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Design and Application of Automatic Control System in a Laboratory Scale Fluidized Bed Coal Combustion System

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Abstract

The air and coal ratio must be calculated according to bed material, bed temperature and emissions to obtain an efficient combustion at energy production foundations. The amount of air which enters the combustion chamber can change according to the properties of fuel, moisture in air, outside temperature and air pressure, so it may change every season, day and hour. During the combustion, high amount of air causes to decreases in combustion temperature and increases in the NOx emissions, on the other hand, low amount of air causes to incomplete combustion products like CO. Automatic control systems are indispensable helpers which are able to reduce emissions, prevent pollutants and increase efficiency. In this study, the planned application is collecting flue gas data by sensors which are installed to the circulating fluidized bed. With the help of these signals the coal combustion system which has a laboratory size, produces feedback signals according to an algorithm which has determined before. Thus, the motor of the coal feeder and air flow fan which control the system can be actuated. The circulating fluidized bed (CFB) coal combustion system has been provided to operate in a proper and automatic manner.

1. INTRODUCTION

To generate steam or hot water fossil fuel boilers use the chemical energy from fuels. A nuclear boiler uses energy from nuclear fission. A waste heat recovery boiler uses the sensible heat of hot gases from a process, and a solar boiler uses energy from the sun to generate steam. Although the name boiler or steam generator implies conversion of water into steam, boilers used for space heating do not necessarily generate steam [1].

Fuel burns in the furnace of a boiler, generating heat, which is then absorbed by the heating surfaces located around it and further downstream. Figure 1 shows a schematic of a boiler, where steam is generated. This process is best explained by using the temperature-heat content (enthalpy) diagram of water. This diagram (Fig. 1B) shows the effect of addition of heat to a unit mass of water. Water is pressurized to the required pressure by a feed water pump. It is then preheated in a heat exchanger called an economizer. On the temperature-enthalpy diagram we see that as water moves from state (A) to state (B), it gains in both heat and temperature. However, the water is still below its boiling point (Fig. 1B). The preheated water then enters the evaporator section of the boiler, which forms the vertical walls of the boiler furnace shown in Figure 1A. These walls absorb heat from the combustion of fossil fuels in the boiler furnace. While traveling through the evaporative tube the water picks up heat, but does not necessarily rise in temperature because the heat is used in transforming water (liquid) to steam (gas). This process is represented by the horizontal line BC.

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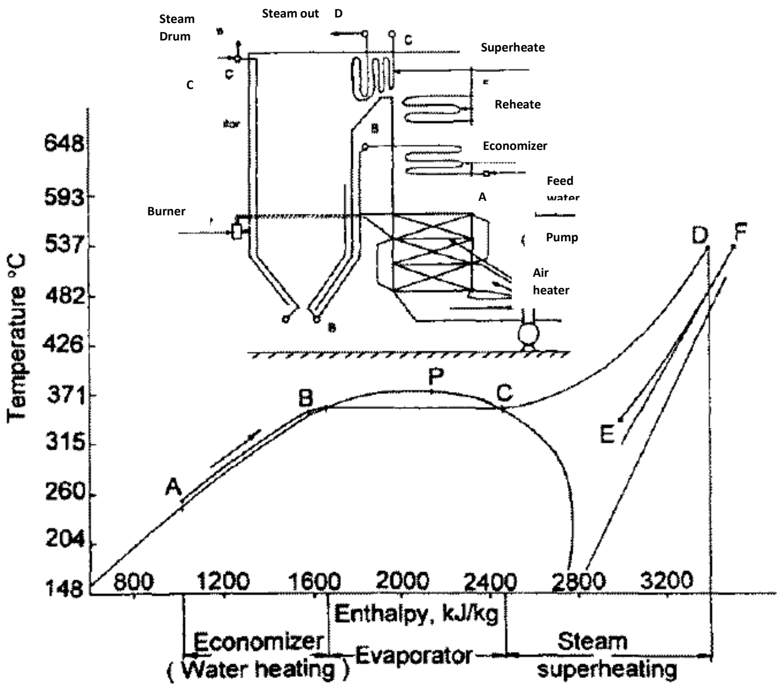


Figure 1. *Temperature enthalpy diagram of water showing the heating and phase transformation of water in a boiler [1].*

It is suitable to divide our study into two systems. These are fluidized bed coal combustion systems and automatic controlling systems. First of all, we are going to dwell upon the Fluidized Bed Coal Combustion Systems, and then we are going to investigate the Automatic Controlling Systems [2].

It is best to first understand the fluid bed structure and hydrodynamics before beginning to automate fluid beds. This is because the stability of the combustion and the suitability of the emission characteristics in steam boilers used for energy production from fuels such as coal or biomass is closely related to the stable operating condition.

In industrial applications, coal combustion systems can be divided into three main categories: pulverized combustion systems, fluidized bed combustion systems and fixed or moving grate combustion systems. Combustion is the appearing of the chemical energy, which exists in the constitution of combustible material, with mixing burning and combustible materials. In order to better understand the combustion systems, some basic properties are given in Table 1 below in a comparative manner [3].

Table 1. *Comparison of Coal Combustion in the Fluidized Beds and Other Coal Burning Technologies [3].*

	Powder Coal Combustion System	Fluidized Bed coal Combustion Systems	Fix or Moving Grate Coal Comb. System
Operation temperature	1600-1900 °C	750-900 °C	1600 °C
Coal types	High quality lignite and hard coal	High or low quality lignite and hard coal	Only high quality and standard coals
Coal particle size	10-180 μm	dp < 12mm	25mm < dp < 30mm
Automatic system	required	important	not required
Emission control mechanism	required	not required	required

Numerous modeling and experimental studies have attempted to determine the behavior of fluidized bed combustion systems in the literature. One of them, Huilin at all studied a hydrodynamic, heat transfer and combustion stable mode model of a circulating fluidized bed burning coal in 1998. This model predicted coal concentrations, flue gas temperature and chemical gas components (O_2, H_2O, CO, CO_2 and SO_2) in the axial and radial regions containing the upper and lower parts of the reactor. The model's validity was confirmed by experiments on a commercial boiler with a low circulation rate of 35 t/h [4].

1.1. General Information about Fluidized Bed Coal Combustion Systems

Fluidized bed combustion is one of the most effective and reliable technologies for fuel utilization. In spite of rather long history of utilization in various industrial applications, only in the 1970s this technology was firstly applied to the large-scale utility. The principle of combustion is based on burning fuel in layer of air-suspended mass of particles located at the bottom part of furnace. It consists of silica sand or other inert material. The fuel is introduced into this layer and combustion air is supplied from the furnace bottom through the sand layer. In dependence on the velocity of the applied stream of air, the layer gets different types of fluid-like behaviour that illustrated on the Figure 2 [5].

Fluidization is to gain properties of fluid’s behaviors to solid particles or another description is the operation, which is converting the solid particles to fluid like particles in a gas or liquid medium [6,7].

1.2. Process of Fluidization of Particules at Fluidized Bed

A bed of particles behaves like a porous structure when a fluid of relatively small flow rate is allowed to pass through it. In this situation the fluid percolates through the void spaces between densely packed particles. This is called as fixed bed. Increasing the flow rate of fluid until a pre-determined value is reached causes an increase in the pressure drop measured across the bed. Further increase in the flow rate of fluid causes the particles to undergo restricted movements or vibrations and this intermediate behavior is called as expanded bed. As the flow rate of fluid is still increased, a situation is reached where the drag forces exerted on the particles due to the fact that upward flow of fluid will be sufficient to support the weight of the particles. This is called as minimum fluidization condition. If the fluid flow rate is still increased within a range the fluid bed behaves like a boiling liquid. This state is called as bubbling fluidized bed.

After a fluid flow rate exceeds a point which is characteristics of a specific particle size and surface area, such particles will be conveyed by the fluid. Finally, a situation will be reached where the fluid flow rate is sufficient to convey almost all the particle sizes in the bed. In this stage the particles are under regime of pneumatic transport of solids and this state of fluidization is called as circulating bed [8].

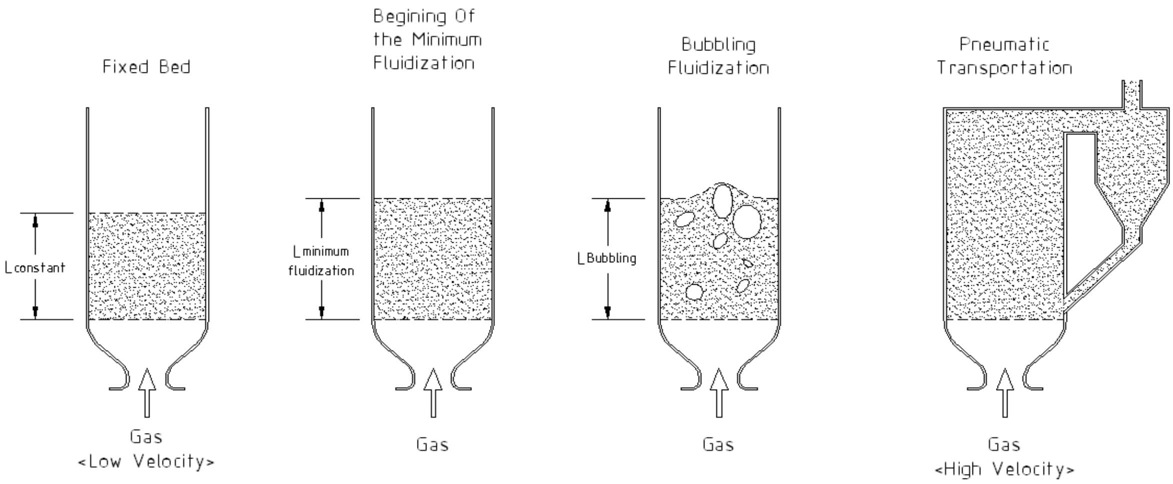


Figure 2. *Phases of Fluidization and Formation of Bubbling*

1.3. Classification of Fluidized Bed Furnaces

Classification of fluidized beds can be divided into two groups. First group is according to operational pressure. This group includes atmospheric fluidized bed furnaces and pressurized fluidized bed furnaces. Second group is according to fluidization conditions. This group includes bubbling fluidized bed furnaces and circulating fluidized bed furnaces (Figure 3).

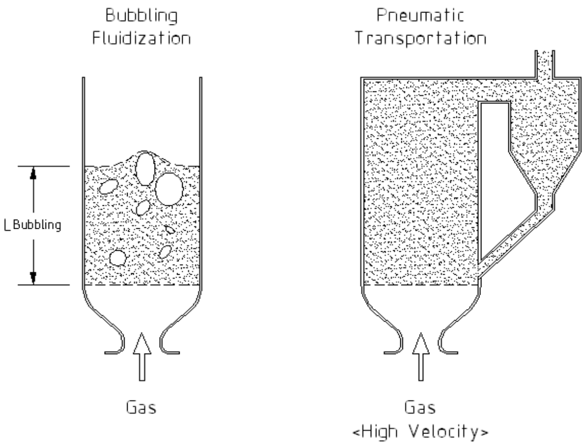


Figure 3. *Scheme of Bubbling and Circulating Fluidized Bed Column*

General Descriptions

There are three kind of fluidized bed. These are;

Bubbling Fluidized Bed

It supplies a mixing which is close to perfect. There is a bed surface between the bed region and free region. Volatile ashes and very small particles are kept by electrostatic or sack filters, relatively big particles are kept by cyclone and if it is needed, it will be returned to system, again. System heat absorption pipes are placed to bed regions and regions where flue gases pass through. It supplies 800-900°C constant temperature. It is not preferred for high capacity applications.

Circulating Fluidized Bed

Circulating fluidized bed boiler can be divided into two sections. First section includes the furnace, gas-solid separator, recycle device, and possible external heat exchangers. Another section, that typically named back-pass, consists of heat exchangers for absorption flue gasses heat, such as reheater, superheater, economizer, and air preheater.

Separation of bed and free surface cannot be made. Need of limestone is smaller than BFB. They are faster than BFB. Combustion is carried on whole furnace volume with gradated air supply. Circulation becomes fact due to particles, which are smaller than 450μ, are kept and returned to the system, after particles are removed with 4-6 m/s velocities from reactor. Furnace pipes are placed to walls, not to burning room. Transformation of fuel origin NO_X to atmospheric origin NOX is obtained by gradated air supply. Therefore, emissions are decreased on a large scale.

Pressurized Fluidized Bed

They run between 5-20 atm pressures. They produce combustion gases to feed gas turbines, not only steam production. They are more efficient to atmospheric fluidized bed. Cleaning of hot gas problem is existent.

1.4. Parts of Fluidized Bed Combustion Systems

A general fluidized bed combustion system consists of wind room, distributor sieve, burning room, coal feeder unit, ash absorption unit, fan units, ignition units and controlling units. Automation in fluidized bed combustion systems is extremely important. Bubbling type of fluidized beds are more stable systems and that's why easy to control. Because of the instability in the hydrodynamic structures of the fast fluidized beds is that, automatic control system is more important.

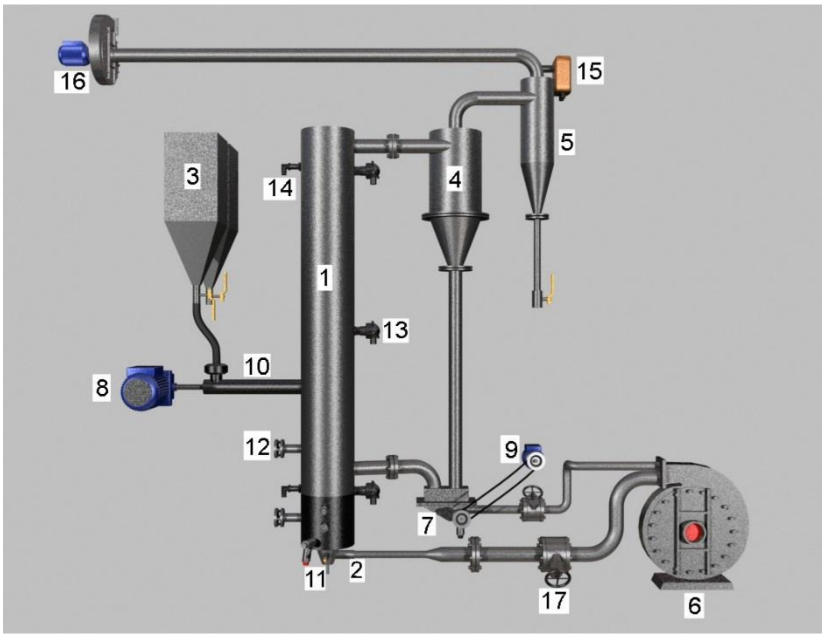
2. EXPERIMENTAL SYSTEM AND PROGRAMMING

This section describes the general description of the fluidized bed combustion system and the automatic control system.

2.1. System Description

The CFBC system used in this study included a 125 mm i.d., 3000 mm tall main column (Riser), two high efficiency cyclones in series, a re-circulation bed, fuel feeding and ash discharging systems and a flue gas analysis system [9,10]. A schematic of the CFBC apparatus is shown in Figure 4. The riser of 310 mm outer diameter was made of stainless steel and was insulated from inside with insulation material down to the diameter of 125 mm. The riser is connected to the first cyclone at the top by 80 mm i.d. insulated pipe. This is a small scale CFB combustor. The solid materials carried by combustion gases are returned to the main column by a re-circulation bed. The re-circulation bed has dimensions of 100 mm x 140 mm x 100 mm. It has a distributor plate with 500 orifices, each with a diameter of 1.0 mm. The re-circulating bed is mounted with the main column at a level 370 mm above its distributor plate. The air split ratio between the re-circulation bed and the riser is 1/5. Air from the re-circulation bed to the riser is not a secondary air. The re-circulation bed is mainly used to collect the material from the cyclone and to transfer the gases and solids to the riser by pneumatic conveying.

In the experiments, a blower of capacity 1000 m^3/h (7.5 hp) was used. Air was introduced to the system from four pipes. This air was used as fluidization air as well as the combustion air. Hot solids were separated from the gas in the first and second cyclones. Natural gas was used to preheat the bed material. It was introduced into the system from a nozzle below the distributor plate.



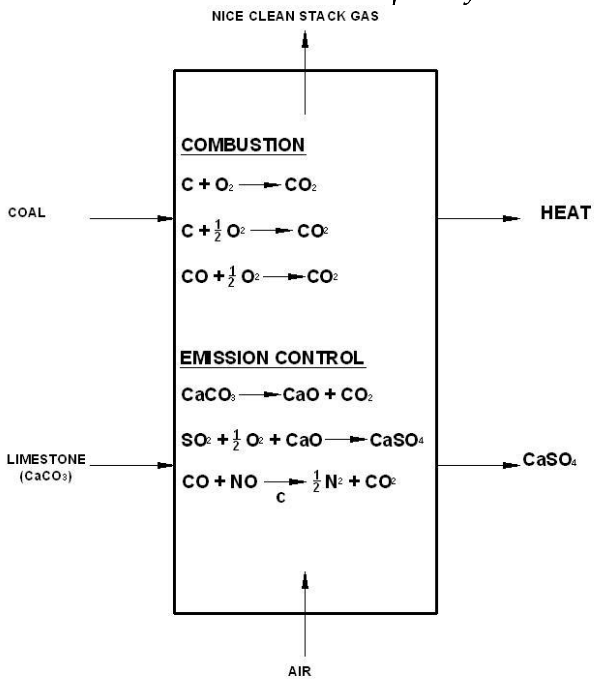
1-Main column (Riser)
2-Air entrance
3-Coal and adsorbent silo
4-1st cyclone
5-2nd cyclone,
6-Air blower,
7-Back feeding bed,
8-Fuel feeding system,
9-Ash handling system
10-Screw feeder
11-Ash handling system (Riser)
12-Observation hole
13-Temperature measurement
14-Pressure measurement
15-Flue gas handling
16-Induced ventilation fan
17-Primary air control valve

Figure 4. *Scheme of the Gazi University Thermal Power Laboratory CFB*

2.2. Automatic Controlling Systems

Reasons of why we need the automatic controlling system are increase in the energy requirement, environment pollution due to emissions and requirement of more efficient systems. Table 2 shows us the most general reactions, which occurs in fluidized bed coal combustion systems and gives to us an idea about mechanisms in the fluidized bed [6].

Table 2. *Black Box Model of the System*



There is a philosophy about the automatic control of these types of systems. This philosophy includes several loops. These are steam pressure control, drum level control, furnace pressure control, steam temperature control, bed temperature control, bed inventory control, coal feeder's control, combustion air control, SO_2 emission control, de-aerator pressure control [11].

These loops provide and control the most important variables of the system process. In all loops, there are two main values, generally. One of them is calculated value or approximate value. Other is measured value or real value. The differences between these values give the feedback signal. This signal provides the continuity of the processes in a range of desired values with using actuators.

Five basic parameters are controlled: bed temperature control, bed inventory control, coal feed control, SO_2 emission control, and combustion air control.

Bed Temperature Control

Bed temperature must be kept between 840-900°C (Figure 5). Bed temperature value affects the motor of coal feeder system. There are four thermocouples. These devices are placed at the specific heights of bed, hence temperature variations is always under control along the bed's height. A determined temperature value must be chosen as operation temperature. This determined value is our stability line. In the situation of unexpected temperature changing, our controller will take data of temperature from our thermocouples and calculate the difference between measured temperature and determined temperature. These differences are converted to analog signals and sent to relevant actuators of system. This process is a close loop operation and causes a fluctuation in the operation temperature, until the operation temperature will keep the determined value (set temperature).

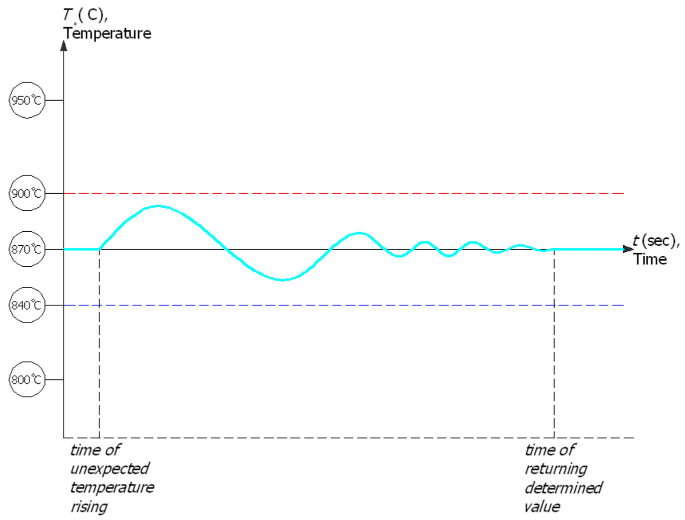


Figure 5. *Illustration of temperature fluctuation [12].*

Bed Inventory Control

Bed inventory control is another loop. This control is made to determine the amount of material in the bed. This is an important parameter for fluidization and combustion. There are two DPT - Differential Pressure Transmitters and these devices are used for reading the pressure variations in the bed. One of them is located to the top of the bed. It can be named as lower pressure tap, then other is located to the splash zone and it can be named as upper pressure tap. Difference between these pressure taps is a great helper to determine the bed height. There are some correlations about relation between pressure drop, bed height, fraction voids etc. One of them is correlated by Ergun and this correlation is named with his name. The correlation is;

$$\frac{\Delta P}{L} g_c = 150 \frac{(1-\varepsilon_m)^2}{\varepsilon_m^{\ 3}} \frac{\mu u_0}{\left(\phi_s d_p\right)^2} + 1,75 \frac{1-\varepsilon_m}{\varepsilon_m^{\ 3}} \frac{\rho_g u_0^{\ 2}}{\phi_s d_p}$$

At the situation of non-randomly packed beds, beds of solids of abnormal void content and highly porous beds $\varepsilon_m = 0.6 \text{ to } 0.98$, the pressure drop can be much greater than predicted value by Ergun correlation [13]. In reality, particles are not uniformly sized. There will be mixed particles in the bed. So, we need the mean diameter of the particles. This term is shown with $\bar{d}_p$ and can be calculated as;

$$\bar{d}_p = \frac{1}{\sum^{all\ i} \left(x/d_p\right)_i}$$

Pressure drop in beds of mixed particles follows the Ergun equation for single size of particles with d_p replaced by $\bar{d}_p$. Thus for a size distribution of particles Ergun equation becomes,

$$\frac{\Delta P}{L} g_c \cong 150 \frac{(1-\varepsilon_m)^2}{\varepsilon_m^{\ 3}} \frac{\mu u_0}{\left(\phi_s \bar{d}_p\right)^2} + 1,75 \frac{1-\varepsilon_m}{\varepsilon_m^{\ 3}} \frac{\rho_g u_0^{\ 2}}{\phi_s \bar{d}_p}$$

Coal Feeder Control

There is a coal feeder located on the front wall of the reactor. The coal requirement of the reactor is compensated by it. It is a kind of screw type conveyer and is controlled by an electric motor. Our actuator in this control will be it.

There are two factors in this section; these are amount of coal in the reactor and amount of temperature error. Amount of temperature error will adjust amount of coal in the reactor. If we consider the relation between these factors is according to a mathematical correlation, we can use PID controller. PID controller is abbreviation of proportional, integral, derivative [14]. These type controllers are designed to eliminate the need for continuous operator attention. Cruise control in a car and a house thermostat are common examples of how controllers are used to automatically adjust some variable to hold the measurement (or process variable) at the set-point.

Proportional Band – With proportional band, the controller output is proportional to the error or a change in measurement (depending on the controller).

$$\begin{pmatrix}\text{Controller}\\ \text{Output}\end{pmatrix} = (\text{Error}) \times 100 \Big/ \begin{pmatrix}\text{Proportional}\\ \text{Band}\end{pmatrix}$$

With a proportional controller offset (deviation from set-point) is present. Increasing the controller gain will make the loop go unstable. Integral action was included in controllers to eliminate this offset.
Integral – With integral action, the controller output is proportional to the amount of time the error is present. Integral action eliminates offset.

$$\begin{pmatrix}\text{Controller}\\ \text{Output}\end{pmatrix} = (1/\text{Integral})(\text{Integral of }) e(t)\, d(t)$$

Derivative – With derivative action, the controller output is proportional to the rate of change of the measurement or error. The controller output is calculated by the rate of change of the measurement with time.

$$\begin{pmatrix}\text{Controller}\\ \text{Output}\end{pmatrix} = \text{Derivative}\left(\frac{dm}{dt}\right)$$

Where m is the measurement at time t.

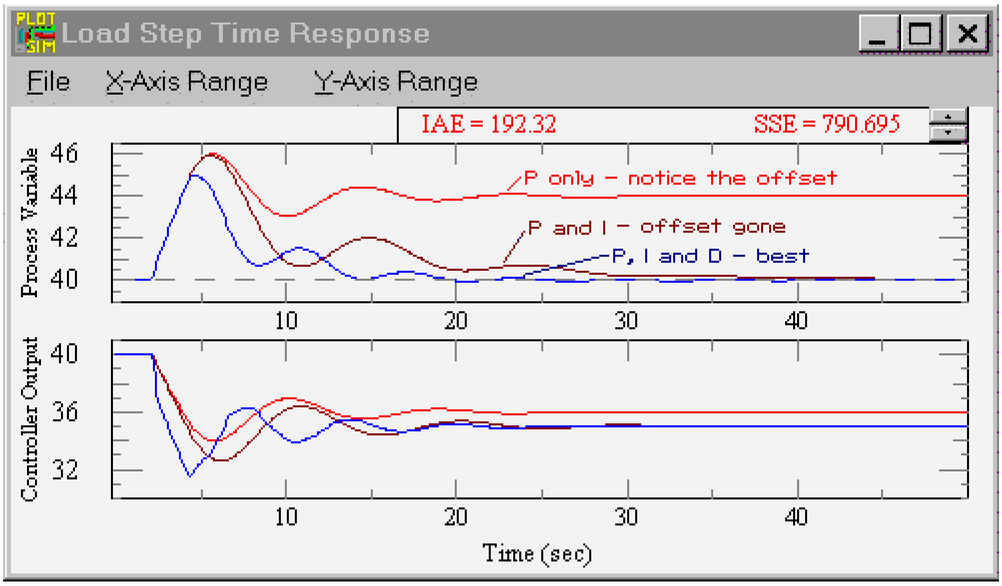


Figure 6. *Proportion, Integral and Derivative (PID Controller)*

According to this information, we can send analog signals to the receiver of the actuator according to the variation in the temperature level of the reactor. In other word, coal flow trim is obtained by difference between set temperature and measured temperature (Figure 6).

Combustion Air Control

There is a fan to provide the requested amount of air flow through the reactor and requirements in the system. The main problem in this control is the amount of air or velocity of air flow. The gas flow rate through a fluidized bed is limited on one hand by u_{mf} and on the other by u_t entrainment of solids by the gas.

Firstly, air flow in the reactor is the principle element of the fluidization. Our fan can be thought as the air flow actuator. Therefore, it must be overcome the load which comes from the fluidization process. If we remember the conditions of the fluidization, air flow velocity must provide minimum fluidization conditions. It can be calculated by the equations at below;

In general, this gives a quadratic in u_{mf} [15]:

$$\frac{1{,}75}{\phi_s \varepsilon_{mf}^{\;3}}\left(\frac{d_p u_{mf} \rho_g}{\mu}\right)^2 + \frac{150(1-\varepsilon_{mf})}{\phi_s^{\;2} \varepsilon_{mf}^{\;3}}\left(\frac{d_p u_{mf} \rho_g}{\mu}\right) = \frac{d_p^{\;3} \rho_g (\rho_s - \rho_g) g}{\mu^2}$$

For small particles:

$$u_{mf} = \frac{(\phi_s d_p)^2}{150} \frac{\rho_s - \rho_g}{\mu} g \left(\frac{\varepsilon_{mf}^{\;3}}{1-\varepsilon_{mf}}\right) \quad , \mathrm{Re}_p < 20$$

For large particles:

$$u_{mf}^{\;2} = \frac{(\phi_s d_p)}{1{,}75} \frac{\rho_s - \rho_g}{\rho_g} g \varepsilon_{mf}^{\;3} \quad , \mathrm{Re}_p > 1000$$

If ε_{mf} and ϕ_s are unknown,

For the whole range of Reynolds numbers:

$$\frac{d_p u_{mf} \rho_g}{\mu} = \left[(33{,}7)^2 + 0{,}0408 \frac{d_p^{\;3} \rho_g (\rho_s - \rho_g) g}{\mu^2}\right]^{1/2} - 33{,}7$$

For small particles:

$$u_{mf} = \frac{d_p^{\;2} (\rho_s - \rho_g) g}{1650 \mu} \quad , \mathrm{Re}_p < 20$$

For large particles:

$$u_{mf}^{\;2} = \frac{d_p (\rho_s - \rho_g) g}{24{,}5 \rho_g} \quad , \mathrm{Re}_p > 1000$$

Air flow velocity is increased until it reaches to the minimum fluidization velocity. This value is minimum required value of air. The upper limit of air flow velocity is terminal velocity and if air flow reaches and overcome terminal velocity, entrainment of solid occurs. When entrainment occurs these solids must be recycled or replaced by fresh material to maintain steady – state operations. It can be estimated from fluid mechanics by [15];

$$u_t = \left[\frac{4 g d_p (\rho_s - \rho_g)}{3 \rho_g C_d}\right]^{1/2}$$

C_d is experimentally determined drag coefficient.

$$\mathrm{Re}_p = \frac{d_p \rho_g u_t}{\mu}$$

And the velocity independent group

$$C_d \,\mathrm{Re}_p{}^2 = \frac{4 g d_p{}^3 \rho_g \left(\rho_s - \rho_g\right)}{3\mu^2}$$

To calculate u_t, first we find $C_d \,\mathrm{Re}_p{}^2$ and corresponding Re_p is found from figure of $C_d \,\mathrm{Re}_p{}^2$ versus Re_p. Alternative way of finding u_t for spherical particles uses analytic expressions for the drag coefficient C_d. These are;

$$C_{d,\text{spherical}} = \frac{24}{\mathrm{Re}_p} \quad \text{for} \ \ \mathrm{Re}_p < 0{,}4$$

$$C_{d,\text{spherical}} = \frac{10}{\mathrm{Re}_p{}^{1,2}} \quad \text{for} \ \ 0{,}4 < \mathrm{Re}_p < 500$$

$$C_{d,\text{spherical}} = 0{,}43 \quad \text{for} \ \ 500 < \mathrm{Re}_p < 200{,}000$$

Replacing these values with C_d in the main u_t calculation equation gives analytic expressions for u_t,

$$u_{t,\text{spherical}} = \frac{g\left(\rho_s - \rho_g\right) d_p{}^2}{18\mu} \qquad \text{for} \ \ \mathrm{Re}_p < 0{,}4$$

$$u_{t,\text{spherical}} = \left[\frac{4}{225} \frac{\left(\rho_s - \rho_g\right)^2 g^2}{\rho_g} \right]^{1,3} d_p \qquad \text{for} \ \ 0{,}4 < \mathrm{Re}_p < 500$$

$$u_{t,\text{spherical}} = \left[\frac{3{,}1 g\left(\rho_s - \rho_g\right) d_p}{\rho_g} \right]^{1,2} \qquad \text{for} \ \ 500 < \mathrm{Re}_p < 200{,}000$$

After the calculation of the u_t, finally we have all limits about air flow set velocity.

$$u_{mf} < u_{set} < u_t$$

Fan unit is controlled by an electric motor. We want to change the velocity of the air flow. But we cannot make this with changing structural properties of the fan (blade geometry or number of blade). The fan control must be made by changing the position of the fan damper. So, a combustion air flow trim can be obtained. In addition to all these calculation, we must use a sensor to analyze the amount of oxygen and temperature of the flue. The air must be excessive in the reactor. So, we must measure the excess air in the system. Our sensor is TRIMOX Zirconium Oxygen Sensor (16). This sensor can measure the amount of oxygen in the flue and temperature of the flue. According to these variables can manage the system. According to analog I/O, various types of motors and system actuators can be controlled. Hence, Zirconium Oxygen Sensor is one of the most important system elements. It has already PID controller.

SO_2 Emissions Control

The Ca/S molar ratio is set by either the boiler demand signal or the operator and hence the requested limestone or dolomite, is calculated. The requested and the actual flows are compared to generate the error signal that is used to control the speed of the rotary valve mounted under the limestone silo.

$$CaCO_3 \rightarrow CaO + CO_2$$

$$SO_2 + \frac{1}{2}O_2 + CaO \rightarrow CaSO_4$$

$$CO + NO \rightarrow \frac{1}{2}N_2 + CO_2$$

These are the chemical reactions of the processes of the limestone in the reactor. We will need an online SO_2 analyzer. Value which is obtained by the analyzer, determines the amount of requested limestone. Difference between measured amount of limestone and the required amount of limestone, generates an error signal. This signal performs the limestone flow trim. Therefore, we have all the loops (Figure 7,8,9).

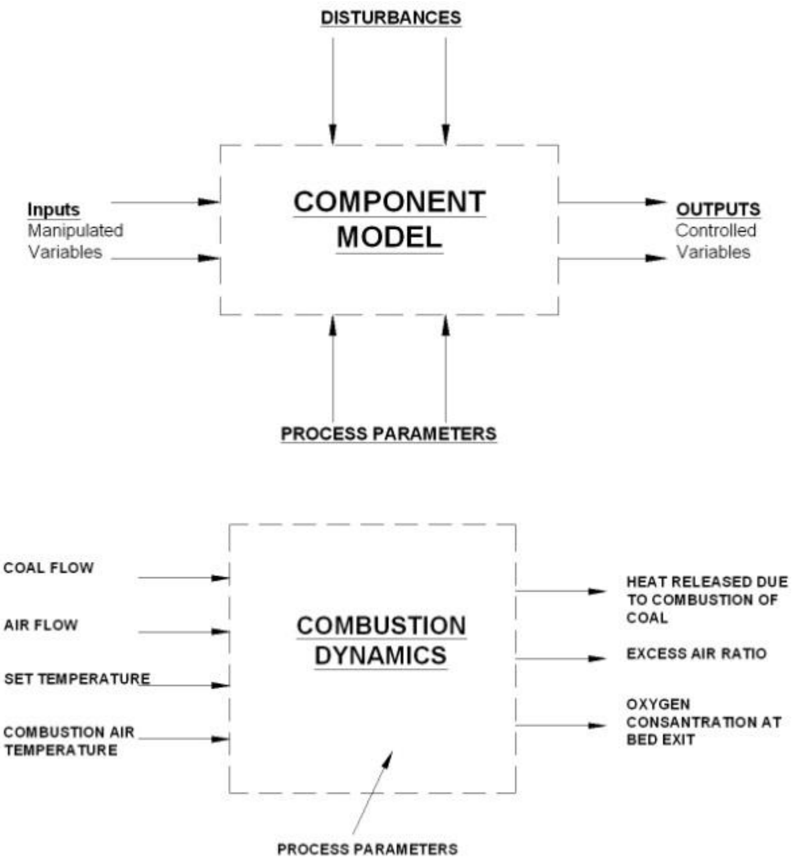


Figure 7. *Block Diagrams of Component Model and Combustion System [6].*

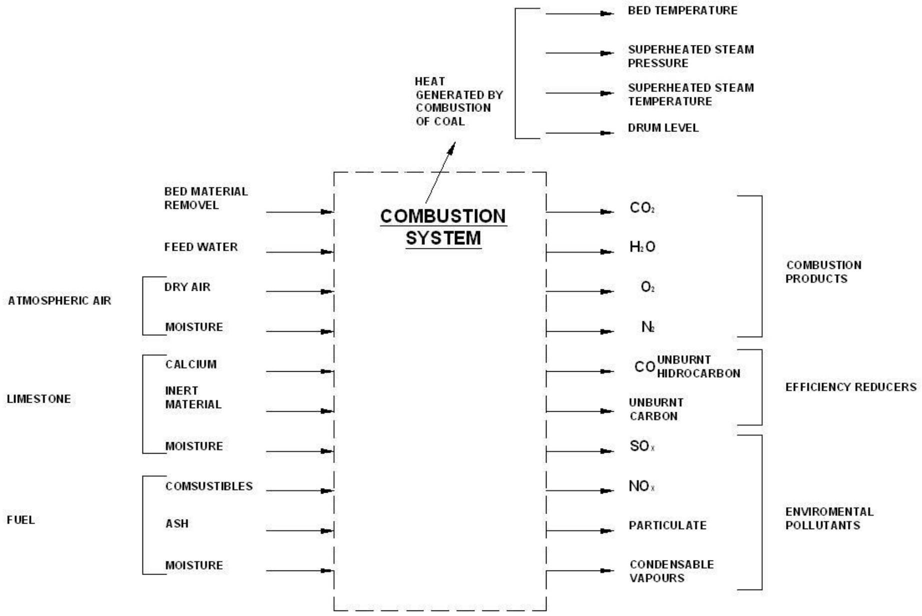


Figure 8. *Block Diagram of Combustion System [6].*

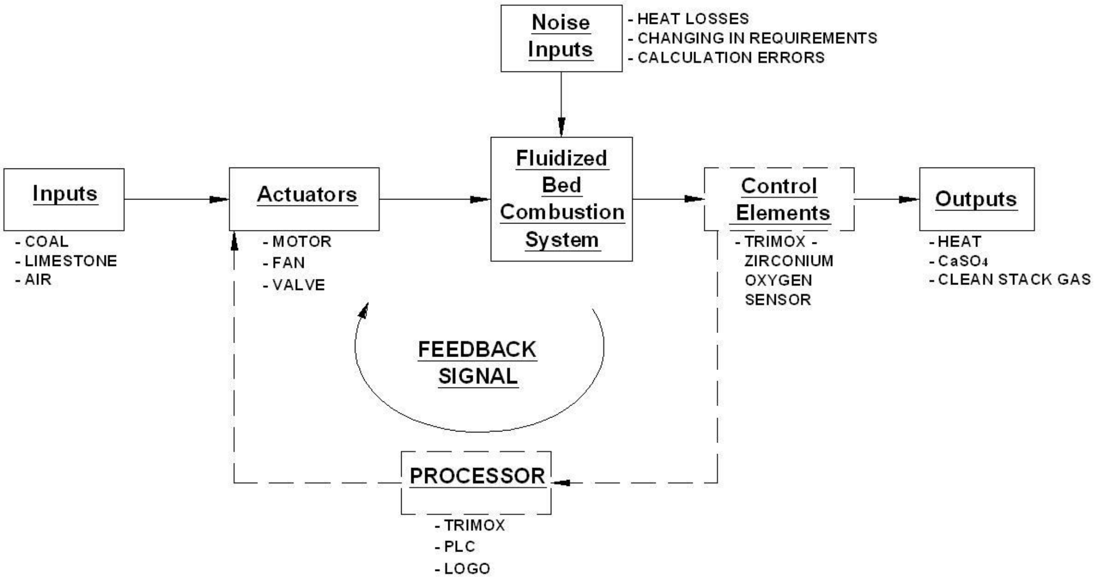


Figure 9. *General Automatic Control Philosophy of Fluidized Bed Coal Combustion System [12].*

The OB35 organizational block was used to control the cycle time in the STEP 7 program. It is targeted that the cycle time is compatible with the sampling time of the SCADA software. Otherwise, the time of occurrence of the activities in the system and the events cannot be followed. In this respect, it may be advisable to make adjustments to the system's time factor based on an experimental background. In this way, the response time of the system can be reached at an appropriate value. The effects on the temperature of the instantaneous changes in the system indicate that the time settings are correct and the end result system works consistently. In this study, cycle time and sampling time are set to 1000ms. One of the reasons why the periods are chosen so short is to shorten the period of observation. In fact, the occurrence and convergence times of events specified in system tests it takes longer than the current review of the system.

3. CONCLUSIONS

The circulation type fluidized bed combustion system in the Gazi University Engineering Faculty Mechanical Engineering Department Thermal Power Laboratory was studied and a capacity for the reactor to be constructed by STEP 7 mathematical equation is made. Through this equation a simulation is prepared in software. All the data in the prepared simulation are related to each other in terms of hydrodynamic structure and combustion conditions. Interactions have been tried to be brought close to real conditions.

The temperature in the bed is affected by too many parameters. Therefore, in such an application, the calculation can be performed and the processing time it must be kept within a reasonable range. Our formula for calculating the temperature in the bed is totally iterative and only the heat from the burning of the char is turned into heat by reducing various losses. The obtained temperature value is recalibrated in each cycle and the amount of error is continuously calculated between the received values of the multi-component temperature function at 1000ms. Depending on the amount of error, the function components are interfered and the new position of the system is determined, and the system performs the process on the final convergence path in each iteration.

In the system, the bed material and ash control were made by pressure drop. Inside the system, the air supplied by the fan is converted to superficial gas velocity after losses are reduced at certain rates. The surface gas velocity has emerged in experiments in which the basic combustion functions and the established hydrodynamic structure are kept at a value that allows circulation above the minimum fluidization rate in circulating fluidized bed combustion systems. This was presented as evidence of consistent operation of the system.

There is also a structure in the system that determines the amount of limestone to be fed according to the characteristics of the burned char. Because the system is fed with mixing of coal and limestone, limestone penetration is not shown. However, details regarding the limestone are visible in the design parameters. The results were added to the system in the pressure drop category as bed material and in the flue gas analysis category. In this section, the Ca/S index is presented as a parameter to determine the amount of limestone in the system. It has been observed that the Ca/S ratio is increased in the experiments conducted in the system related to this section, and the CO_2 amount in the end of flue gas is increased. This observation in real systems supports the consistency of the system.

During the system operation of the number of excess air layers measured from the flue gas close changes to real systems. The system is under control with 40% excess air layer in industrial systems. As a result, when the air excess coefficient in the air is above this value, the air concentration inside the bearing is increased and the air supply fan's temperature is modified within the limits of temperature, pressure and coal requirements. This was in accordance with the results of excess air in the bed.

Some scenarios were created within the system for clearer examination of changes in the system and automation response. These scenarios are for system test. With the basic parameters related to the system, the momentary changes that the system could experience were tried to be animated. As a result, it has been observed that the system returns to the stable state again by converging the set values.

Scenarios;

1-Variation in the ultimate analysis of coal
2-Change in average reactor temperature,
3-Change of Ca/S ratio,
4-Change of the average particle size in the bed,
5-Change of combustion efficiency
as the system was installed.

As a result, a coal combustion system in a Circulating Fluidized Bed, temperature, pressure and O_2 level in the flue gas should be established and the system should be fed coal, limestone and air values and the amount of ash that should be transported from the system has been developed. In the design of the system, the PLC S7-300 is accepted and necessary software is prepared according to the algorithm prepared in STEP 7 software. The system has a control panel in SIMATIC WinCC software and all data are recorded with sampling times of 1000ms.

System were carried out with high combustion efficiency and low air pollutant emissions by automatic control systems in the laboratory-scale CFBC with accepted data.

SYMBOLS

C	: Carbon
CS	: Fixed carbon
Ca	: Calcium
CaO	: Calcium oxide
CaCO3	: Calcium carbonate
CaSO4	: Calcium Sulphate
CmHn	: Total hydrocarbons, ppm
CO	: Carbon monoxide
CO_2	: Carbon dioxide
dP	: Particule diameter, μm
dP, ΔP	: Pressure drop, mbar, Pa
g	: Gravitational acceleration, m/ s2
L	: Height of riser, m
N2	: Nitrogen
NO	: Nitrogen oxide
NO2	: Nitrogen dioxide
NOX	: Total nitrogen oxides
O2	: Oxygen
P	: Pressure, Pa, mbar
ρS	: Solid particle density, kg/m3
ρg	: Gas density, kg/m3
ρb	: Bulk density, kg/m3
Re	: Reynolds number
S	: Sulphur
SO2	: Sulphur dioxide
SO3	: Sulphite
SOX	: Total sulphur compounds
U0	: Superficial velocity, m/s
Umf	: Minimum fluidization velocity, m/s
Ut	: Terminal velocity, m/s
ρ	: Density
ε	: Bed void ratio
μ	: Viscosity
Ø	: Spherical factor
η	: Efficiency
FBCCS	: Fluidized Bed Coal Combustion System
CFB	: Circulating Fluidized Bed
CFBC	: Circulating Fluidized Bed Combustion
FCC	: Fluid Catalytic Cracking
BFB	: Bubbling Fluidized Bed

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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