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Performance Enhancement of a Boiler Using Flame Image Processing

[1]ABI P. Mathew, [2]A. Asokan, [3]K. Batri and [2]D. Sivakumar

[1]St. Joseph's College of Engineering &Technology, Palai, Kerala, India
[2]Instrumentation Engg, Annamalai University, India
[3]Department of ECE, PSNA College of Engineering and Technology, Dindigul, Tamilnadu, India

Abstract: The efficiency of combustion in terms of heat generated inside the combustion area can be improved by careful analysis and mathematical modelling. In this proposed method, model formulated from mathematical regression using the empirical data collected through experiments is used to estimate the air fuel ratio and video based temperature measurement system is used to estimate combustion temperature for faster control of combustion in a diesel fired boiler. The proposed method is experimentally proven to be better than conventional intrusive methods in terms of minimizing loss due to time lag in temperature control operations of combustion control.

Key words: Boiler efficiency · Combustion optimisation · Air-fuel flow control

INTRODUCTION

Combustion efficiency analysis and modelling for improvement of combustion process has always been an area of research. Improvement of combustion efficiency in terms of reduction of harmful emissions and improvement in extracting maximum possible energy from the fuel supplied are methods on which experiment are done. Literature [1] details a method for combustion efficiency in terms of emission data analysis at various loads. Analysis of CO_2 absorption from exhaust flue gas and newer methods for CO_2 absorption is proposed in literature [2, 3]. Improvement of combustion efficiency in terms of fuel used is determined in literature [4]. Improved combustion by bio energy generation and use is detailed in literature [5].

Researches have been done on improving combustion efficiency and thereby overall efficiencies. The factors which affect combustion and the temperature generated inside the boiler includes the air fuel ratio, quality of inlet air supply in terms of temperature and moisture content, quality of fuel supplied in terms of calorific value. Controller design for overall efficiency improvement of boiler by modelling a robust controller considering the uncertain inputs associated with combustion has been done by many researchers. Studies on pressurised combustion system and efficiency improvement is discussed in literature[3]. Indirect method of efficiency calculation with different quality of coal supply has been done by Chetan *et al.* [6]. Performance comparison of combustion by using water-continuous emulsions stabilised by bio-based macromolecule has been done [7]. The effects on bio-oil as fuel in combustion are discussed in literature [8]. The recent development in the design of regenerative combustion systems is discussed in literature [9] through which a new low NOx regenerative burner is presented. The effect of inlet air temperature on reducing the energy requirement as fuel for combustion is analysed [10],[11] details the effect of intake air temperature and air fuel ratio variations on combustion and performance parameters.

Through the details of the researches done on combustion efficiency system analysis, it is observed that a compensation for the unpredictable disturbance in combustion is rare. The sophisticated system detailed in this literature is a solution for uncontrollable disturbances on combustion through air fuel inlet manipulation along with a fast and reliable feedback system.

Corresponding Author: ABI P. Mathew, Assistant Professor, St. Joseph's College of Engineering &Technology, Palai, Kerala, India.

Factors Affecting Combustion Efficiency

Fuel Characteristics: The fuel characteristics have a dramatic effect on combustion efficiency [12]. With gaseous fuel, the higher the hydrogen content, the more the water vapour formed during combustion. The result is energy loss as the vapour absorbs energy in the boiler and lowers the combustion efficiency.

Heat Content of the Fuel: The efficiency calculation requires the knowledge of the calorific value (heat content) of the fuel and its carbon to hydrogen ratio. The energy content of fuels used in combustion is widely published as

- The higher heating value is also known as Gross Calorific Value (GCV)
- The lower heating value or Net Calorific Value (NCV)

The GCV is the higher figure and assumes that all heat available from the fuel is to be recovered, including latent heat

MATERIALS AND METHODS

Through mathematical evaluation, the relationship is established between temperature generated due to combustion and required min fuel supply. Air flow rate is also predictable for the quality of optimum fuel flow through the studies. This air-fuel estimation system modelled with the feedback system based on video forms the intelligent system for combustion control.

Mathematical Method of Air-fuel Estimation: Experiments were done on 25 litres diesel fired boiler prototype. The empirical data collected from the experiments were used to formulate the models for estimating

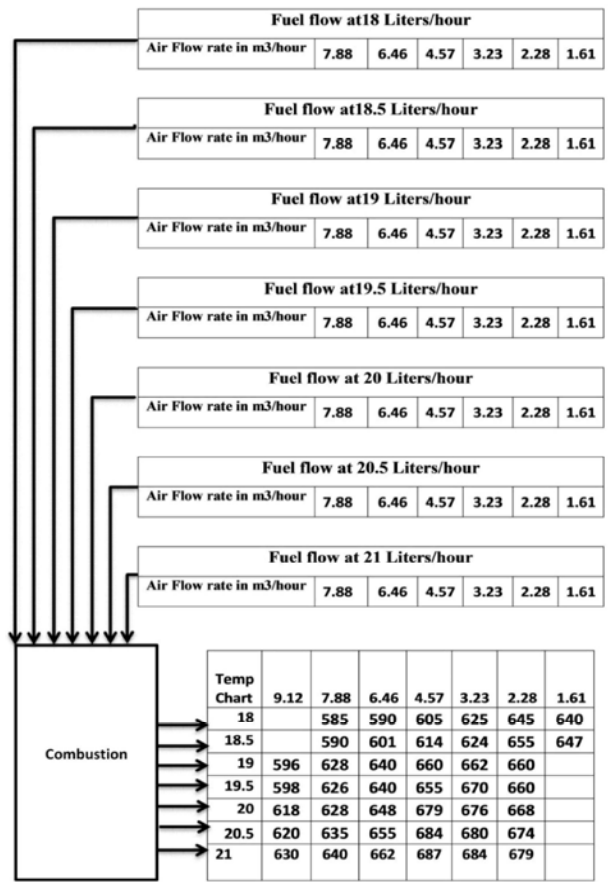
Minimum fuel essential for generating required flame temperature

Inlet air flow rate proportional to estimated minimum fuel flow rate

The required flame temperature inside the boiler is proportional to the boiler load requirement. Researchers have already proved the relationship between load and generated boiler temperature through their studies [13-15].

Empirical data collected from the experiments conducted are detailed in figure 1. The known/required boiler temperature is the input from which the required minimum fuel flow rate and air flow rate proportional to the fuel rate is estimated as shown in figure. 2. Equation 1 represents relationship between temperature and minimum fuel supply for achieving that temperature

$$f_f = 0.0757T_c - 31.224 \quad (1)$$



Temp Chart	9.12	7.88	6.46	4.57	3.23	2.28	1.61
18		585	590	605	625	645	640
18.5		590	601	614	624	655	647
19	596	628	640	660	662	660	
19.5	598	626	640	655	670	660	
20	618	628	648	679	676	668	
20.5	620	635	655	684	680	674	
21	630	640	662	687	684	679	

Fig. 1: Empirical data from experiments.

where T_c, is the temperature and f_f is the required inlet-fuel flow rate for achieving 'T_c' temperature.

The correlation coefficient between fuel-inlet rate and air-inlet flow while achieving maximum temperature is 0.9591 and the mathematical model formulated between air flow rate and fuel flow rate for achieving maximum boiler temperature is

$$a_f = -0.3022f_f^3 + 17.592f_f^2 - 339.93f_f + 2183.5 \quad (2)$$

where, a_f is the air-inlet flow rate that generates maximum possible boiler temperature with f as the inlet fuel flow rate.

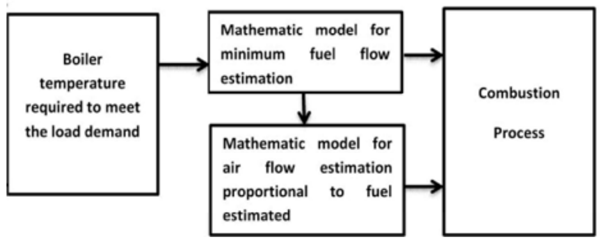


Fig. 2: Schematic of air-fuel estimation method

Video Based Temperature Measurement: The temperature generated inside the boiler can be measured by intrusive and non-intrusive methods. The features of video which are closely related with temperature can be used to measure temperature [16]. Temperature variations inside the boiler depend on load requirements. Variations in the air-fuel ratio of combustion bring in the change inside the boiler. The time lag in building variations in temperature is proportional to the range of required temperature change. Quick verification of expected temperature from the given air-fuel ratio can be done by video-based temperature measurement method, as a fast and accurate alternative. Whenever there is a change in air-fuel ratio as per load requirement, video based temperature measurement can be employed for quick verification of expected temperature. The air-fuel estimated by model formulated as explained for required generation of temperature may not produce expected results because of quality variations in fuel supplied and properties of air supply. To compensate the change in temperature generated with the estimated air-fuel ratio, a controller can be incorporated.

Control System Model for Combustion: A controller design with improved efficiency is developed through the experimental study. The empirical data collected from the experiments were used for designing the system.

The process variables being measured in combustion control using split control techniques are Inlet air flow rates, Inlet fuel flow rates and boiler temperature. Temperature measurement using a non-intrusive method using flame video can be selected for fast measurement of boiler temperature during changes. The parameter being controlled by combustion control is boiler temperature and the manipulated variables are inlet air flow control and inlet fuel flow control. The scheme of combustion control is shown in figure. 3. The temperature generated during combustion can be controlled by controlling the inlet air flow rate and inlet fuel flow rate. The feedback or the process variable can be measured using a thermocouple during regular operation.

Sudden change in boiler temperature may be required during load changes and for providing fast temperature measurement, video based temperature measurements can be employed as shown in figure 4.

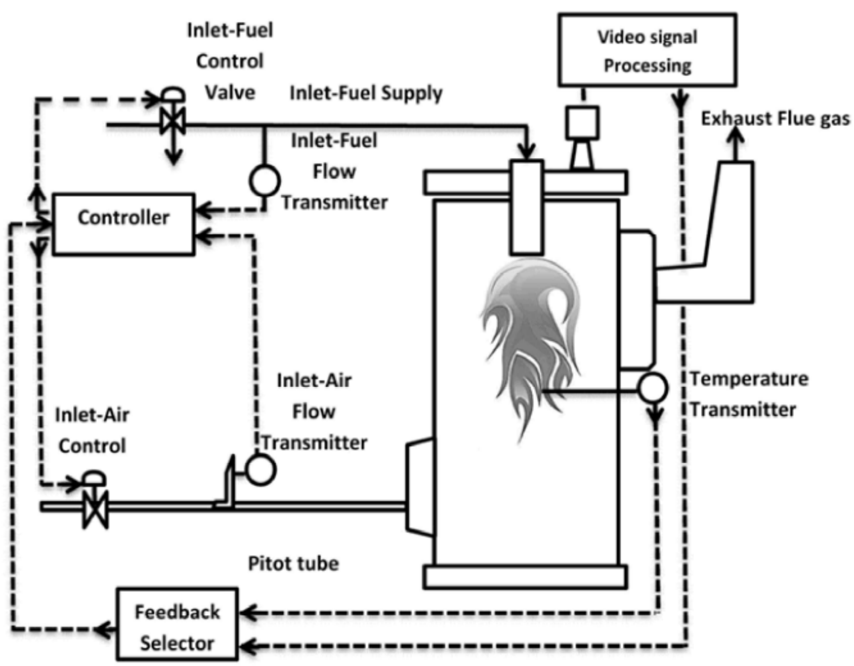


Fig. 3: Schematic of combustion control

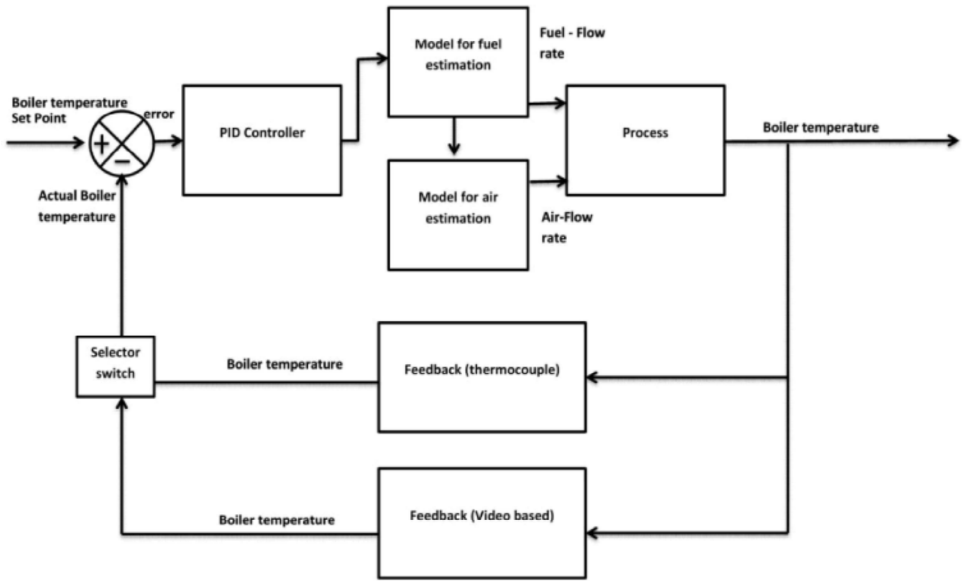


Fig. 4: Combustion Control system- Block diagram

Table 1: Combustion temperature with inlet air flow of 36^0Celcius

Air Supply (m3/Hour)	18 liters/hour	18.5 liters/hour	19 liters/hour	19.5 liters/hour	20 liters/hour	20.5 liters/hour	21 liters/hour
9.12			599	601	621	623	633
7.88	588	593	630	630	631	637	642
6.46	592	604	643	644	650	657	665
4.57	607	618	663	657	682	688	690
3.23	627	627	666	673	680	682	687
2.28	648	658	662	663	670	677	682
1.61	634	649					

Table 2: Combustion temperature with inlet air flow of 28^0Celcius

Air Supply (m3/Hour)	18 liters/hour	18.5 liters/hour	19 liters/hour	19.5 liters/hour	20 liters/hour	20.5 liters/hour	21 liters/hour
9.12			594	595	615	618	627
7.88	583	587	625	624	625	632	637
6.46	587	598	638	638	645	652	659
4.57	601	612	658	652	676	681	685
3.23	623	620	659	666	673	677	682
2.28	642	652	657	658	665	671	677
1.61	637	643					

Process Disturbances: The temperature generated during combustion process are primarily affected by the inlet air-fuel flow ratio and disturbed by changes in fuel quality, inlet air temperature and air humidity. Experimental studies have proved that inlet air temperature has a direct relationship with the generated temperature during combustion. Experiments were conducted at different inlet air temperature to measure the effects of inlet air temperature in combustion. Table 1 and 2 shows the generated combustion temperature with different inlet air temperatures.

The proposed closed loop control system is designed to overcome the change in the output of combustion regarding generated temperatures because of unprecedented and uncontrollable changes in fuel quality or disturbances caused due to changes in inlet air temperature. It is proved that inlet air temperature has a very significant role in generated combustion temperature for sustainability; controller designed has to compensate for fuel loss due to changes in air temperature. The range of inlet air temperature varies from 10 to 20 degree Celsius in a day in certain areas as per studies conducted in

Gujrat, India [17]. Change in inlet air temperature of 20 degrees brings in noteworthy changes in combustion temperature where inlet air is supplied directly without preheating

The temperature of the air may be taken into account for a fine tuned controller design as the disturbance in the process caused due to changes in inlet air temperature is large.

Control System Design Methodology: Mathematical relationships formulated from the empirical data are used for modelling the control system. Minimum fuel and air for combustion are predicted from the mathematical relationship formulated. The effect of uncontrollable disturbances due to change in inlet air temperature are taken into consideration in the design process. Mathematical regression is used to formulate the process model to which the uncontrollable and controllable parameters are affected. The formulated model is shown in equation 3.

$$T_c = -8.68788077227974a_f + 20.4670228928465f_f + 0.675595238095232a_t + 266.652942760515 \quad (3)$$

Where f_f is fuel flow rate a_f is air flow rate and a_t is inlet air temperature and T_c is the temperature generated by combustion. The fuel flow rate and inlet air flow rates are controllable parameters whereas inlet air temperature is an uncontrollable parameter in case of furnace or boilers with no air preheaters.

Feedback System: The parameters that influence combustion include controllable parameters like inlet fuel flow, inlet air flow and uncontrollable parameters like quality of fuel, inlet air temperature (where air preheaters are not used). Controllable parameters can be manipulated according our requirement to meet the demands as an open loop control, but as combustion process are influenced by uncontrollable disturbances, the feedback system is required to nullify the effects due to these uncontrollable parameters. Taking uncontrollable parameters into account, closed loop system with temperature feedback will help in further optimising fuel flow to meet the combustion temperature requirement.

RESULTS AND DISCUSSIONS

The motivation behind the experimental work done is to find out a method through which the usage of fossil fuel for combustion can be optimised. The first stage of experimental results was used to extract the features from the flame video for establishing a relationship between combustion temperature and flame image feature. For optimising the combustion, from the set of empirical data collected with different air fuel ratio, a relationship was established to predict the minimum fuel required for generating a required temperature. The temperature generated in combustion is primarily affected by air fuel ratio. Formulating a relationship to estimate correct air supply required for combustion for generating combustion temperature with the estimated fuel supply was the next step. A mathematical relationship was established to estimate the air supply required along with optimum fuel supply to generate required combustion temperature.

The proposed combustion control strategy uses the fuel estimation model which is proposed in the previous chapter, is used to fix the inlet fuel flow rate to a minimum for the generating the required combustion temperature.

The total response time of the temperature measurement consists of the response time of several components in the temperature measurement system. Building up combustion temperature from the flame generated by the given air-fuel ratio requires time. Tuning the air-fuel ratio to generate required temperature further consumes time. Optimisation of combustion process requires fast estimation of temperature from the supplied air-fuel ratio. The flame image based temperature estimation is proposed as a solution for faster estimation of temperature that is generated from the supplied air-fuel ratio. When measuring boiler temperature, the temperature sensors are installed in thermowell to protect the sensors from the harsh operating conditions. The thermowell is heavy metal tubes and, consequently, slow down the temperature response at the sensor. Other factors in the overall temperature measurement response time include the heat transfer from the flame to the thermowell, conduction across the thermowell, heat transfer from the thermowell to the sensor sheath and heat transfer to the sensor itself. If the sensor is not fully inserted in the bottom of the well, the heat transfer between the well and the sensor will be significantly degraded.

The advantage of using the non-intrusive method of temperature measurement by image processing is the capacity of image processing method for faster estimation of combustion temperature. Thus, the effect of process disturbance on the process can be rectified faster for efficient combustion. The major disturbances which may affect the combustion process are identified as changes in quality of fuel supplied, the temperature of inlet airflow and humidity of inlet air flow. Figure 3 shows the comparison of feedback response of combustion system using flame image system as feedback and non-intrusive (thermocouple) as feedback.

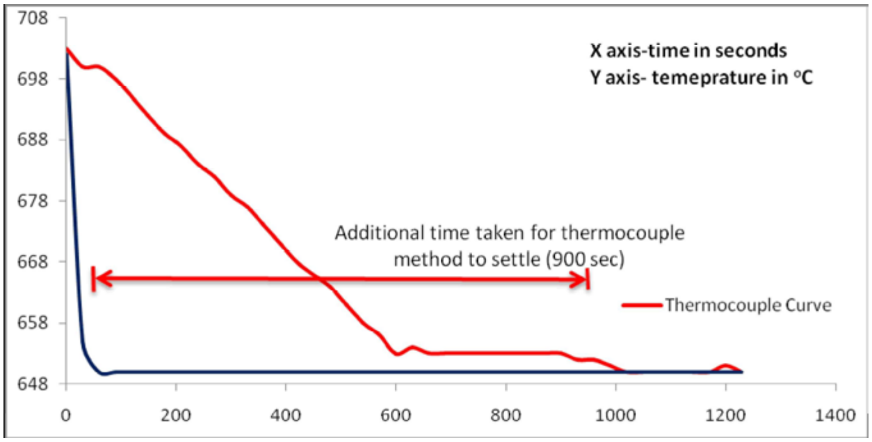


Fig. 5: Combustion temperature response curve (700oC to 650 oC change)

Table 3: Combustion temperature change from 700 °C to 650 °C

	Intrusive(Thermocouple) Method			Image Processing Method		
Time (Seconds)	Estimated fuel	Estimated air	Temperature generated	Estimated fuel	Estimated air	Temperature estimated
0	17.981	2414.82	703	17.981	2414.82	702
30	17.981	2414.82	700	17.6025	2499.43	655
60	17.981	2414.82	700	17.6025	2499.43	650
90	17.981	2414.82	698	17.6025	2499.43	650
120	17.981	2414.82	695	17.6025	2499.43	650
150	17.981	2414.82	692	17.6025	2499.43	650
180	17.981	2414.82	689	17.6025	2499.43	650
210	17.981	2414.82	687	17.6025	2499.43	650
240	17.981	2414.82	684	17.6025	2499.43	650
270	17.981	2414.82	682	17.6025	2499.43	650
300	17.981	2414.82	679	17.6025	2499.43	650
330	17.981	2414.82	677	17.6025	2499.43	650
360	17.981	2414.82	674	17.6025	2499.43	650
390	17.981	2414.82	671	17.6025	2499.43	650
420	17.981	2414.82	668	17.6025	2499.43	650
450	17.981	2414.82	666	17.6025	2499.43	650
480	17.981	2414.82	664	17.6025	2499.43	650
510	17.981	2414.82	661	17.6025	2499.43	650
540	17.981	2414.82	658	17.6025	2499.43	650
570	17.981	2414.82	656	17.6025	2499.43	650
600	17.981	2414.82	653	17.6025	2499.43	650
630	17.981	2414.82	654	17.6025	2499.43	650
660	17.981	2414.82	653	17.6025	2499.43	650
690	17.981	2414.82	653	17.6025	2499.43	650
720	17.981	2414.82	653	17.6025	2499.43	650
750	17.981	2414.82	653	17.6025	2499.43	650
780	17.981	2414.82	653	17.6025	2499.43	650
810	17.981	2414.82	653	17.6025	2499.43	650
840	17.981	2414.82	653	17.6025	2499.43	650
870	17.981	2414.82	653	17.6025	2499.43	650
900	17.981	2414.82	653	17.6025	2499.43	650
930	17.6025	2499.43	652	17.6025	2499.43	650
960	17.6025	2499.43	652	17.6025	2499.43	650
990	17.6025	2499.43	651	17.6025	2499.43	650
1020	17.6025	2499.43	650	17.6025	2499.43	650
1050	17.6025	2499.43	650	17.6025	2499.43	650
1080	17.6025	2499.43	650	17.6025	2499.43	650
1110	17.6025	2499.43	650	17.6025	2499.43	650
1140	17.6025	2499.43	650	17.6025	2499.43	650
1170	17.6025	2499.43	650	17.6025	2499.43	650

Figure 5 shows analysis of response curve of thermocouple method of feedback measurement took 900 seconds more to conclude that with the given air-fuel ratio, the temperature generated is 653 °C and not 650 °C. To maintain the combustion temperature to the required temperature of 650 °C, corrected air fuel ratio was supplied after that. By the time correction was made, an additional fuel of 94.62 millilitres was consumed. The detailed response of two feedback methods are shown in Table 3.

CONCLUSION

The difference in response time between both these feedback methods are because flame image processing method estimates the temperature from the image features whereas thermocouple method measures the temperature in synchronisation with the actual temperature change. Actual temperature change consumes time and that time is taken for the change can be avoided by using flame image processing method of temperature estimation. Thus, the additional fuel supplied to the combustion system can be evaded and optimum combustion can be achieved.

Through the detailed analysis, the proposed method of combustion control substantiated its better efficiency through air-fuel estimation procedure in control part and image processing method for feedback.

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