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Biomass Downdraft Gasifier Controller Using Intelligent Techniques

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Additional information is available at the end of the chapter

1. Introduction

In this world of deteriorating amount of non-renewable resources, the relevance of a biomass gasifier is immense. Biomass is the biological material from living, or recently living organisms. As an energy source, biomass can either be used directly, or converted into other energy products such as biofuel. Biomass is carbon, hydrogen and oxygen based. It is used as a good source of power generation. The gas composition in the producer gas, the final product of the gasification process is as follows: - CO: 15-20 %, H_2: 15-20 %, CH_4: 2-6 %, CO_2: 7-10 %, N_2: 40-50 %.

Power generation from biomass has become a complement to conventional sources of energy due to its contribution to the reduction of greenhouse effect. Biomass ranks fourth as an energy source and, in developing countries, it provides 35% of their energy. It must be noted that gasification is cheaper as well as having considerable efficiency compare with non renewable energy sources. Also, downdraft gasifiers with throat are known to produce the best quality gas for engines. There are mainly two types of biomass gasifiers, which are the fixed and the fluidized bed types. The fixed bed gasifiers have been the traditional setup used for gasification, operated at temperatures around 1000 ^{0}C. Among the fixed bed gasifiers, there are three major types and these are updraft, downdraft and cross-draft gasifiers. The updraft configuration is the simplest and oldest form of gasifier and is still used for coal gasification. In this, the biomass is introduced at the top of the reactor and a grate at the bottom of the reactor supports the reacting bed. The downdraft gasifier has the same mechanical configuration as the updraft gasifier except that the oxidant and product gases flow down the reactor, in the same direction as the biomass. Crossdraft gasifiers are used for charcoal gasification.

In the updraft gasifier, gas leaves the gasifier with high tar vapour which may seriously interfere the operation of internal combustion engine. This problem is minimized in downdraft

gasifier. In this type, air is introduced into downward flowing packed bed or solid fuels and gas is drawn off at the bottom. A lower overall efficiency and difficulties in handling higher moisture and ash content are common problems in small downdraft gas producers.

The time (20-30 minutes) needed to ignite and bring plant to working temperature with good gas quality is shorter than updraft gas producer. It undergoes in four different zones namely combustion zone, reduction zone, pyrolysis zone and drying & heating zone. The full view of the process zones are shown in the Figure 1. [1, 2].
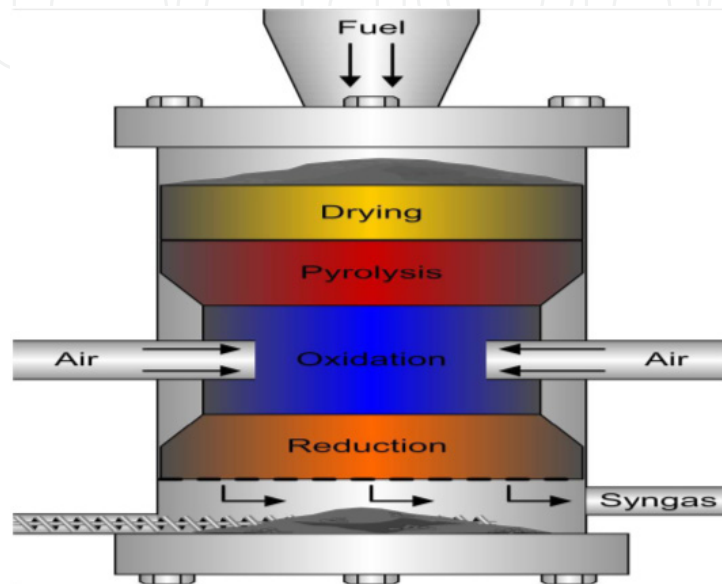

Figure 1. Downdraft gasifier producers

The various zones in the downdraft gasifier are as follows:

i.   Combustion zone

In complete combustion of solid fuel composed of Carbon, Hydrogen and Oxygen, CO_2 is obtained from Carbon is fuel and water is obtained from Hydrogen usually as steam. This takes place in the combustion zone. Also, exothermic reaction takes place here. The main reactions are:

$$C + O_2 = CO_2$$

$$2H_2 + O_2 = 2H_2O$$
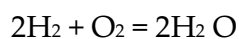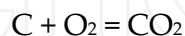
ii.   Reduction zone

The products of partial combustion (water, CO_2 and combusted partially cracked pyrolysis products) now pass through a red-hot charcoal bed where the reduction reaction occurs as follows:

$$C + CO_2 = 2CO$$

$$C + H_2O = CO + H_2$$
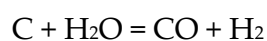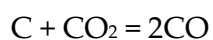
These reactions being endothermic have the capability of reducing the gas temperature. The temperatures are normally 800-1000 ^{0}C.

iii.   Pyrolysis zone

Wood pyrolysis is an intricate process. Products depend on temperature, pressure and heat losses. Up to 200 ^{0}C, only water is driven off. In 200-280 ^{0}C range, CO_2, acetic acid and water are given off. In 280-500 ^{0}C range, real pyrolysis occurs and produces large quantities of tar and gases containing CO_2. In the range of 500-700 ^{0}C, gas production is small and contains Hydrogen.

iv.   Drying zone

 Wood is being dried in the drying zone. Usually moisture content of wood is 10-30 per cent. Some organic acids come out during drying process which may cause corrosion of gasifiers.

2. Biomass gasification process

2.1. Wood gasification plant

The biomass downdraft gasifier is mostly used for power generation applications. It is basically a reactor into which fuel/feed stock is fed along with a limited supply of air. The heat that is required for gasification is generated through partial combustion of the feed material. This incomplete combustion leads to chemical breakdown of the fuel through internal reactions resulting in production of a combustible gas usually called Producer Gas. The calorific value of this gas varies between 4.0 and 6.0 MJ/Nm^3 or about 10 to 15 percent of the heating value of natural gas. Producer gas from different fuels produced in different gasifier types may considerably vary in composition. However, it consists always of a mixture of the combustible gases namely Hydrogen (H_2), Carbon Monoxide (CO), and Methane (CH_4) as well as incombustible gases such as Carbon Dioxide (CO_2) and Nitrogen (N_2). Because of the presence of CO, producer gas is toxic in nature. In its raw form, the gas tends to be extremely dirty, containing significant quantities of tars, soot, ash and water. In downdraft gasifier the fuel slowly moves down by gravity. During this downward movement, the fuel reacts with air, which is supplied by the suction of a blower or an engine and is converted into combustible producer gas in a complex series of oxidation, reduction, and pyrolysis reactions [3]. Ash is removed from the bottom of the reactor. The simplified diagram of this electric power plant (100 kW) is shown in Figure 2, where the following parts can be seen biomass and air feeding, ash removal, gas cleaning and conditioning.

The gasifier is a cylindrical reactor of 0.45 m inside diameter with a throat diameter of 0.36 m and 2 m of bed height. The moving bed of biomass rests on a perforated eccentric rotating grate which is at the bottom of the gasifier. The grate is driven by an electric motor, which operates at programmable time intervals. The frequency of motion could be modified to control the biomass residence time inside the reactor. The ashes fall through the perforated grate to be collected in a lower chamber. From this chamber the ashes are extracted by a screw conveyor. A roots blower supplies air into the gasifier through a circular pipe located

in the reactor throat, which has three injectors with a radial distribution that enters 4cm inside the bed. Temperature is measured inside the reactor using four Type-K thermocouples located at different levels. An online gas analyzer allows continuous measurements of CO and CO_2 using infrared absorption.
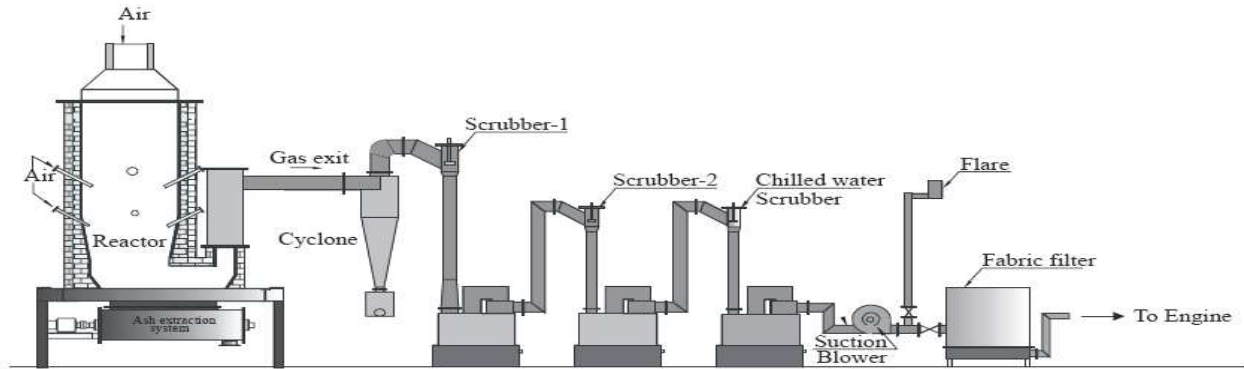

Figure 2. Biomass electric power plant

2.2. Parameters selection

The simple block diagram of the gasifier control system is shown in Figure. 3, the basic variables of a feedback controller are classified as process variables, which are important to maintain under control, and manipulated variables which are adjusted by the controller to obtain the desired behavior for the process variables. In addition, there exist disturbance variables which cannot be adjusted by the controller. The set points are the desired values for the process variables. Manipulated variables were used through the controller to obtain the desired effect on the process variables. The sampling time to measure the process variables, temperature and CO/CO_2 was 120s. The heating value of the produced gas should be higher than 4 MJ/Nm^3 in order to be used in a gas engine [4].
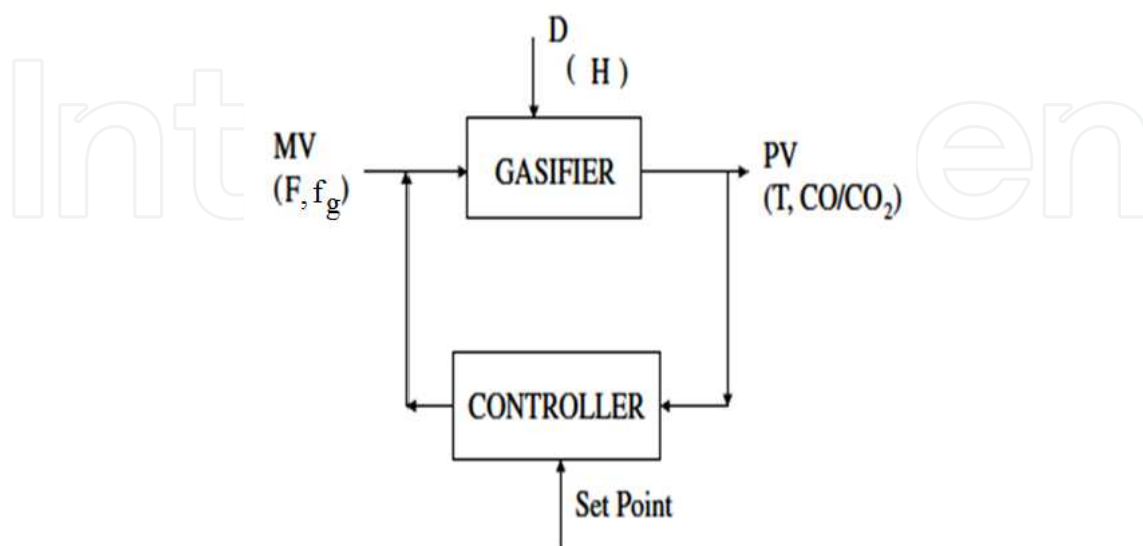

Figure 3. Basic block diagram of the process

The few of main parameters involved in the gasifier process are:

i.   Manipulated variable (MV): Air flow rate (F_A), and frequency of grate (f_g)
ii.   Process variables(PV) :Throat temperature (T), and CO/CO_2 ratio
iii. Disturbance(D): Moisture content (H_P)

The throat temperature is very closely related to the quality of the gas being produced. The CO/CO_2 ratio is also very crucial in the process. The heating value of the produced gas was calculated from the average gas composition during each run.   Based on experimental study, it seems that CO/CO_2 ratio can be a useful measure of combustion performance for downdraft gasifier in service. Also investigations are in hand to make comparisons with measurements of CO alone. This is the reason for taking it as another process variable. In order to control the temperature (T) and CO/CO_2 ratio, air flow rate (F_A) and frequency of grate are manipulated respectively. The correct composition of producer gas found that during the temperature ranges from 650 to 700 ^{0}C, while CO/CO_2 ratio has an optimum value in the range of 1-1.5. The detailed block diagram of gasifier control system is shown in Figure 4. From the process, the measured value of temperature and CO/CO_2 ratio are fed back. Thus, error in temperature and CO/CO_2 ratio can be fed in to the controller in order to generate the necessary control signal to control the process variables.
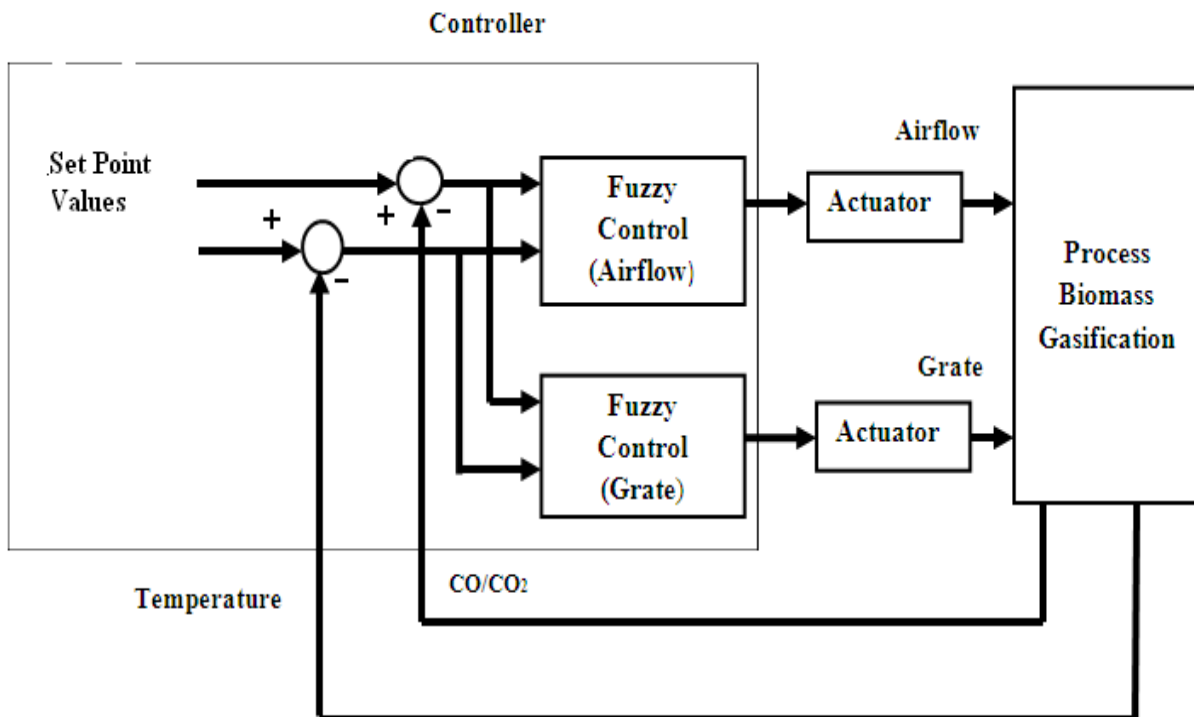

Figure 4. Block diagram of the gasifier control system

3. Transfer function model of the gasifier

Experiment have been carried out on the development of models of the downdraft gasifier to investigate the effects of varying biomass moisture, amount of fluidizing agent, gasification temperature and gas composition, viewing that gasification temperature has the highest influence on the efficiency. For studying the dynamic response of the gasifier, only temperature (T) is considered as a controlled variable and air flow rate (F_A) as a manipulated variable. Multi input and multi output system (MIMO) of the gasifier has been proposed later in this chapter for developing fuzzy controller as shown in figure 4. The Step response method is based on momentary response tests. Many industrial processes have step responses of the system in which the step response is varied after an initial time. A system with step response can be approximated by the transfer function. From the data of temperature values at different times obtained from the gasifier plant. A steady state response is plotted as shown in Figure 5. and from the response assumed that the process is a first order. The general transfer function of first order system is G(s) = K/ Ts+1. Where K is static gain and T is time constant.
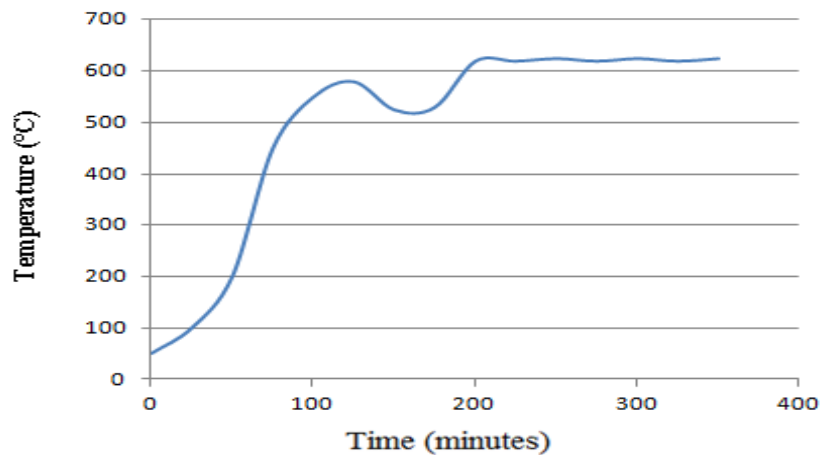

Figure 5. Temperature versus time curve

The calculations are as follows from the response:

i.   (K) = (Final steady state value- Initial steady state value) / step change

= (620-50) / (115-15)

= 570/ 100

= 5.7

ii.   Time constant (T) = time for the response to reach   temperature   T1

T1   = 63.2 % of (change in process variable) + offset

= 63.2 % of (620-50) + 50

= 410.24 ^{0}C

Time constant = 80 minutes = 4800 seconds

Then substitute the values of K and T in the Transfer function G(s) = 5.7/ (80 s + 1). The step change from 15-115 is optimum region for controlling the particular gasifier.

4. PID controller

Proportional-Integral-Derivative (PID) algorithm is the most common control algorithm used in industry presently. Often, people use PID to control processes that include heating and cooling systems, fluid level monitoring, flow control and pressure control. PID controller is not an adaptive controller, hence the controller has to be tuned frequently and whenever load changes. Auto- tuning of these controllers becomes difficult for complex systems [5, 6]. In order to prove the drawbacks of conventional controller in downdraft gasifier a little attempt is made to design a PID control which is designed to ensure the specifying desired nominal operating point for temperature control of gasifier and regulating it, so that it stays closer to the nominal operating point in the case of sudden disturbances, set point variations, and noise. The proportional gain (Kp), integral time constant (Ti), and derivative time constant (Td) of the PID control settings are designed using Zeigler- Nichols tuning method. The simulink model of PID control is shown in Figure 6. The results of PID controller for temperature set point 750∘C shown in Figure 7 and it is observed that the performance of the gasifier system with PID controller is almost oscillating and takes more time to settle with reference temperature. The conventional controller has not suitable for this type of highly non-linear and slow process. In order to improve the gasifier control process the intelligent control techniques are proposed further in this paper.
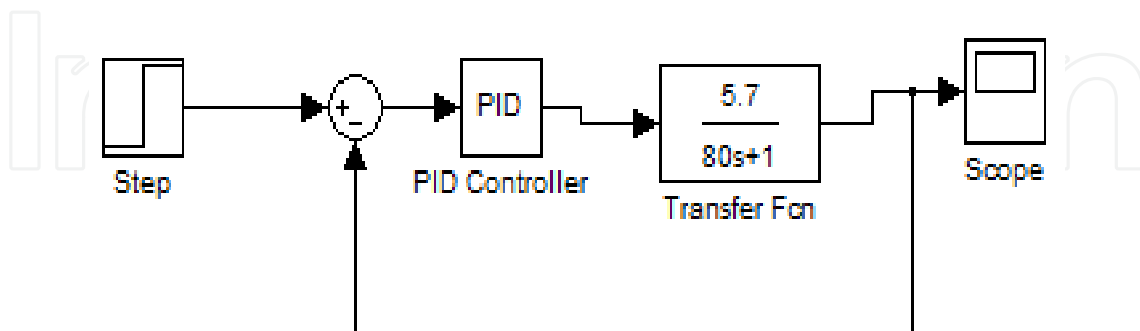

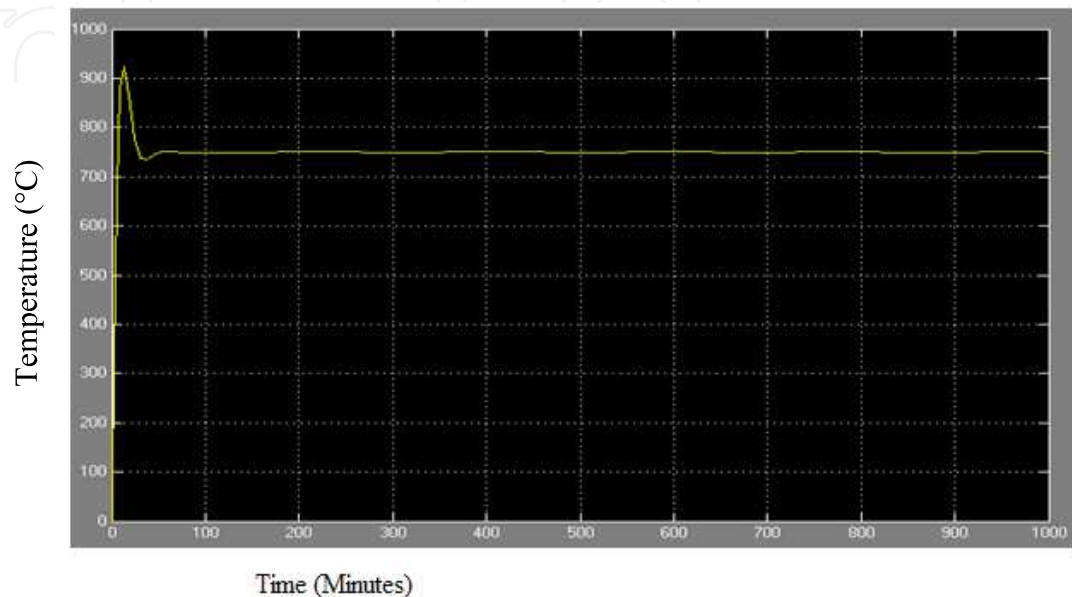**Figure 6.** PID controller for downdraft gasifier

Figure 7. PID controller response

5. Static model of gasifier

The process of gasification is a highly non-linear and slow process, and hence the development of an accurate model is very difficult. The model must be representing the non-linear dynamic characteristics of the process. A plant model for biomass gasification process of woody wastes is proposed for control purpose, based on the plant data in a typical biomass gasification process in the biomass gasifier [7]. In this paper, a steady state model is developed with the collected plant data. In order to fit the collected plant data to the steady state model of the plant, certain simple mathematical equations were developed by adjusting the mathematical relations between the variables with reference to the recorded data. Four sub-systems were thus developed using the MATLAB. The recorded plant data are as shown in the Table 1. One of the objectives of the control model developed here is to tune the controller.

EX No	F_A (m³/h)	f_g (s/s)	H_P (%)	F_{hb} (kg/h)	ER (%)	T -⁰C	CO/CO₂ Ratio (%)
1	3	0.006	7.15	1.69	0.3348	720	0.17
2	3.9	0.006	7.15	1.65	0.4356	760	0.31
3	4.8	0.006	7.15	1.69	0.5316	628.2	0.35
4	5.7	0.006	7.15	1.73	0.6232	629.2	0.5
5	6.3	0.006	7.15	1.77	0.7107	633.3	0.5
6	6.9	0.050	7.15	1.81	0.7943	594.4	0.81
7	12	0.050	7.15	1.85	0.8742	810	0.78
8	18	0.080	7.15	1.79	0.1154	860	1.6
9	21	0.080	7.15	1.81	0.1250	900	1.9
10	22	0.085	7.15	1.84	0.1343	910	2.1
11	24	0.090	7.15	1.87	0.1432	920	2.2
12	25	0.095	7.15	1.90	0.1520	924	2.4
13	3.0	0.006	20	1.97	0.1604	655	0.28
14	3.9	0.050	20	1.98	0.1686	640	0.29

Table 1. Data collected from the plant

5.1. Biomass consumption (Fhb)

It is the amount of biomass consumed for the gasification process being considered for monitoring. It depends upon the flow rate (F_A), frequency of rotation of the grate (f_g) and moisture content (H_P). Figure 8 shows the simulink model for biomass consumption. The mathematical expression for biomass consumption is equation (1).
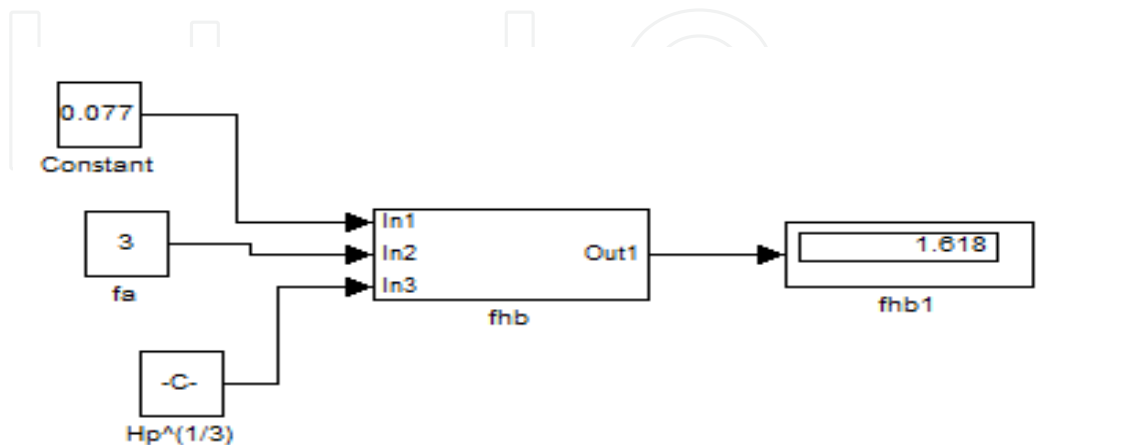
$$F_{hb} = [0.077 \, F / H^{1/3}] + 1.5 + f_g \tag{1}$$

Figure 8. Subsystem for biomass consumption

5.2. Equivalence ratio (ER)

It depends on as F_{hb}, F_A, H_p and the type of material expressed as a function of a material factor m_b which represents the amount of of air needed to obtain combustion of 1 kg of dry biomass. Figure 9 shows the simulink model of the equivalence ratio. The expression for ER is as follows equation (2).
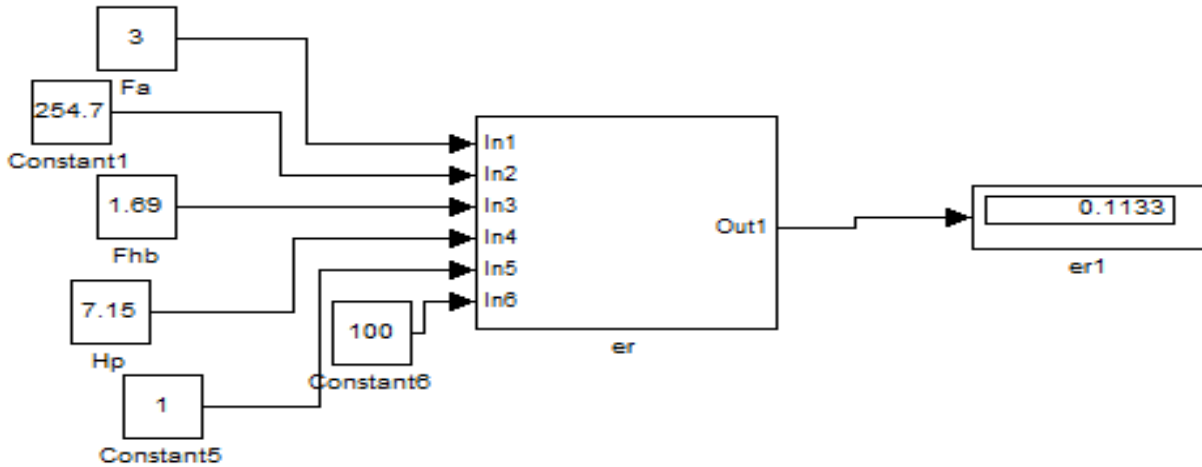
$$ER= [F / (254.7\ F_h\ (H-1)m_b)\ ]\ 100 \qquad (2)$$

Figure 9. Subsystem for equivalence ratio

5.3. CO/CO2 ratio

It depends on ER and H_p. When H_p is low, the ratio increases with ER to reach a maximum. Figure 10 shows the simulink model of CO/CO_2 ratio. The expression derived for the ratio is eqution (3).

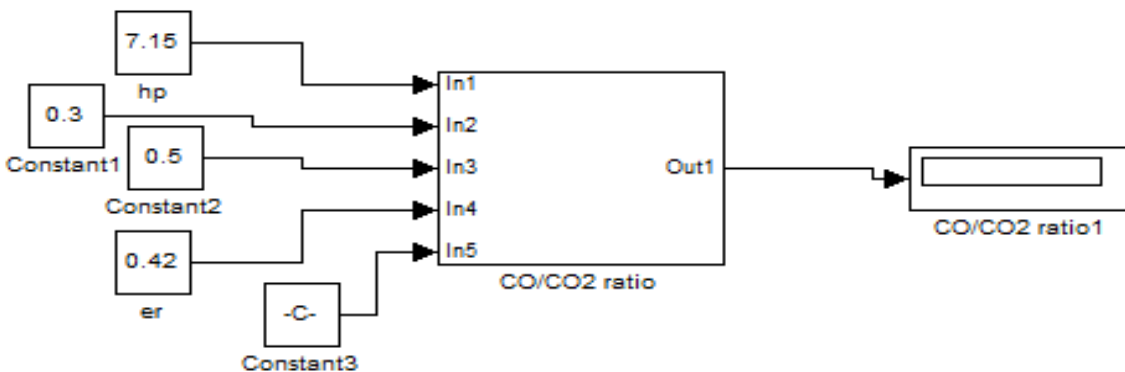$$CO/CO_2\ ratio = (0.3\ H + 0.5)\ ER\text{-}\ 0.2761 \qquad (3)$$

Figure 10. Subsytem for CO/CO_2 ratio

5.4. Temperature (T)

Temperature is related to the quality of produced gas very closely. It depends on ER, H_P and F_A. The value of T first decreases with ER, then increases and finally, again decreases. Figure 11 shows the simulink model for the temperature.

The expression for T is equation (4).

$$T = m_c\, ER + 33/H + m_a + 220 + 100\, ER + 100\, f_g \tag{4}$$

The equations 1-4 some constant values are assumed in order to fit with experimental data.

Using the simulink models of four subsystems, the complete steady state model of the biomass gasifier was developed. The gasifier model for control is shown in figure.12. This model can be used to validate the rules and membership functions of the fuzzy model.
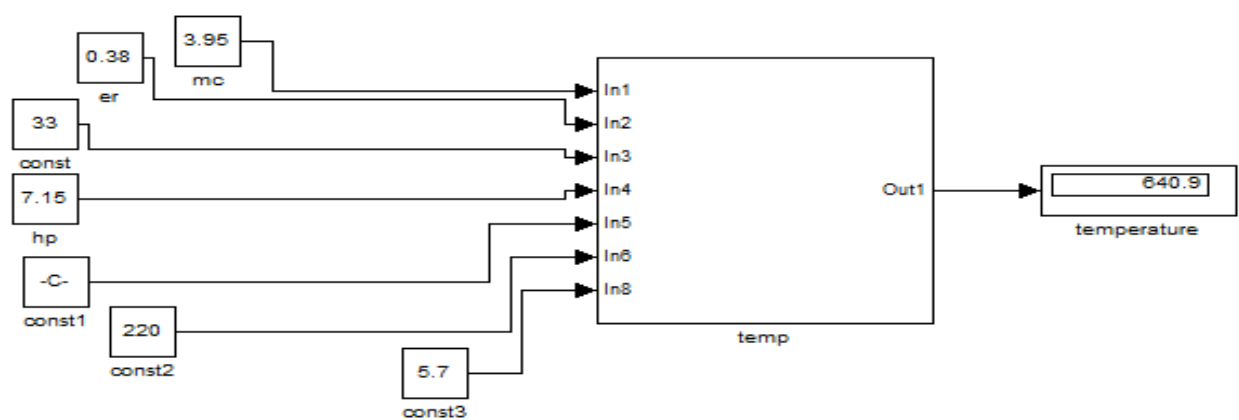

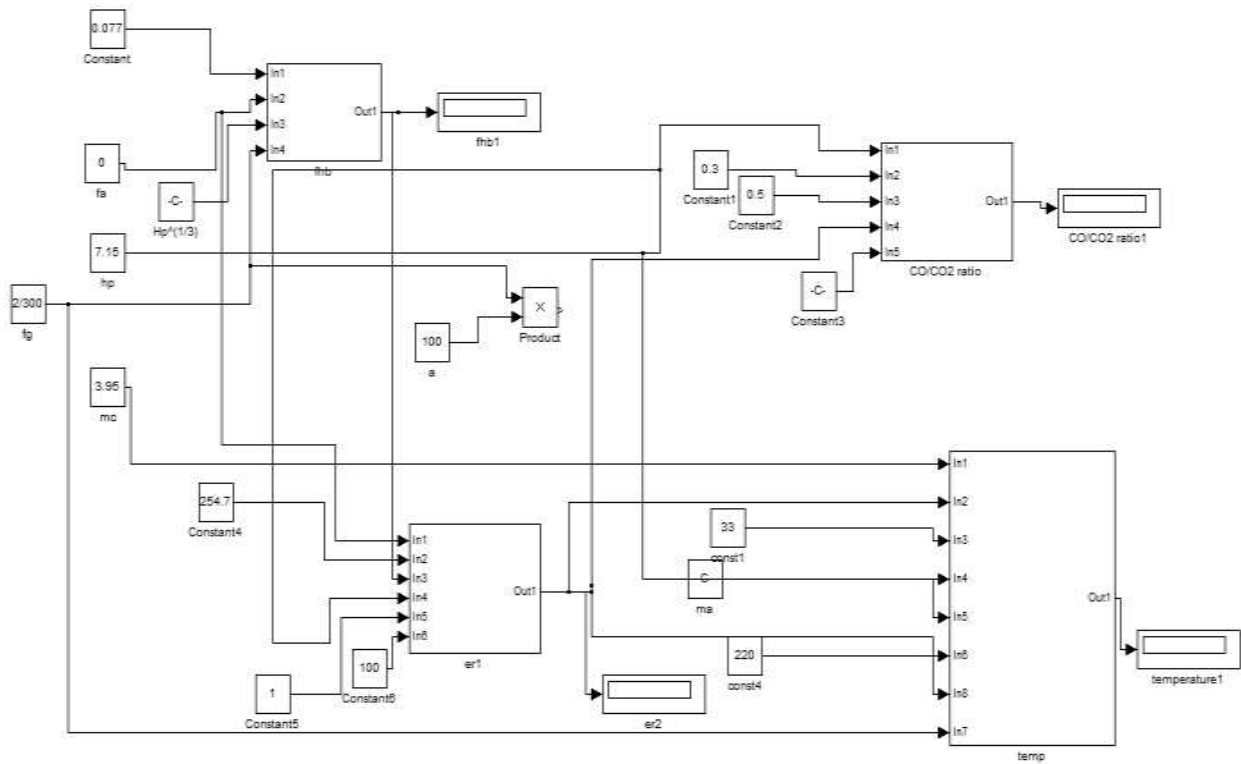**Figure 11.** Subsystem for temperature

Figure 12. MATLAB simulink model of the gasifier

6. Fuzzy logic controller

A fuzzy system is a static nonlinear mapping between its inputs and outputs. Fuzzy system provides a formal methodology for representing, manipulating and implementing a human heuristic knowledge about how to control a system [8, 9-10, 11].
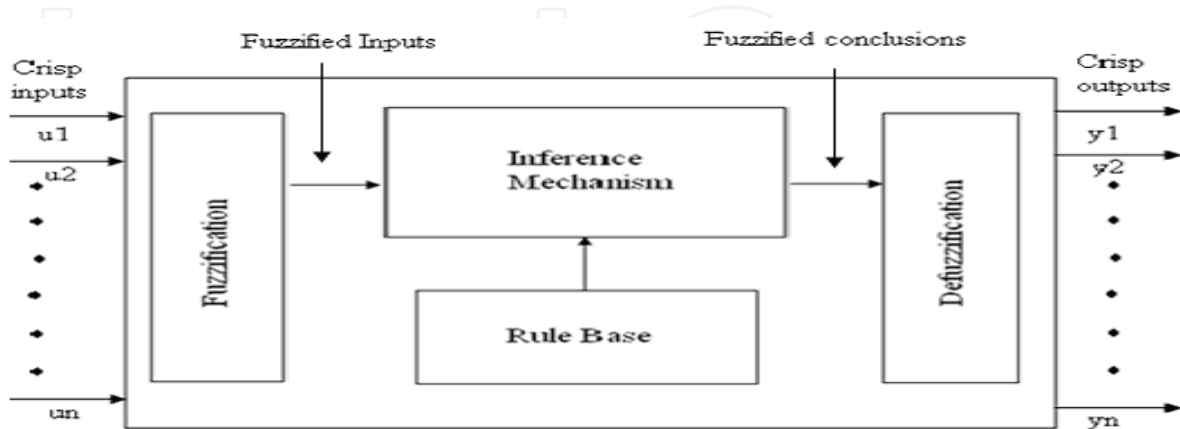

Figure 13. Fuzzy system

The block diagram of a Fuzzy system as shown in figure 13 includes fuzzification, inference mechanism, rule base and defuzzification.

Rule Base

It contains the fuzzy logic quantification of the expert's linguistic description in the form of a set of rules of how to achieve good control.

Inference Mechanism

The Inference mechanism also called an "inference engine" or "fuzzy inference module" emulates the expert's decision making in interpreting and applying knowledge about how best to control the plant. The inference mechanism evaluates which control rules are relevant at the current time and then decides what the input to the plant should be.

Fuzzification

A Fuzzification interface converts the inputs into information that the inference mechanism can easily use to activate and apply rules in the rule base.

Defuzzification

The defuzzification interface converts the conclusions reached by the inference mechanism into the actual inputs to the plant. Hence this is a process of converting decisions into actions.

6.1. Fuzzy system design

The design procedure of a Fuzzy system involves the following steps.

1. Choosing the fuzzy system inputs and outputs
2. Putting control knowledge into rule base.
3. Fuzzy quantification of knowledge.
4. Matching/Determining which rules to use.
5. Inference Step of determining conclusions.
6. Converting decisions into actions.

6.1.1. Choosing inputs & outputs

The fuzzy system is to be designed to automate how a human expert who is successful at the task would control the system. Essentially the objective is to make sure that the fuzzy system will have the proper information available to be able to make good decisions and have proper inputs and outputs needed to achieve high performance operation.

6.1.2. Putting control knowledge into rule base

Once the inputs and the outputs to the fuzzy system are decided, we have to load into the Fuzzy system, the linguistic description of the control knowledge of how best to control the plant as suggested by a human expert. This process consists of specifying the Linguistic descriptions, Rules and Rule- bases.

6.1.2.1. Linguistic descriptions

The Linguistic Description provided by the expert can generally be broken into two major parts as Linguistic variables and Linguistic values.

The **linguistic variables** describe each of the time-varying inputs and outputs of the Fuzzy system such as error, error change, force etc.

The **Linguistic values** are those characteristics that the Linguistic variables take on over time change dynamically. Examples of Linguistic values are negative large, negative small, zero, positive small, positive large etc.

6.1.2.2. Rules

The mapping of the inputs to the outputs for a fuzzy system is in part characterized by a set of condition → action rules or in If-Then form.

If premise **Then** consequent.

Usually the inputs to the fuzzy system are associated with the premise and the outputs with the consequent. These if-then rules can be represented in many forms. Two standard forms are MIMO (Multiple Input Multiple Output) and MISO (Multiple Input Single Output).

MIMO

If premise$_1$ **and** premise$_2$ and…….premise$_n$ **then** consequent$_1$ **and** consequent$_2$.

MISO

If premise$_1$ **and** premise$_2$ and…….premise$_n$ **then** consequent.

6.1.2.3. Rule base

This contains the rules for all possible combinations of the inputs and the outputs. For example, a fuzzy system with three inputs and five linguistic values, there can be at the most $5^3 = 125$ rules possible (all possible combinations of premise linguistic values for the three inputs)

6.1.3. Fuzzy quantification of knowledge

In a fuzzy system, the membership functions quantify, in a continuous manner, the values of a Linguistic variable into Fuzzy sets. Some of the membership function choices are Triangle, Trapezoid, and Gaussian etc.

6.1.4. Inference process

The inference process of matching/determining which rules to use involves two steps:

1. The premises of all rules are compared to the controller inputs to determine   which rules apply to the current situation. This matching process involves the determining of the uncertainty that each rule applies, strongly taking into account, the recommendations of rules that we apply at the current situation.
2. The conclusions (what controls actions to take) are determined using the rules that have been determined to apply at the current time. The conclusions are characterized with a fuzzy set (or sets) that represent(s) the certainty that the input to the plant should take on various values.

6.1.4.1. Defuzzification

The final component of a fuzzy system is the defuzzification block. It operates on the implied fuzzy sets produced by the inference mechanism and combines their effects to provide the "most certain" controller output which is the input to the plant. Defuzzification can also be thought of as the process of decoding the fuzzy set information produced by the inference process (i.e. implied fuzzy sets) into numeric fuzzy controller outputs. Two commonly used defuzzification methods are Center of Gravity (COG) Method and Center - Average Method

7. Design of FLC for downdraft gasifier

Since the process of gasification is a highly non-linear and slow process [12], the formation of an accurate model is very difficult .The model must be representing the non-linear dynamic characteristics of the process. The knowledge of experts about biomass gasification can be determined in fuzzy if/then rules in such a way that the fuzzy systems can deal with the indistinguishable and inaccurate biomass condition. Here, fuzzy system is modeled with three inputs and two outputs. The three inputs are ErrorT (error in temperature), Error CO/ CO2 and Hp (moisture content) and the output is airflow and frequency of grate [12, 13-14, 15].

Fuzzy rules are formulated based on error temperature ,error CO/ CO2 ratio and Hp (moisture content) which are   converted to non-fuzzy values by defuzzification,. These values are fed to the final control element for control action is shown in Figure 14.
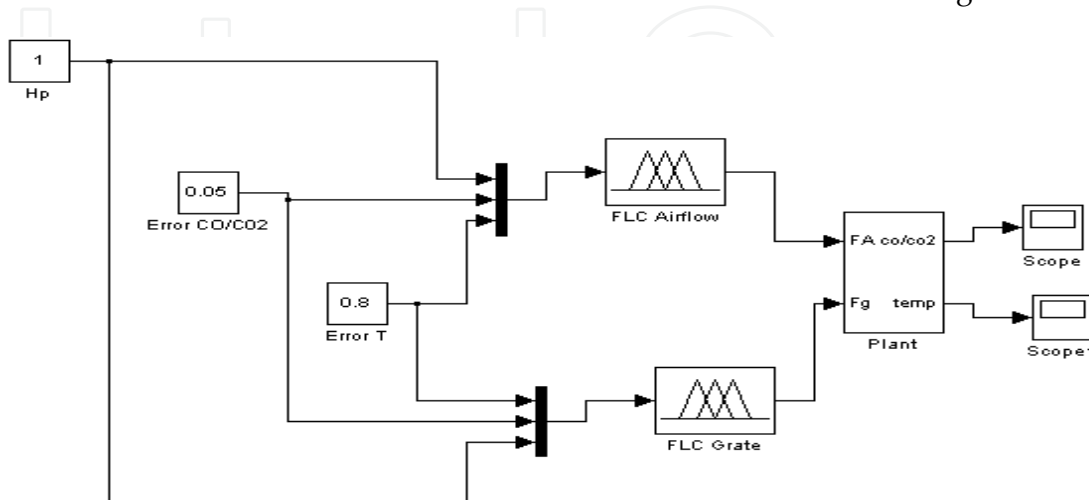

Figure 14. Simulation of control system

For the Error CO/ CO2 variable, five linguistic values were defined: very low, low, zero, high, very high, and for the Error T variable, five linguistic values, very low, low, zero, high, very high,were also defined. For the output variable Airflow five fuzzy values, extreamly low, very low, base, very high, extremely high and for the Grate variable, the values f1, f2, f3, f4, f5, were defined. The membership functions are shown in Figures 15.
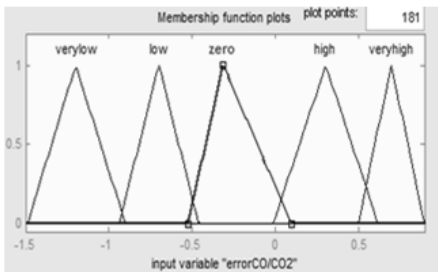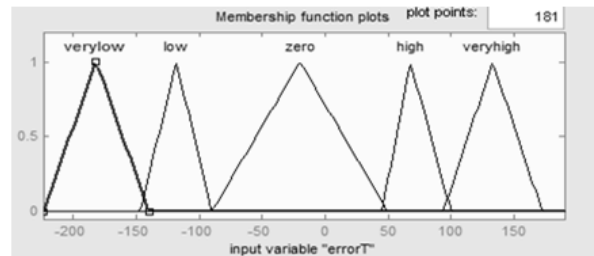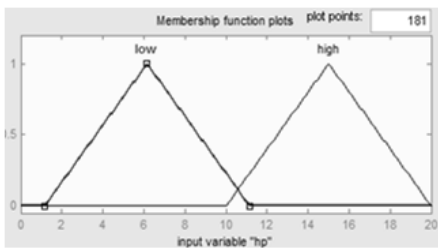

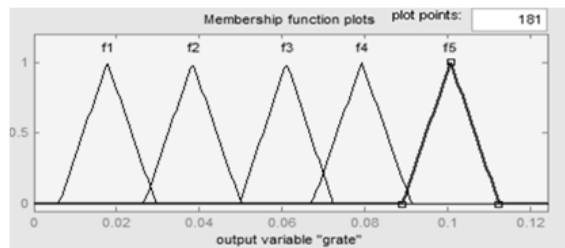(a) Error CO/ CO2 Ratio

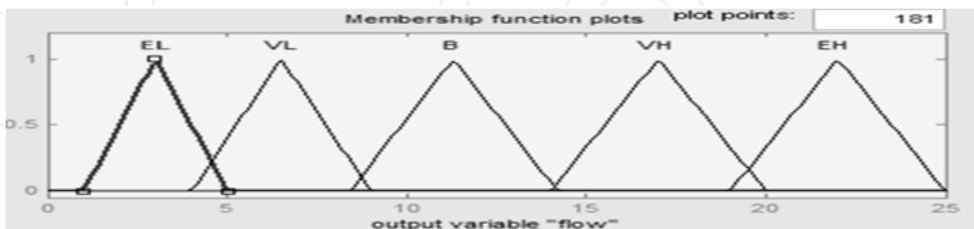(b) Error temperature

(c) hp

(e) Frequency of Grate

(d) Airflow

Figure 15. Figure 15. Membership function of (a)Error CO/ CO$_2$ Ratio , (b) Error temperature (c) hp, (d) Airflow and (e) Frequency of Grate

The rules that have been framed for the controller are as shown in Table 2 and 3.

Sl.No	If hp	and errorT	and errorCO/CO$_2$	Then grate
1.	low	verylow	verylow	f4
2.	low	verylow	low	f3
3.	low	verylow	zero	f1
4.	low	verylow	high	f3
5.	low	verylow	veryhigh	f1
6.	low	low	verylow	f3
7.	low	low	low	f2
8.	low	low	zero	f2
9.	low	low	high	f2
10.	low	low	veryhigh	f1
11.	low	zero	verylow	f3

Table 2. Rules for adjusting frequency of grate

Sl .No	If hp	and errorT	and errorCO/CO$_2$	Then flow
1.	low	verylow	verylow	EH
2.	low	verylow	low	VH
3.	low	verylow	zero	VL
4.	low	verylow	high	VH
5.	low	verylow	veryhigh	VL
6.	low	low	verylow	VH
7.	low	low	low	VH
8.	low	low	zero	B
9.	low	low	high	B
10.	low	low	veryhigh	VL
11.	low	Zero	verylow	VH
12.	low	Zero	low	B
13.	low	Zero	zero	VL
14.	low	Zero	high	VL
15.	low	Zero	veryhigh	EL
16.	low	high	verylow	B
17.	low	high	low	B
18.	low	high	zero	VL
19.	low	high	high	VL
20.	low	high	veryhigh	EL
21.	low	veryhigh	verylow	VH
22.	low	veryhigh	low	B

Sl .No	If hp	and errorT	and errorCO/CO₂	Then flow
23.	low	veryhigh	zero	VL
24.	low	veryhigh	high	VL
25.	low	veryhigh	veryhigh	VL
26.	low	verylow	Verylow	EH
27.	low	verylow	low	EH
28.	low	verylow	zero	EH
29.	low	verylow	high	EH
30.	low	verylow	veryhigh	EH
31.	low	low	verylow	EH
32.	low	low	low	EH
33.	low	low	zero	EH
34.	low	low	high	VH
35.	low	low	veryhigh	VL
36.	low	zero	verylow	VH
37.	low	zero	low	B
38.	low	zero	zero	VL
39.	low	zero	high	VL
40.	low	zero	veryhigh	VL
41.	low	veryhigh	verylow	VL

Table 3. Rules for adjusting air flow rate

This developed fuzzy logic controller of MIMO system of gasifier was based on the static model of the gasifier that have been proposed, which can be used in tuning the controller. The controller that has been developed in this manner was implemented in microcontroller [16, 17]. The CO/CO_2 ratio has effectively controlled with fuzzy logic controller by adjusting the frequency of motion to control the biomass residence time inside the reactor. The temperature also effectively controlled with fuzzy logic controller by adjusting the airflow rate. The performance of MIMO system of the gasifier cannot be verified by simulation because doesn't have proper dynamic model of the gasifier. In this paper temperature control system of the gasifier (SISO) has been verified by the simulation in order to prove the efficiency of fuzzy controller in comparison with the conventional controller.

8. Implementation results

Fuzzy logic controller has been implemented for the transfer function model of the gasifier. To prove the efficiency of fuzzy controller in comparison with the conventional controllers, a fuzzy logic controller for the SISO system of gasifier, where flow is the input and temperature is the output has been proposed. The simulation of the fuzzy logic control system is shown in Figure 16. The responses of the process to fuzzy controller for various set points have been shown in Figures 17, 18 and 19. From the responses it is

observed that settling time and overshoot have been reduced. The settling time is found to be 51.5 seconds.
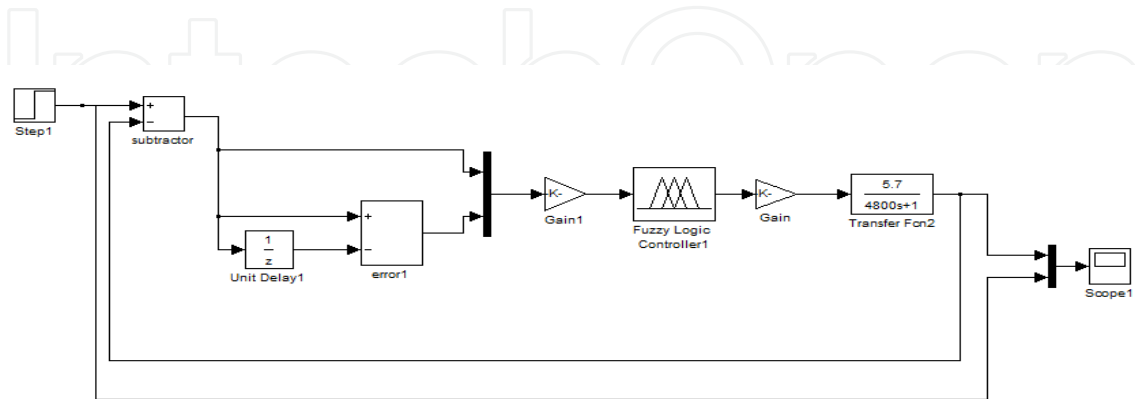

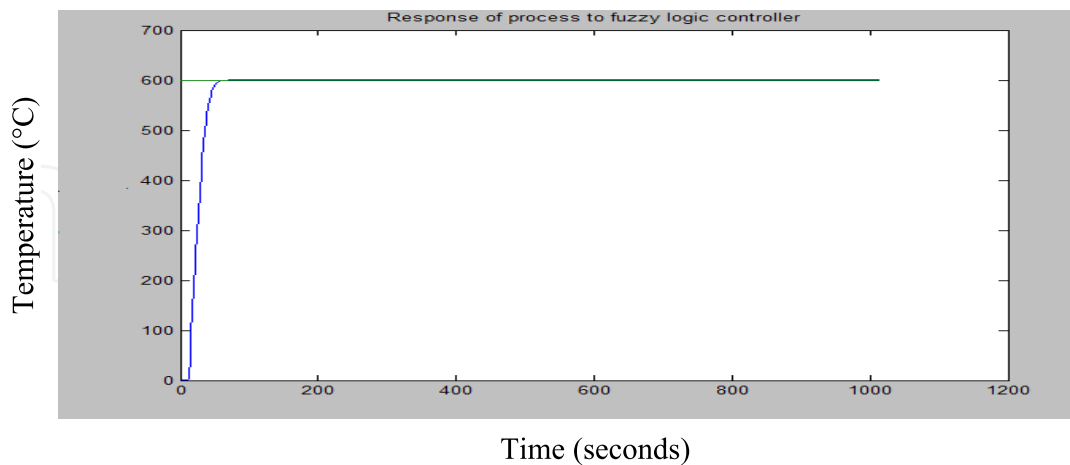**Figure 16.** Fuzzy logic controller for transfer function model of the process

Time (seconds)

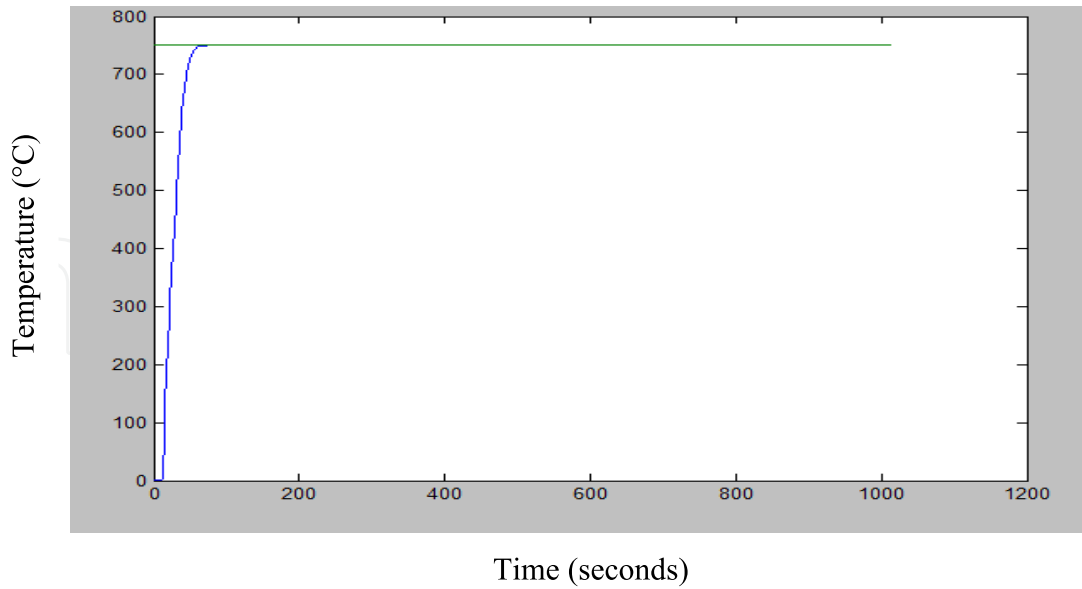**Figure 17.** Response of process with fuzzy controller (for set point of 600 ^{0}C)

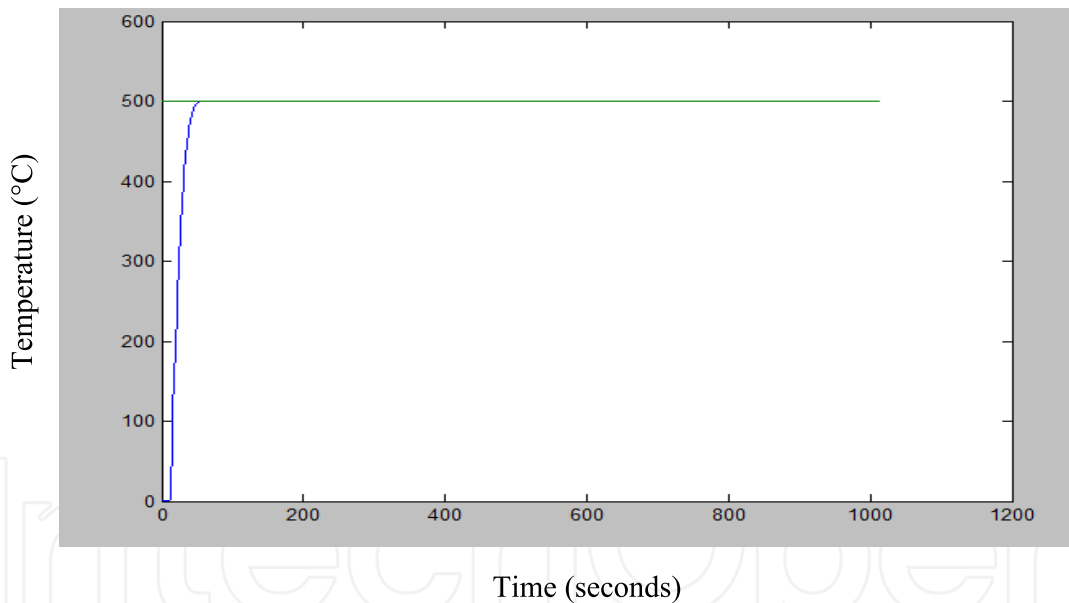**Figure 18.** Response of process with fuzzy controller (for set point of 750 ^{0}C)

Figure 19. Response of process with fuzzy controller (for set point of 500 ^{0}C)

9. Conclusion

A static model for the gasifier has been developed based on the experimental data of the plant successfully and this could be used to tune the fuzzy logic controller. The implementation results for the gasifier system are found to be better than conventional control and pc based measurement. Fuzzy control is used to control the temperature with less overshoot and settling time . In this paper, it has been observed that fuzzy control gives better performance for the control of biomass gasification.

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