is oxygen in the flue gas.

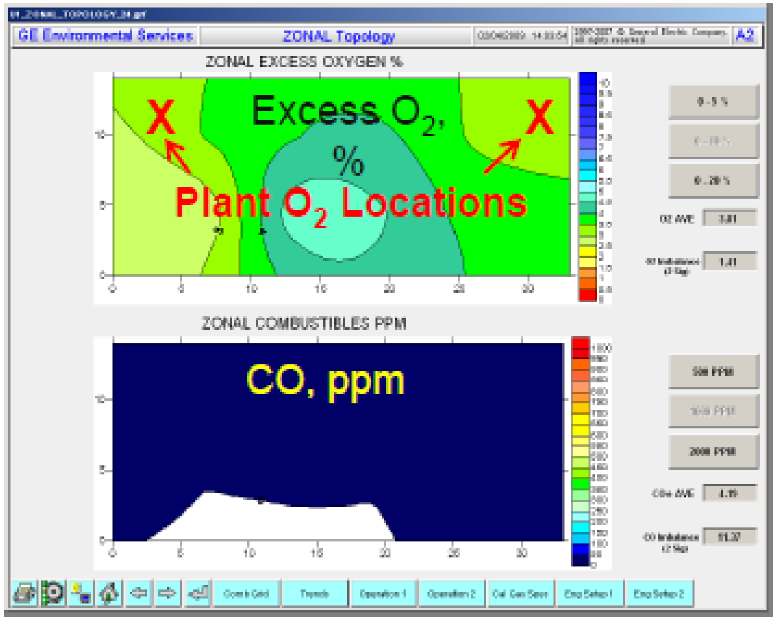
Maximum boiler efficiency when the CO is between 100 and 400 ppm.

CO is a very sensitive indicator of improperly adjusted burners;

The CO analyzers cannot operate at high temperatures usually located downstream of the economizer.



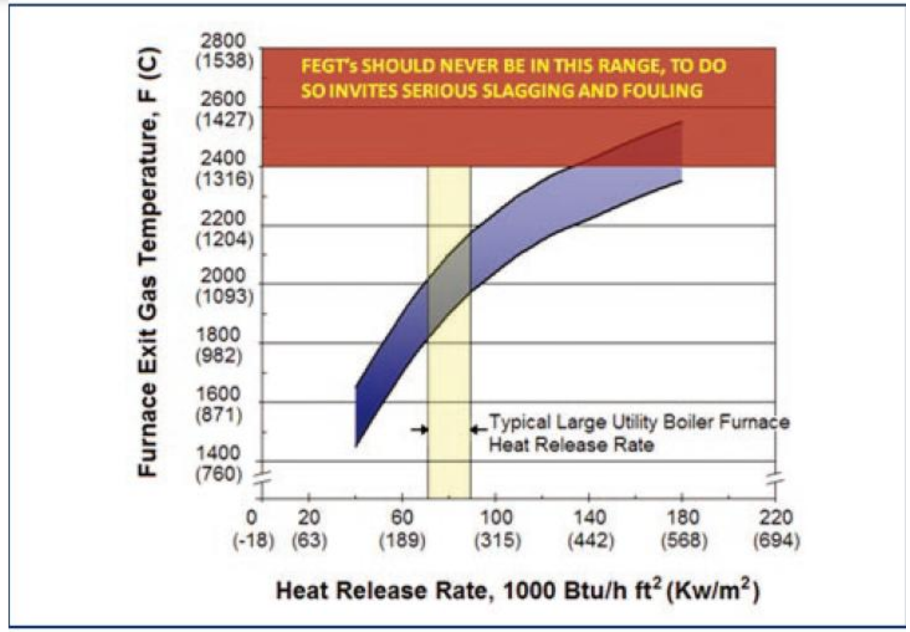
Sensor based approach

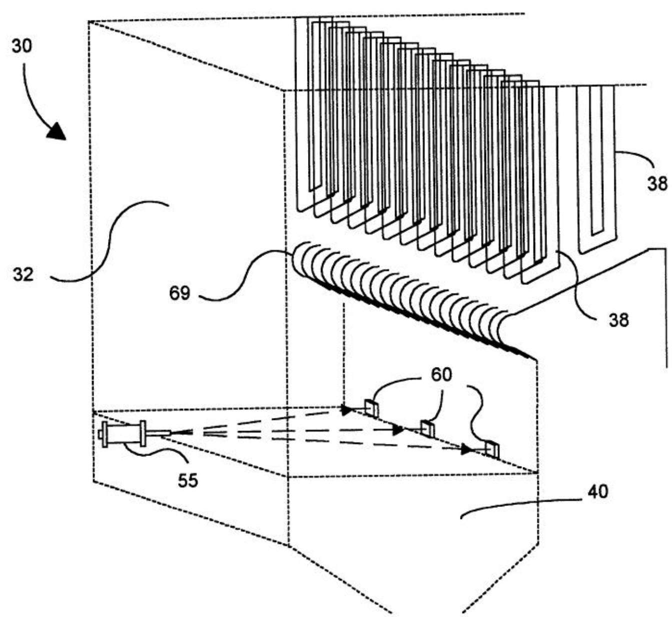


Acoustic Pyrometer for flue gas exit temperature

Principle:
velocity of sound varies with temperature. Changes in sound speed can provide temperature of the medium

C=√ṛRT





Acoustic waves are strongly attenuated by hot gases;
a controlled high intensity sound source is required.
Robust signal detection techniques must be employed to achieve precise and accurate time-of-flight measurements

Combustion control through online optimization-PADO

Online combustion optimization

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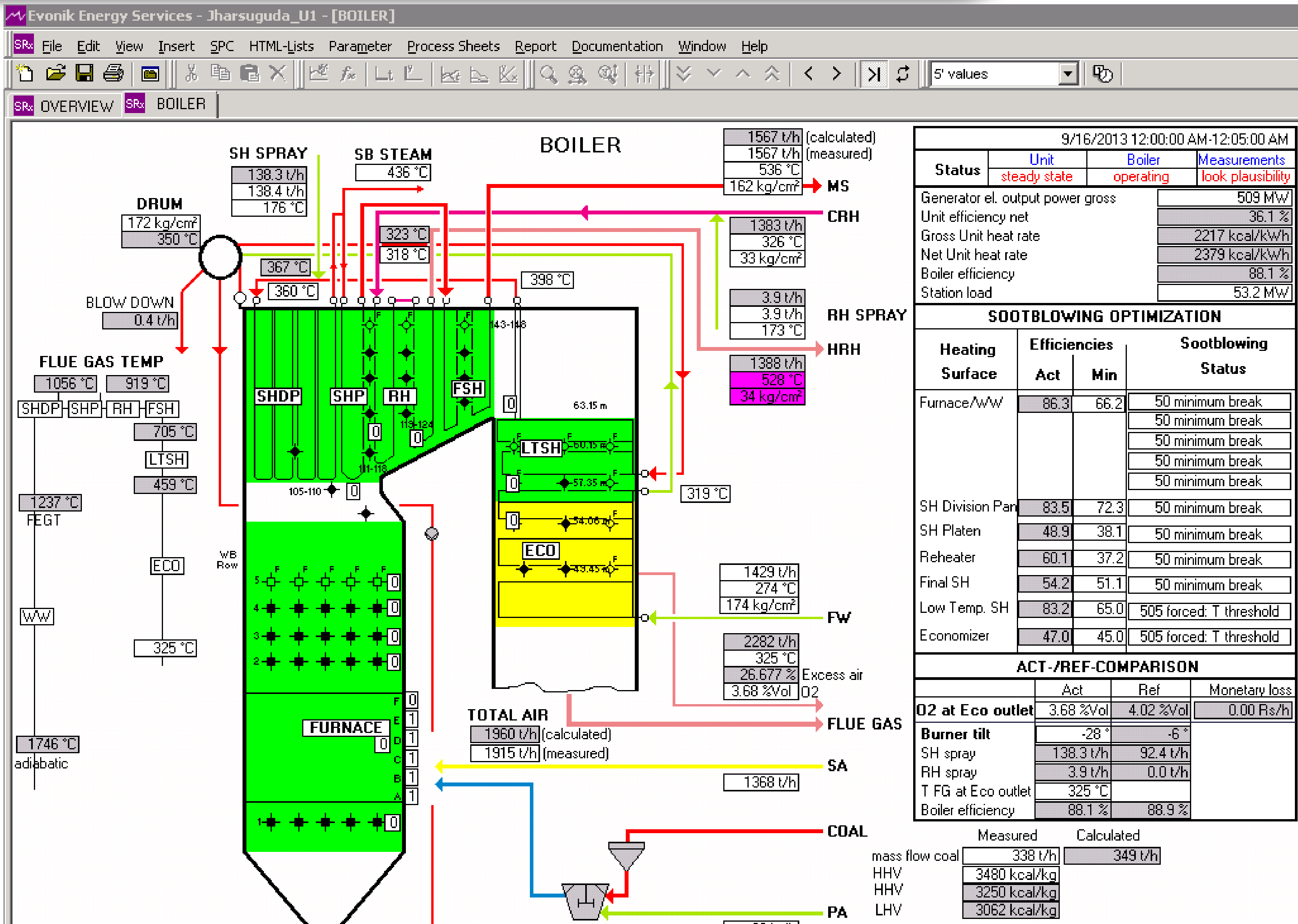

Process overview

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Evonik Energy Services - Jharsuguda_U1 - [BPOS]

File Edit View Insert SPC HTML-Lists Parameter Process Sheets Report Documentation Window Help

5' values

OVERVIEW | BOILER | BPOS

BPOS Backward Calculation Screen

9/16/2013 12:00:00 AM-12:05:00 AM

Load [MW]	509
MS flow [t/h]	1567
MS temp [°C]	536
RH temp [°C]	528

Ambient air temperature [°C]	27	
Relative humidity [%]	60	
Flue gas oxygen at Eco outlet	4.01	
Flue gas oxygen at AH outlet	6.05	
Burner tilt [°]	-28	
Mills in operation	A	on
	B	on
	C	on
	D	on
	E	on
	F	off

Boiler Thermal Performance Data

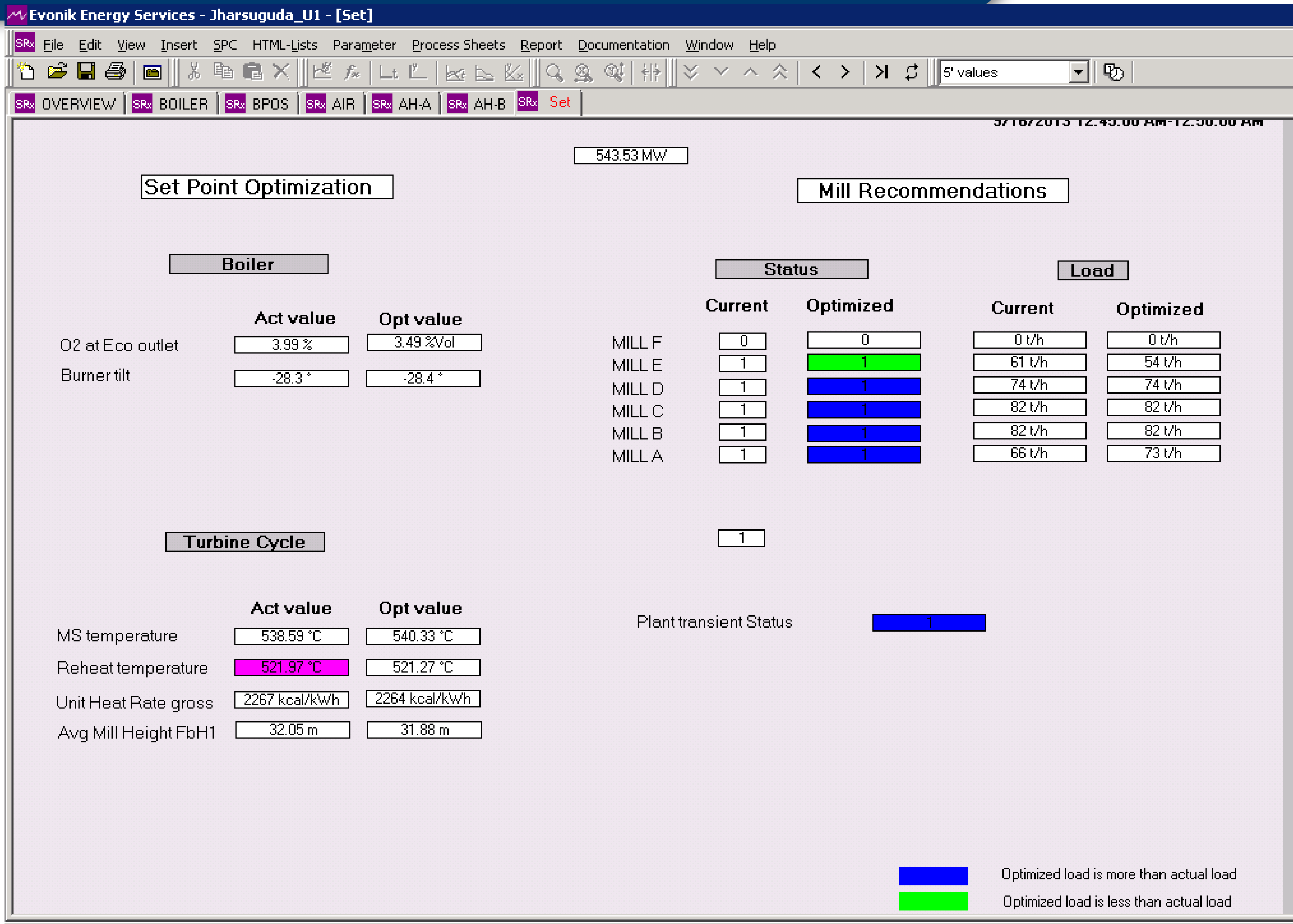
Section	Flue gas temperature [°C] Inlet	Flue gas temperature [°C] Outlet	Fluid temperature [°C] Inlet	Fluid temperature [°C] Outlet	Fouling factor	Zonal heat absorption [MW]	Maximum Metal Temperature [°C]
Waterwalls	1746	1237	350	350	0.86	439	
Div.Panel SH	1237	1056	367	436	0.83	151	
Platen SH	1056	919	436	536	0.49	100	
Reheater	919	705	323	528	0.60	182	596 °C
Final S.H.	705	653	502	537	0.54	42	575 °C
LTSH	653	459	350	398	0.83	147	
Economiser	459	325	274	319	0.47	97	
Air heater	325	131			0.98	126	

Coal mass flow [t/h]	338
Bottom ash removal rate [%]	20
Duct ash removal rate [%]	5
AH ash removal rate [%]	3
Fly ash removal rate [%]	72
UBC in ash [%]	0.2

Coal analysis	Calculated
GCV [kcal/kg]	3250.00
Ultimate	
Carbon [%]	35.0
Hydrogen [%]	1.9
Nitrogen [%]	1.7
Oxygen [%]	7.6
Sulphur [%]	0.4
Total moisture [%]	15.2
Ash [%]	38.3
Proximate	
Total moisture [%]	15.0
Ash [%]	36.6
Volatile matter [%]	22.5
Fixed carbon [%]	25.8

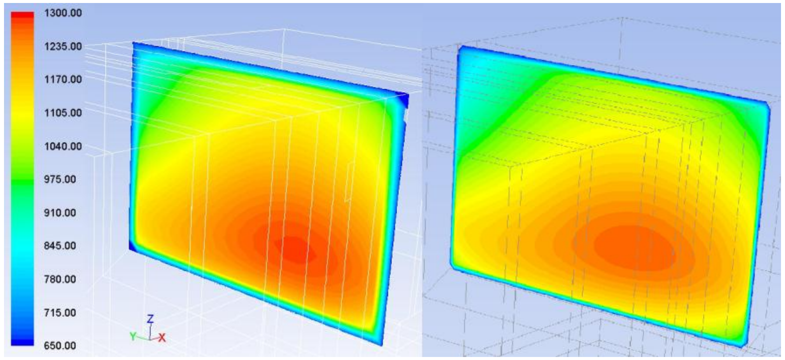
Heat balance	Act	Ref
Boiler efficiency [%]	88.14	88.91
Losses		
Dry gas [%]	4.71	3.86
H2O in fuel [%]	2.91	2.26
H2O from H2 in fuel [%]	3.27	3.55
H2O in air [%]	0.06	0.15
UBC [%]	0.23	0.74
Radiation [%]	0.11	0.22
Others [%]	0.68	0.30
Total losses [%]	11.98	11.09

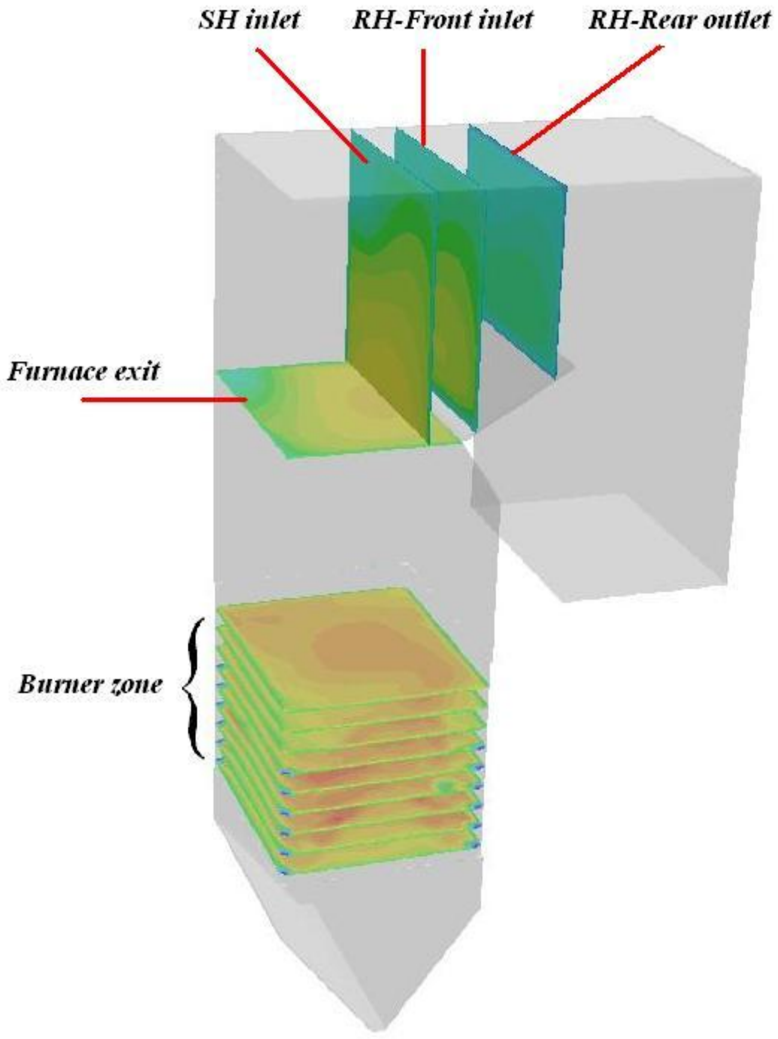
Set point optimization



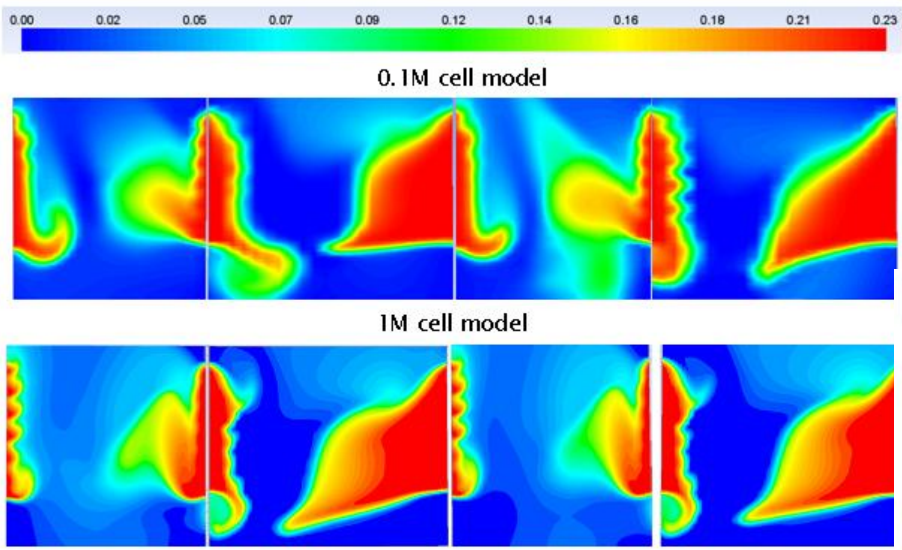
Combustion optimization with CFD modeling

CFD model development



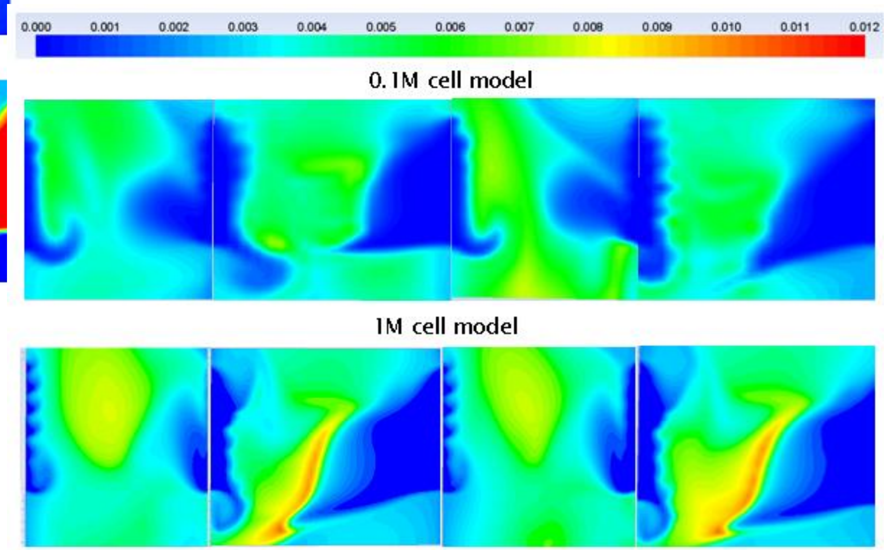


Oxygen and CO profiles in the furnace



O_2 profile at Combustion zone wall

CO profile at Combustion zone wall



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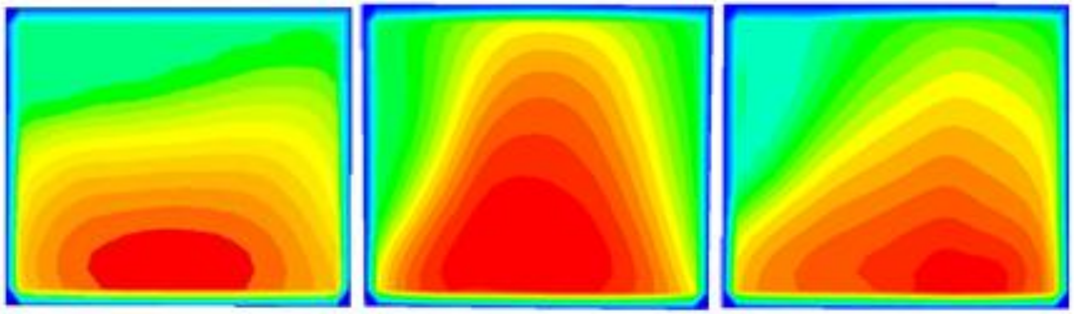
Effects of coal quality on combustion

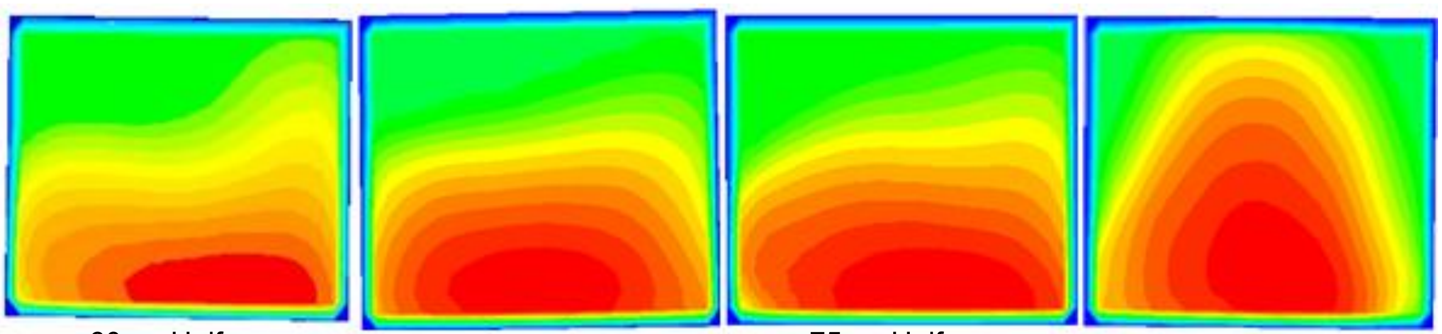
Results:

- ***Coal quality variation***



Design Coal | Worst Coal | Best Coal

- ***Coal quality variation***

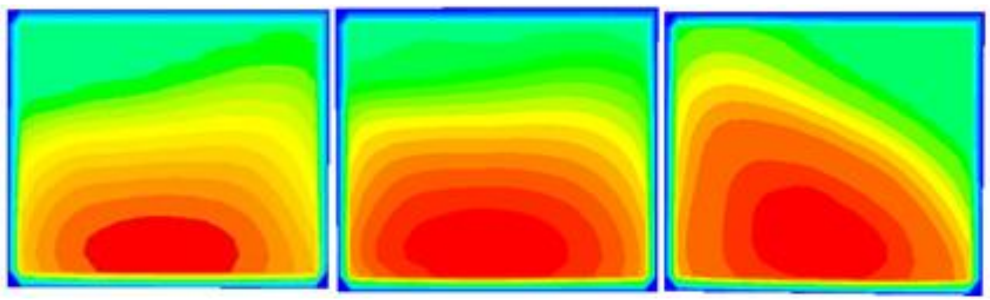


60µm Uniform Distribution | 70µm Uniform Distribution | 75µm Uniform Distribution | Risin-Rammler Distribution

Effects of burner tilt on combustion

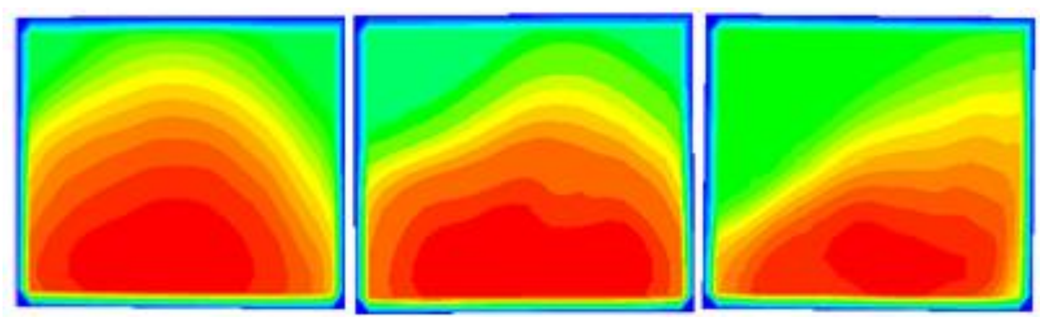
Results:

- ***Coal mill variation***



Top 6 mills | Middle 6 mills | Bottom 6 mills

- ***Burner tilt variation***

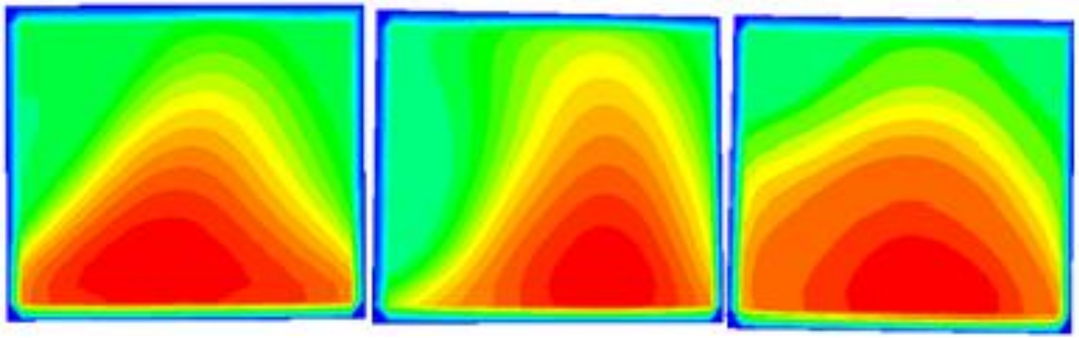


Burner Tilt = 0 Degree | Burner Tilt = +15 Degree | Burner Tilt = +30 Degree

Effects of biased coal flow

Results:

- ***Coal flow biasing for making uniform temperature distribution in reheater***



15% flow bias in corner 2&4

15% flow bias in corner 1&3

10% flow bias in corner 1&3

15% flow bias in corner 2&4

Advance models for combustion optimization

Advance techniques for optimisation

steag

Tools

- Soft Techniques: CFD, Artificial Neural Networks, A mathematical modelling developed by using CFD technique, calculates zone wise temperatures, Oxygen and CO, which is applied for controlling the O2 etc

Techniques

- Conventional techniques: coal velocity measurement, air leaks control

- Mathematical operations developed by using Artificial Neutral Networks are used for **learning the behavior** of the boiler/plant like variation of O2 in one corner and its effect on SH/RH spray etc.

- Development of **advance controls** through mathematical models

- www.powitec.de, a subsidiary of Steag Energy, Germany involved in Combustion Optimisation techniques.

Combustion Optimization through control modifications

A case study

Problem definition

Furnace had right and left temperature imbalance .

This phenomenon is noticed in three main parameters

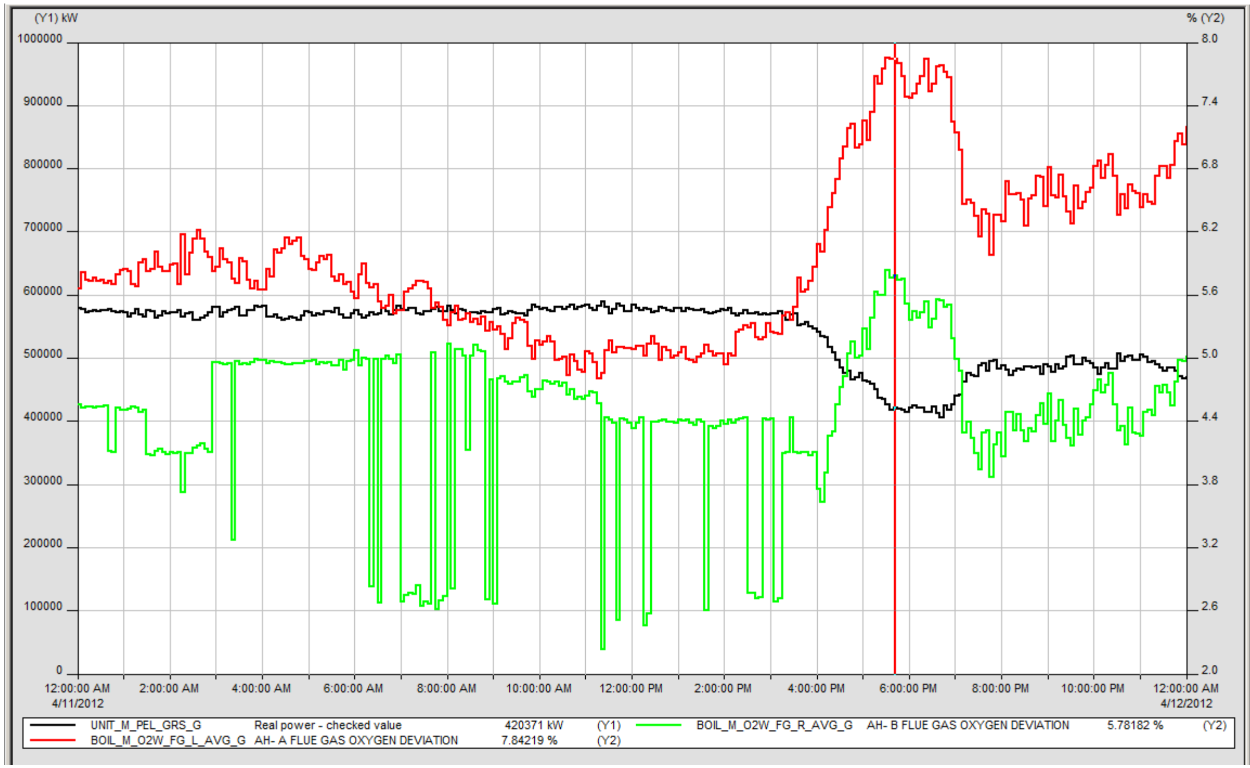
- ✓ **Flue gas temperature between right and left at Reheater outlet**
- ✓ **Oxygen difference between right and left at economizer outlet.**
- ✓ **Main steam and re-heater spray difference between right and left**

Process Parameters

Si.No	Parameter	Right Hand Side		Left Hand Side		Difference	
		min	max	min	max	min	max
1.	Oxygen content (%)	2.2	5.8	4.8	7.8	0.17	3.1
2.	Re-Heater flue gas inlet temperature(C)	651	740	624	795	-35	107
3.	Super Heater Spray(kg/sec)	0	20.13	12.0	24.2	-7.7	21.2
4.	Re-Heater Spray(kg/sec)	17.3	26.2	6.8	26.2	-19.3	5.3

Analysis of parameters

- SADC dampers corner wise opening
- Coal flow of a mill
- Burner Tilt corner wise



check the plausibility of the solution a manual test on SADC dampers was carried out
Results were successful

Solution

CLOSE LOOP COMBUSTION TO ADAPT

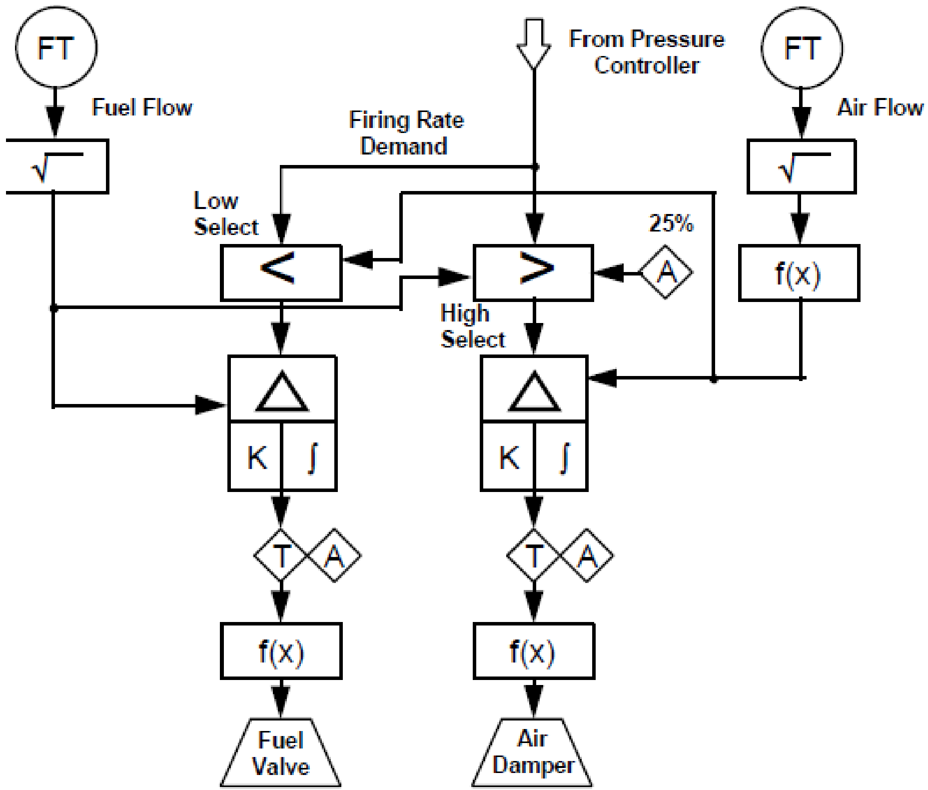
Closed loop combustion optimisation

steag

Steps in a closed loop combustion optimization

1. Communication: to communicate with a DCS, MODBUS (TCP/IP)
2. Control modification: different control loops   Biasing the set point
3. Exploration: A process of generating a step tests to create a learning set for data driven models (Neural Nets, Auto regression models, etc.,)
4. Defining the. Right and left imbalance is the objective

Combustion control

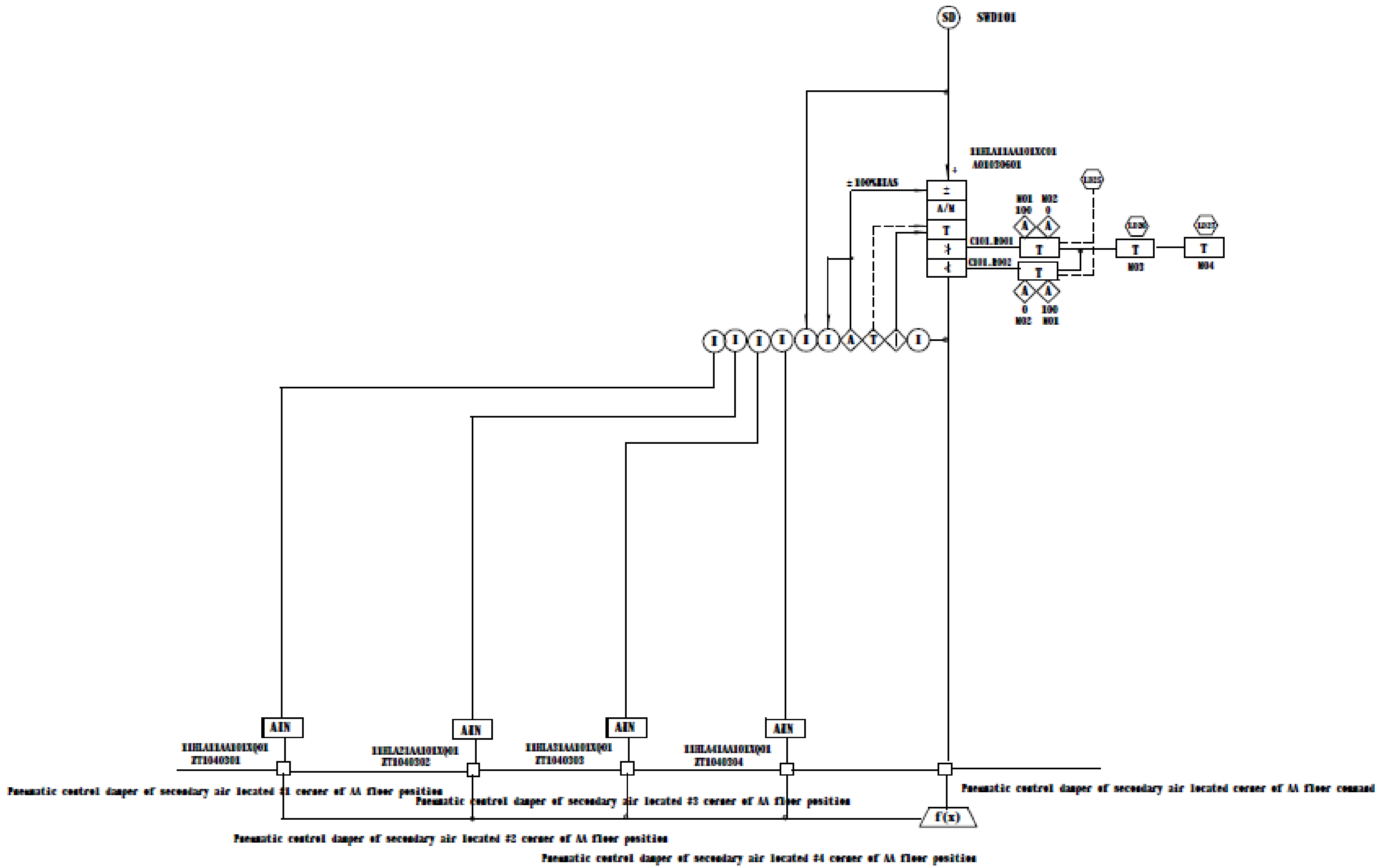


Combustion controls have two purposes:

(1) maintain constant steam conditions under varying loads by adjusting fuel flow,

(2) maintain an appropriate combustion air-to-fuel flow

Control Modification (actual loop)



Thank You

... Ideas & Solutions for Tomorrow