Co-firing Coal: Feedlot and Litter Biomass Fuels

Quarterly Progress Report # 10

Grant #: DE-FG26-00NT40810

Project Name: *Feedlot and Litter Biomass Co-firing in Pulverized Fuel and Fixed Bed
Burners*

Contractor name: Texas Engineering Experiment Station, Texas A&M University

Sponsor: US Dept of Energy, National Energy Technology Laboratory

Principal Investigator: Dr. Kalyan Annamalai, Mech. Eng., Texas A&M, College-
Station, TX 77843-3123
979-845-2562
Kannamalai@mengr.tamu.edu

Other Investigators: Dr. John Sweeten, Professor of Agricultural Eng. and
Resident Director of Agricultural Extension Service,
Dr. Saqib Mukhtar, Asst. Prof., Agricultural Engineering.

Graduate Students: Soyuz Priyadarsan (PhD)
Arunvel Thangamani (ME)

Quarterly Report #: 10

Report Period: 9/15/02-12/14/2002

PROGRESS REPORT # 10

A. Proposed activities for quarter 10 (9/15/2002 – 12/14/2002)

If extension is granted, the following activities shall be done

Modeling and Simulation: (Task 4)

1. If approved for modification to the proposal, the fixed bed studies modeling shall be interchanged with zero dimensional reburn model.

B. Achieved during quarter 10 (9/15/2002 – 12/14/2002)

1. Contract extension was granted.
2. Ben Thien and Gengsheng Wei have graduated with PhD 's.
3. Mr. Soyuz Priyadarsan joined for PhD program
4. A simplified zero dimensional models simulating the reburn process have been developed. It uses the concept of characteristic mixing time between reburn and main burner gases. The present Matlab code handles only simulated gaseous reburn fuels. Details of the model and preliminary results are presented (Appendix A).

C. Proposed activities for quarter 11 (1/15/2002 – 03/14/2003)

1. Modify the zero dimensional transient code with suitable mixing time scale to handle solid biomass fuels directly, and incorporate the pyrolysis, char oxidation, and N evolution model into the code. The modified code shall be developed in FORTRAN, and compared with experimental data.
2. Prepare the final report

Milestone Log- **DE-FG26-00NT40810-Annamalai-Quarter # 10; Report Period:**
9/15/2002-12/14/2002.

Appendix A: A NO_x Reduction Model for Reburn Process using Biomass Volatiles (Task 4)

1a. Objective and Tasks:

It has been observed from the review that very limited experimental study has been conducted on using FB as re-burn fuel and there exists no model using FB as re-burn fuel. The objective of the current research is to develop a simplified numerical model for NO_x reduction process with FB volatiles as the re-burn fuel and compare results with experimental data.

In order to satisfy the objective, the proposed work has been divided into 4 tasks.

1. Modeling the combustion process involving the main fuel, ammonia mixture in the main burner.
2. Developing of a simple mixing model of main gases with reburn jet.
3. Selection of a suitable overall global mechanism of reactions for the re-burn fuels, coupling the reaction model with the mixing model and thereby developing the complete re-burn model.
4. Comparing the simulation results with the experimental results obtained from TAMU combustion facility.

1b. NO_x Control and Reburn Technology

Several technologies have been proposed by various researchers to control nitrogen oxide emissions. One of the technologies adopted for NO_x reduction in co-firing plants is “Re-burn Technology”. Re burn is a process in which a hydrocarbon fuel is injected in the downstream of the combustion zone (i.e. the zone where NO_x is produced from main source of fuel) to establish a fuel rich combustion process in order to convert the NO_x to harmless N₂. The re-burn fuels currently used are Coal or Natural gas (methane). In general, the amount of re burn fuel used is 10% to 30% of the total fuel [1]. In ‘Advanced Re-burn Technology’, a hydrocarbon fuel along with Ammonia is injected in the downstream of the combustion zone to establish a fuel rich combustion process in order to convert the nitric oxide to harmless molecular Nitrogen. The new technology can achieve reduction levels ranging from 35% to 65% depending upon the re burn fuel type and the supply mechanism [1].

A simplified reaction scheme for NO_x reduction via HC based re-burn is as follows.

Other reaction schemes for NO_x reduction via HCN, NH₃, and char are follows.

The reaction rate constants are described by an Arrhenius type expression e.g. for reaction (I) the reaction rate constant (k_1) is

$$k_1 = A_1 \exp(-E_1 / RT)$$

Fenimore [2] has expanded the kinetics with more complex chemical kinetics scheme. Abbas et al. [3] have incorporated the NO_x kinetics of De Soete [4] and Fenimore [2] in the predictive code and concluded that the De Soete's model yields better results for NO_x predictions. The kinetic parameters for the above reaction scheme are taken from DeSoete [4] except for reaction III kinetics that are from Levy et al. [5]. More details on time scales of various NO_x reductions are reported by Sami [6]. Chen et al [7] reported the global kinetics for reactions of NO_x with hydrocarbon fuels.

In coal-fired boilers, re-burn fuel is injected into the upper furnace region. The overall furnace process occurs in 3 main zones in a boiler. They are,

- 1.primary zone
- 2.reburn zone
- 3.burn out zone

Table 1, and figure 1 explain the processes that occur in all the 3 zones in a coal fired boiler furnace.

Zone	Process
Primary Zone	NO _x forms due to the combustion process of the main fuel.
Re-burn zone	NO _x is reduced with injection of re-burn fuel. N ₂ and HCN are formed.
Burn out Zone	Unreacted fuel, CO, HCN are burnt due to the addition of additional air after the re-burn zone.

Table 1: Reburn Process

Figure 1: Schematic of a typical Reburn process

Some of the important factors affecting the degree of NO_x reduction in the re-burn zone are,

- 1.Reburn fuel type and composition
- 2.Reburn zone temperature
- 3.Boiler Load.
- 4.Reburn Fuel Percentage.
- 5.Reburn zone Stoichiometry.
- 6.Flue Gas recirculation rates to the reburn zone.
- 7.Reburn Fuel Injection Type.
- 8.Amount of O₂ associated with the reburn fuel.
- 9.Characteristic time for mixing of reburn fuel with main gases.

1c. Model Description:

1c.1. Main-burner Modeling:

Burning a premixed mixture of propane, air, and a small amount of NH₃ simulates the NO_x from the coal-fired boiler. The NH₃ % is adjusted to yield 600 ppm of NO from the main burner. The following equation represents the overall reaction.

For a given thermal input, equivalence ratio and desired NO concentration the mole and mass fractions of all the product species are calculated. The required amount of NH₃ (x) in kmole per kmole of propane is calculated for desired NO in the exhaust from main burner zone.

Approximately 5% excess air is supplied and the Air-Fuel ratio for the stoichiometric mixture and the actual mixture are calculated based on the following equations.

From the above equation the stoichiometric air fuel ratio is,

$$O_2: F \text{ ratio stoic} = 5$$

$$O_2 : Fratio_{actual} = O_2 : Fratio_{stoic} \times (1 + (\text{excessair}/100))$$

Using the following equations both the dry and wet analysis results are obtained.

$$X_{NO_{main}} = x / (3 + (4 + 3x/2) + b + 3.76a + x)$$

$$x = (3 + b + 3.76a) \times z / (1 - z) \text{ Where } z = X_{NO_{main \text{ dry}}}$$

$$X_{NO_{maindry}} = x / (3 + b + 3.76 \times a + x)$$

$$X_{O_{2main}} = b / (3 + 4 + 1.5 \times x + b + 3.76 \times a + x)$$

$$X_{N_{2main}} = (3.76 \times a) / (3 + 4 + 1.5 \times x + b + 3.76 \times a + x)$$

$$X_{CO_{2main}} = 3 / (3 + 4 + 1.5 \times x + b + 3.76 \times a + x)$$

$$X_{H_2O_{main}} = (4 / (3 + 4 + 1.5 \times x + b + 3.76 \times a + x)) + (1.5 \times x / (3 + 4 + 1.5 \times x + b + 3.76 \times a + x))$$

Molecular weight of the mixture is assumed to be 28 kg/kmole and remains constant. The mass fractions are calculated from the mole fractions.

$$Y_{k,main} = X_{k,main} \left(\frac{MW_k}{MW_{mixmain}} \right)$$

Where k: NO, CO₂, H₂O, N₂, O₂.

The density of the mixture is calculated from the ideal gas law.

$$\rho_{mixmain} = \text{Pressure} \times MW_{mixmain} / (T_{main} \times R_u)$$

1c.2. Mixing Model Development:

The mixing models used can be categorized to two different types. In the first type, the reburn jet is entrained into the main flue gas flux, whereas in the second type, the main flue gas is entrained into the reburn jet. The second type of model experiences greater change in the

stoichiometry during the mixing and appears to lead to favorable results. Figure 2 shows the schematic mixing model in which the main flue gas is entrained into the reburn jet.

Figure 2: Schematic of the mixing model

Mass Conservation is applied to the whole mesh generation process and the mass addition in every mesh is due to the mixing process.

To begin the reburn model process it is necessary to calculate the mass flow rate of the main flow as well as the reburn flow. Both the values are derived from the rating of the burner.

m_{reburn} , m_{main} calculation from the Rating(KW):

Rating of the boiler setup at Texas A&M University is $30 \text{ kW}_{\text{th}}$. Using the heating values of the mainstream fuel as well as the reburn stream fuel the mass flow rates of various species are calculated as below.

Mainburner fraction = 0.85 (heat throughput fraction)

$\text{LHV}_{\text{main}} = 46.36 \text{ MJ/Kg}$

$m_{\text{mainfuel}} = \text{Mainburner fraction} \times \text{Rating} / \text{LHV}_{\text{main}}$

$m_{\text{O2main}} = \text{O2 : F ratioactual} \times m_{\text{mainfuel}} \times \text{MW}_{\text{O2}} / \text{MW}_{\text{C3H8}}$

$m_{\text{NH3main}} = x \times m_{\text{mainfuel}} \times \text{MW}_{\text{NH3}} / \text{MW}_{\text{C3H8}}$

$m_{\text{N2main}} = (77/23) \times m_{\text{O2main}}$

The following values are assumed at the initial condition for the reburn fuel.

$$Y_{\text{NH3reburn}} = 0.01$$

$$Y_{\text{H2Oreburn}} = 10^{-8}$$

$$Y_{\text{CO2reburn}} = 10^{-8}$$

$$Y_{\text{HCNreburn}} = Y_{\text{NH3reburn}} / 2$$

Similar analysis has been conducted for the reburn flow with a modification in the mass flow rate of oxygen in the reburn flow.

The reburn flow has two equivalence ratio values. One is the reburn zone equivalence ratio and the other one is the reburn supply equivalence ratio. Both the values are different due to the different oxygen concentrations in the mixtures.

The desired reburn zone equivalence ratio is given as an input from which the reburn supply equivalence ratio is calculated.

$$\text{LHV}_{\text{reburn}} = 17.5 \text{ MJ/Kg}$$

$$m_{\text{CH4reburn}} = (1 - \text{Mainburner fraction}) \times \text{Rating} / \text{LHV}_{\text{reburn}}$$

ϕ_{RZ} is the input value for this process

$$\text{SR}_{\text{RZ}} = 1/\phi_{\text{RZ}}$$

$$m_{\text{O2reburn}} = ((m_{\text{CH4reburn}} \times 4) - (\phi_{\text{RZ}} * Y_{\text{O2main}} * m_{\text{main}})) / \phi_{\text{RZ}}$$

$$\phi_{\text{RZsupply}} = (m_{\text{CH4reburn}} * 4) / m_{\text{O2reburn}}$$

$$\text{SR}_{\text{RZsupply}} = 1/\phi_{\text{RZsupply}}$$

$$m_{\text{N2reburn}} = (77 / 23) \times m_{\text{O2reburn}}$$

$$m_{\text{NH3reburn}} = (-m_{\text{CH4reburn}} - m_{\text{O2reburn}} - m_{\text{N2reburn}}) / ((3 / 2) + ((Y_{\text{inertreburn}} - 1) / Y_{\text{NH3reburn}}))$$

$$m_{\text{reburn}} = m_{\text{HCNreburn}} + m_{\text{NH3reburn}} + m_{\text{O2reburn}} + m_{\text{N2reburn}} + m_{\text{CH4reburn}} + m_{\text{inertreburn}}$$

$$m_{\text{main}} = m_{\text{mainfuel}} + m_{\text{NH3main}} + m_{\text{O2main}} + m_{\text{N2main}}$$

$$m_{\text{total}} = m_{\text{reburn}} + m_{\text{main}}$$

Various mass fractions are also calculated.

$$Y_{CH4reburn} = m_{CH4reburn} / m_{reburn}$$

$$Y_{O2reburn} = m_{O2reburn} / m_{reburn}$$

$$Y_{N2reburn} = m_{N2reburn} / m_{reburn}$$

1c.2.1 Mixing Model Assumption:

An exponential mixing model is being considered for the analysis. This model assumes a characteristic time constant for the mixing process and the mass added from the main combustion gases to the reburn mixture obeys the following equation.

$$\dot{m} = \dot{m}_{main} \times \exp(-t/\tau)$$

Where τ = characteristic time scale.

With in an elemental period 'dt', the mass flow rate in the re-burn mixture increases by the following amount.

$$|d\dot{m}| = \dot{m}_{main} \times \exp(-t/\tau) \times dt/\tau$$

1c.2.2 Global Mechanism for the Reburn Process:

The supplied re-burn mixture is assumed to consist of CH_x, O_2, N_2 and small amounts of NH_3, HCN, CO_2 , and H_2O to simulate the pyrolysis products of bio-mass fuels. Since the main burner combustion products consisting of CO_2, H_2O, NO, O_2, N_2 mix with the re-burn mixture mostly containing CH_x, O_2, N_2 various chemical reactions occur amongst the constituent species. After a careful consideration, 6 reactions were selected for the re-burn model.

1. NOx reducing equations

This is the most important reaction of the mechanism and this is the major resource for NOx reduction.

$$k = A \exp(-E/RT)$$

Where from ref 5,

$$E = 202600 \text{ KJ/Kmol} \quad A = 1.3 \times 10^8 \text{ 1/s} \quad a = -0.3 \quad b = 1.3$$

$$k = A \exp(-E/RT)$$

Where,

$$A = 2.7 \times 10^9 \text{ 1/s}$$

$$E = 18800 \times 4.184 \text{ KJ/Kmol}$$

The next mechanism comprises of 2 nitrogen-producing equations. One is the reaction between the HCN produced and NO. The other one is NH_3 injected reacting with NO.

Where,

$$A = 3.0 * 10^{12} \text{ 1/s} \quad E = 2.51 * 10^8 \text{ J/Kmol}$$

Where,

$$A = 1.8 * 10^8 \text{ 1/s} \quad E = 1.13 * 10^8 \text{ J/Kmol}$$

2.NOx Producing Reactions:

Due to the fact that there is always some amount O₂ in the reactor, both HCN and NH₃ can react with O₂ to produce some amount of NO.

Where,

$$A = 4.0 * 10^6 \text{ 1/s} \quad E = 1.34 * 10^8 \text{ J/Kmol} \quad b = 0.5$$

Where,

$$A = 1.0 * 10^{11} \text{ 1/s} \quad E = 2.81 * 10^8 \text{ J/Kmol} \quad b = 0.5$$

The reaction kinetics selected from literature review is given below [4].

$$w_1 = \rho_{\text{mix}} \times Y_{\text{HCN}} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{O}_2})^{b_{v1}} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{HCN}}) \times Y_{\text{O}_2}^{b_{v1}} \times k_1 / \text{MW}_{\text{mix}}$$

$$w_2 = \rho_{\text{mix}} \times Y_{\text{HCN}} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{HCN}}) \times Y_{\text{NO}} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{NO}}) \times k_2 / \text{MW}_{\text{mix}}$$

$$w_3 = k_3 \times \rho_{\text{mix}}^{(a_1+b_1)} \times Y_{\text{CH}_4}^{a_1} \times Y_{\text{O}_2}^{b_1} \times \text{MW}_{\text{CH}_4}^{(1-a_1)} / \text{MW}_{\text{O}_2}^{b_1}$$

$$w_4 = \rho_{\text{mix}} \times Y_{\text{NH}_3} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{O}_2})^{b_v} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{NH}_3}) \times Y_{\text{O}_2}^{b_v} \times k_4 / \text{MW}_{\text{mix}}$$

$$w_5 = \rho_{\text{mix}} \times Y_{\text{NH}_3} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{NH}_3}) \times Y_{\text{NO}} \times (\text{MW}_{\text{mix}} / \text{MW}_{\text{NO}}) \times k_5 / \text{MW}_{\text{mix}}$$

$$w_6 = k_6 \times Y_{\text{CH}_4} \times Y_{\text{NO}} \times \text{MW}_{\text{mix}}^2 / \text{MW}_{\text{CH}_4}$$

1c.3. Coupling the Reaction Model and the Mixing model:

A plug flow reactor has been considered and the following assumptions have been made.

1. Steady state, Steady Flow Process.
2. Uniform properties at any given transverse layer.
3. Ideal Frictionless flow
4. Ideal Gas Flow
5. Lagrangian time frame.

The coupling of both the reaction and mixing components yielded in the following equation.

$$d(m\dot{Y}_k) = ((m_{\text{main}} \times \exp(-t / \tau) \times Y_{k\text{main}} / \tau) + (d\rho_k \times \text{volume flowrate} / dt)) \times dt$$

Other quantities are defined with the following differential terms.

$$d\rho_{\text{NO}} = (w_1 - w_2 + w_4 - w_5 - w_6) \times dt \times \text{MW}_{\text{NO}}$$

$$d\rho_{\text{HCN}} = (-w_1 - w_2 + w_6) \times dt \times \text{MW}_{\text{HCN}}$$

$$d\rho_{\text{NH}_3} = (-w_4 - w_5) \times dt \times \text{MW}_{\text{NH}_3}$$

$$d\rho_{\text{N}_2} = (w_2 + w_5) \times dt \times \text{MW}_{\text{N}_2}$$

$$d\rho_{\text{O}_2} = (-w_1 - w_4 - 2 \times w_3) \times dt \times \text{MW}_{\text{O}_2}$$

$$d\rho_{\text{CH}_4} = (-w_3 - w_6) \times dt \times \text{MW}_{\text{CH}_4}$$

$$d\rho_{\text{CO}_2} = w_3 \times dt \times \text{MW}_{\text{CO}_2}$$

$$d\rho_{\text{H}_2\text{O}} = w_3 \times dt \times \text{MW}_{\text{H}_2\text{O}}$$

$$\rho_{k(i+1)} = \rho_{k(i)} + d\rho_{k(i)}$$

1c.4. Temperature Calculation at various nodes:

Temperature prediction at various nodes is done using the energy conservation principle.

Energy added from the main flow due to mixing + Energy in the reburn flow + Energy change due to CH_x Burning = Energy Out from the reacted flow.

Energy in from the Main Flow:

$$(m_{\text{main}} \times \exp(-t_i / \tau) \times T_{\text{main}} \times dt \times C_{p_{\text{main}}} / \tau)$$

Energy in from the Reburn Flow:

$$(m_i \times T_i \times Cp_{\text{reburn}})$$

Energy out from the reacted Flow due to mixing:

$$m_i + m_{\text{main}} \times \exp(-t_i / \tau) \times dt / \tau \times Cp_{\text{mix}} \times T_{(i+1)}$$

Energy generated due to CH4 Burning:

$$d\rho_{\text{CH4}} \times m_i \times \text{LHV}_{\text{reburn}} / \rho_{\text{mix}(i)}$$

The temperature at time step i+1 is calculated from:

$$T_{(i+1)} = ((m_{(i)} \times T_{(i)} \times Cp_{\text{reburn}}) + (m_{\text{main}} * \exp(-t_{(i)} / \tau) \times T_{\text{main}} \times dt \times Cp_{\text{main}} / \tau) + (mY_{\text{CH4}(i)} \times (m_{(i)} + (m_{\text{main}} \times \exp(-t_{(i)} / \tau) \times dt / 2)) \times dt \times \text{LHV}_{\text{reburn}} / \rho_{\text{mix}(i)}) / ((m_{(i)} + m_{\text{main}} \times \exp(-t_{(i)} / \tau) \times dt / \tau) * Cp_{\text{mix}})$$

The complete numerical code has been done using matlab.

1d. Results and Discussion:

The main inferences from the results were,

1. NOx Reduction
2. Effect of Equivalence ratio on the reduction phenomenon.
3. Effect of NH3/HCN ratio on the reduction phenomenon.
4. Temperature Profile.

1d.1. NOx Reduction:

As the process begins, the NO concentration starts to increase as the mixing process precedes the chemical reaction. In addition, it has to be noted that the mixing is assumed in such a way that the main gases mix with the reburn flow.

At some point (at $t = 0.035$ for Equivalence Ratio = 1.1), the chemical reactions dominate and the NO concentration starts to decrease. This reduction effect is due to the dilution due to mixing and the chemical reactions. Out of all the chemical reactions, reaction of CHx with NO is the fastest one and hence plays the major part in the reduction effect.

Figure 3: NO variation in the reduction zone

Figure 3 depicts the above-mentioned explanation at the following conditions:

Percentage of Excess air supplied in the main burner = 5%

Amount of NO at the main burner outlet = 600 ppm

Reburn Fuel is assumed to be biomass volatiles (CH_2)

Characteristic time scale = 0.1 sec.

Ratio of NH_3 to HCN is 3/2.

Reburn Zone Equivalence Ratio = 1.1

1d.2. Effect of Equivalence ratio on the reduction phenomenon:

Effect of Equivalence ratio on the reduction phenomenon is the most important issue in the reburn process. As the equivalence ratio increases, the mixture becomes richer and hence the NO reduction effect is increased. This is reflected by means of the increase in the negative slope of the NO curve. Figure 4a, 4b, 4c, 4d, and 4e show the effect of equivalence ratio on the reduction phenomenon, for various values of Φ ranging from 1.0 to 1.9.

Figure 4a: Effect of equivalence ratio on NO reduction ($\Phi_{RZ} = 1.0$)

Figure 4b: Effect of equivalence ratio on NO reduction ($\Phi_{RZ} = 1.1$)

Figure 4c: Effect of equivalence ratio on NO reduction ($\Phi_{RZ} = 1.3$)

Figure 4d: Effect of equivalence ratio on NO reduction ($\Phi_{RZ} = 1.5$)

Figure 4e: Effect of equivalence ratio on NO reduction ($\Phi_{RZ} = 1.9$)

Figure 4f: Species mole fraction variation in the reburn zone ($\Phi_{RZ} = 1.1$)

The mole fractions of various species at $\Phi_{RZ} = 1.1$ is shown in figure 4f.

1d.3. Effect of NH₃/HCN ratio on the reduction phenomenon:

NH₃: HCN ratio is believed to play a vital role in NO_x reduction as that ratio differs from coal. Figure 5 shows the NO variation with NH₃: HCN = 1:1 and Equivalence ratio = 1.1. A slight change in the negative slope could mean that the reduction is affected due to the change in ratio. Other conditions assumed for the simulation are,

Percentage of Excess air supplied in the main burner = 5%

Amount of NO at the main burner outlet = 600 ppm

No Inert gases are supplied.

Reburn Fuel is assumed to be biomass volatiles (CH₂)

Characteristic time scale = 0.1 sec.

Figure 5: NO variation with NH₃: HCN ratio 1:1

1d.4. Temperature Distribution

Figure 6 shows the temperature profile in the reburn zone.

Figure 6: Temperature profile in the reburn zone (PHI=1.1)

1e. Conclusion:

A complete numerical model to simulate the biomass (gaseous form) rebrun process has been developed. A more advanced model, which can handle solid biomass fuels, and incorporate the pyrolysis, char oxidation, and N evolution, is currently under development.

References

- [1] L.D.Smoot, S.C.Hill,H.Xug “NO_x Control through Reburning”, Prog. Energy Combust. Sci., pp 385-408,1998.
- [2] Fenimore, C. P.1979, Formation of Nitric Oxide in Premixed Hydrocarbon Flames, 17th Symposium (International) on Combustion, The Combustion Institute, pp.373-380.
- [3] Abbas, T., Costa, M., Costen, P., Godoy, S., Lockwood, F.C., Ou, J.J., Romo-Millares, C., and Zhou, J., 1994, NO_x Formation and Reduction Mechanisms in Pulverized Coal Flames, Fuel, Vol. 73, NO. 9, pp.1423-1435.
- [4] De Soete G.G., 1975, Overall Reaction Rates of NO and N₂ Formation from Fuel Nitrogen, 15th Symposium (International) on Combustion, The Combustion Institute, pp.1093.
- [5] Levy, J. M., Chan, L. K., Sarofim, A. F., and Beer, J. M., 1981, “NO Char reactions at pulverized coal flame conditions”, *Proceedings of the 18th Symposium on Combustion*, The Combustion Institute. pp. 111-120.
- [6] Sami, M, 2000, Numerical modeling of coal-feedlot biomass blend combustion and NO_x emissions in Swirl Burner, PhD thesis, Texas A&M university, college station, Texas 77843
- [7] Chen , W., Smoot, L D, Fletcher, T H, and Boardman, R D, “ A Computational method for Determining Global Fuel-NI Rate expressions, Part I,” Energy and Fuels, 10, 1036-1045, (1996)