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Numerical Simulation of Updraft Gasifier in Ceramic Industry under Different Values of Equivalence Ratios

[1] Bhargav Manek, [2] Hardik Ramani
Department of Mechanical Engineering,
Marwadi Education Foundation Group of Institutions, Rajkot

***Abstract:* -- Energy is the vital requirement for any industry and due to more industrialization; its demand is increasing highly. Coal is one of the major fuel sources for power and process heating. Direct combustion of coal is one of the main reasons of pollution. Coal gasification is a Non-Conventional technology to produce heat in an economical way by generating a product of carbon monoxide and hydrogen gas called synthesis gas. In the present study, numerical simulation of updraft gasifier with coal as a fuel has been performed. The Euler-Lagrange approach is used to describe gasification process. The present numerical study is carried out based on the gasifier used for industrial purposes manufactured by Radhe Renewable Energy Pvt. Ltd. situated in Rajkot, Gujarat. ANSYS Fluent V 17.2 has been used for the CFD simulations. The operating parameters for the present simulation were taken from ceramic industry situated in Morbi, Gujarat. Validation of numerical work was done with experimental data that shows good agreement. Effect of equivalence ratio (E.R.) is studied on the output syngas. Results show that industry is working with E.R. value 0.295 and optimized E.R. value is 0.32 in the present study. By increasing E.R. value we found that syngas component fraction is decreasing.**

***Key words*: CFD; Gasification; Updraft gasifier; Equivalence ratio; Ceramic application.**

I. INTRODUCTION

Fossil fuel is a main source of energy and it has been founded that many of fossil fuels will be finished in upcoming 70-80 years. Since coal reservoir is reported available for more than 120 years, Costing of coal for thermal applications is quite cheap compare to petroleum and other fuels [1]. Direct combustion of coal for heating purpose is major reason for air pollution because it produces huge amount of carbon dioxide. So, proper utilization of coal in good way is a big task in industry. Gasification process has advantage to produce clean energy by converting coal into syngas (H2 + CO) in less amount of oxygen [2]. Gasifier is a device to generate syngas. It has been characterized according to flow of gas like downdraft, updraft and entrained flow. Fluidized bed is a technology to provide velocity to coal particles in reactor. Different zones are generated in fixed bed gasifier in gasification process called drying, devolatilization, reduction and oxidation are briefly explained by Higman and van der Brugt [3]. For medium scale applications like ceramic industries in Morbi (Gujarat, India), updraft gasifier is very useful. Due to simple structure, flexibility in fuel and less cost, ceramic industries in Morbi area are using updraft gasifier. For requirement of more energy coal has been used as fuel but due to this fact, industrial area is suffering from pollution. Radhe Renewable Energy Pvt. Ltd. in Rajkot (Gujarat, India) is the main updraft gasifier manufacturing industry in India that provides gasifier to most of ceramic industries. Gasifier users in ceramic industries have only concern with heating temperature. They are not dealing with syngas composition. When flame temperature at burner drops down, workers fed more amount of coal. So, in different amount of feed, proper gas composition cannot be predicted. Specific coal has own E.R. value of feed rate with oxidizer supply to produce best quality of syngas. Thus, in ceramic industries, effective use of gasifier has not been done. For generating best syngas composition, experimental method requires much effort, time and cost. Numerical Simulation is a technology to improve syngas quality by numerical work without any experiments. Several authors have been worked on numerical study of gasifier with different modeling approaches and different solvers. Chen et al. [4] examined the effect of E.R. of three different fuels for entrained flow gasifier and also showed benefits of torrefication of biomass. Murugan and Joseph [5] investigated the effect of

E.R. on fuel as rice husk in downdraft gasifier. Fernando and Narayana [6] used Euler multiphase approach in fixed bed condition for finding optimum air flow rate for maximum syngas production. Jeong et al. [7] used Euler-Lagrange approach to find best coal particle size in downdraft gasifier. Zogala and Jenoszek [8] simulated underground coal gasification (UCG) process under different combination of air and steam as oxidizers. Murgia et al. [9] used Euler-Euler approach for fixed bed operation in updraft gasifier. From above analysis, it is founded that continuous feed in updraft gasifier is not observed. It is also observed that equivalence ratio is leading parameter for performance of gasifier. Also discrete phase modeling is very useful to simulate continuous feed operation.

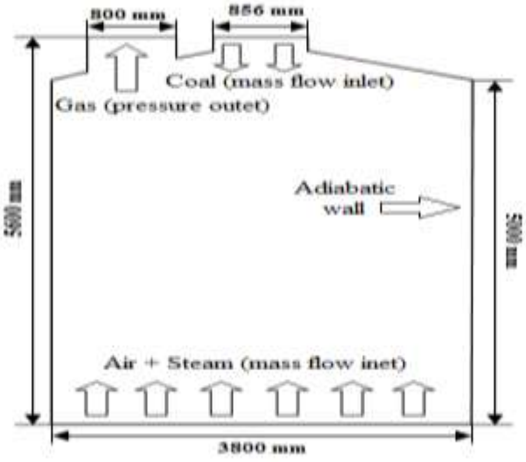


Figure 1. Updraft gasifier

Turbulent Kinetic Energy:

$$\nabla\left(\rho\vec{V}\cdot k\right)=\nabla\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\cdot\nabla k\right]+G_k-\rho\varepsilon$$

II. NUMERICAL METHOD

2.1 Geometry and Dimensions:

Updraft gasifier in present study is shown in Fig.1. This updraft gasifier is cylindrical in shape having two holes on top. Height of gasifier is 5.6m and diameter of cylinder is 3.8m. Dry coal is fed from the top center hole through hopper having diameter of 0.856m. Outlet is just aside of coal inlet having diameter of 0.8m with center distance of 1.172m. Air and steam were fed from the bottom as oxidizer. Coal is pulverized before feeding into the gasifier while syngas is cleaned after passing through outlet. So, other part of gasification system is not considered in present study.

2.2 Assumptions:

Actual reactions in gasifier involve too much complicated chemistry. In the present numerical work, few assumptions were adopted: (1) Steady, incompressible and turbulent flow field has been considered. (2) Thermal radiation is not considered and gasifier wall is considered to be adiabatic. (3) No pollutants like NOx, SOx etc. are formed in the process (4) Coal loading and ash removal processes are continuous. (5) Coal particle size is uniform and also air + steam flow is uniform throughout at bottom. 2-D, steady state time average Nevier-Stokes and species transfer equations have been solved. The governing equations [10] are enlisted below.

2.3 Governing Equations:

Continuity: $\nabla\cdot\left(\rho\vec{V}\right)=S_m$ (1)

Momentum: $\nabla\cdot(\rho\vec{v}\cdot\vec{v})=-\nabla P+\nabla\tau+\rho\vec{g}+\vec{F}$ (2)

Energy: $\nabla\cdot\left(\rho\vec{V}\cdot T\right)=\nabla\left(\lambda(\nabla T)\right)+S_h$ (3)

Species: $\nabla\left(\rho\vec{V}\cdot Y_i\right)=\nabla\left(\rho D\cdot(\nabla Y)\right)+S_r+R_i$ (4)

Kinematic Viscosity: $\mu_t=(\rho C_\mu k^2)/\varepsilon$ (5)

Turbulent Dissipation Rate:

$$\nabla\left(\rho\vec{V}\cdot\varepsilon\right)=\nabla\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\cdot\nabla\varepsilon\right]+C_{1\varepsilon}G_k\frac{\varepsilon}{k}-C_{2\varepsilon}G_k \quad (7)$$

2.4 Euler-Lagrange Approach:

The modeling of fuel particle in fluid is modeled by Euler-Lagrange frame that considers inertia and hydrodynamic forces relevant to mass, momentum and energy. Discrete phase modeling is useful to track the particle trajectories in continuum. Velocity change can be written by [11],

$$m_s\frac{dV_s}{dt}=F_d \quad (8)$$

Where, Vs is particle velocity and Fd is drag force on fuel particle by surrounding fluid. Drag force can be represented by [12],

$$F_d=\frac{(\rho A_c C_d V_r^2)}{2} \quad (9)$$

Here, ρ is density of surrounding fluid, Ac is crossectional area of fuel particle, Cd is drag force co-efficient and Vr is relative velocity of fluid particle and surrounding fluid. Some heat and mass transfer processes also accrue on particle surface. They are considered as source terms in governing equations. These processes consists evaporation of moisture, devolatilization of particle in volatile matter, char and ash and finally char and volatiles converted into gases. The conversion rate(R) of species i into other gaseous phase on solid particle surface is given by,

$$\overline{R}_i=A_p U y_i r_i \quad (10)$$

$$r_i=Z_i'\left(p-\frac{r}{D}\right)^q \quad (11)$$

Where, Ap is surface area of particle; U is effectiveness factor; yi is mass fraction; r is per unit area reaction rate; Z_i' is reaction rate constant; p is partial bulk pressure of gas phase species; D is diffusion constant; q is apparent order of reaction. q=0 shows solid depletion rate equals to chemical reaction rate, while q=1 shows solid depletion rate equals to diffusion controlled rate.

2.5 Chemical Process modeling:

Devolatilization:

At high temperature, coal particles decomposed into char, volatiles and ash. The equilibrium condition of volatile release of dry ash free fuel is describe by two step devolatilization model known as kobayashi model.

$$Fuel \overset{r_l}{\rightarrow} (1 - X_l)Char_l + (X_l)Volatile$$

(For low temperature) (12)

$$Fuel \overset{r_h}{\rightarrow} (1 - X_h)Char_h + (X_h)Volatile$$

(For high temperature) (13)

Where, X is stochiometric coefficient and r is reaction rate. *l* and *h* stands for high and low temperature. Combine reaction kinetics is given by,

$$\frac{dm}{dt} = (r_l X_l + r_h X_h)Fuel \qquad (14)$$

$$r_l = A_l e^{(-\frac{E_{a,l}}{RT})}, \quad r_h = A_h e^{(-\frac{E_{a,h}}{RT})} \qquad (15\text{-}16)$$

Here, m is mass fraction of species, R is universal gas constant, A is Arrhenius type pre-exponential factor, E_a is activation energy of reaction and T stands for temperature. The values of X_l, X_h, A_l, A_h, E_{al}, E_{ah} are taken from [13].

Solid phase reaction:

$$C_s + 0.5O_2 \overset{r_1}{\rightarrow} CO \qquad (17)$$

$$C_s + H_2O \overset{r_2}{\rightarrow} CO + H_2 \qquad (18)$$

$$C_s + CO_2 \overset{r_3}{\rightarrow} 2CO \qquad (19)$$

Gaseous phase reaction:

$$H_2 + 0.5O_2 \overset{r_4}{\rightarrow} H_2O \qquad (20)$$

$$CO + 0.5O_2 \overset{r_5}{\rightarrow} CO_2 \qquad (21)$$

$$CO + H_2O \overset{r_6}{\rightarrow} CO_2 + H_2 \qquad (22)$$

$$CH_4 + 0.5O_2 \overset{r_7}{\rightarrow} CO + 2H_2 \qquad (23)$$

$$CH_4 + H_2O \overset{r_8}{\rightarrow} CO + 3H_2 \qquad (24)$$

Here, k is reaction rate and it can be represented by,

$$r = AT^b e^{(\frac{-E_a}{RT})} \qquad (25)$$

A is Arrhenius type pre-exponential factor; T is temperature; b is temperature exponent; E_a is activation energy and R is universal gas constant. All values of these chemical parameters are taken from [14]

2.6 Boundary Conditions:

The boundary conditions are set as per the operating conditions at ceramic industry defined by gasifier producers (Radhe Renewable Energy Pvt.Ltd.). Coal was fed from the top at 300K atmospheric temperature at 0.033 kg/s. Standard Indian bituminous class II type coal has been used. Coal parametric data like proximate and ultimate analysis is given in the table 4. Air as oxidizer was fed from the bottom that passed from steam generator at nearly 430K temperature with rate of nearly 0.067 kg/s. Steam was added to air as oxidizer to produce more hydrogen with constant rate of 0.016 kg/s. Both these conditions are set as mass flow inlet. Gauge pressure at inlet was nearly 200mm of water column. Outlet of gasifier was set as pressure outlet with gauge pressure of 120mm of water column. Wall of gasifier was considered as adiabatic wall with no slip condition. Fig. 1 also indicates all boundary conditions.

Table 4. Proximate and ultimate analysis of Indian bituminous coal class II (%wt. basis)

F.C.	0.36	**C**	0.67
V.M.	0.29	**H**	0.08
Ash	0.35	**O**	0.24
HHV	29.72MJ/kg	**N**	0.01

2.7 Numerical Considerations:

The commercial software ANSYS Fluent was used in present study for numerical work. SIMPLE algorithm is used to solve the governing equations with Second order upwind scheme incorporated for calculating various convection and diffusion flux equations. Grid dependency has been carried out under same operating conditions as shown in table 5. Result shows that for grids with 30.7k cells and the finer grids show less change in results in terms of maximum temperature simulated in gasifier. So, the grid with 30.7k cells has been considered for the present numerical simulation

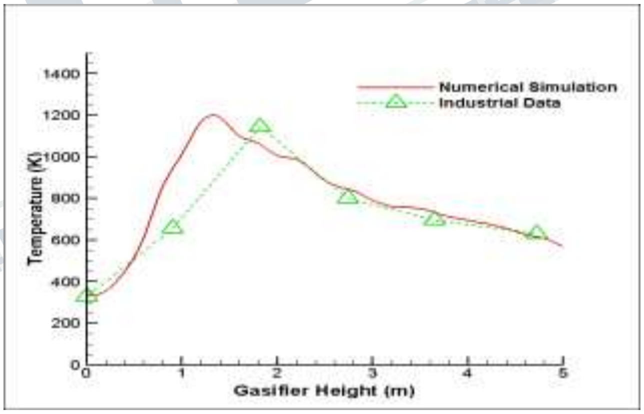


Fig. 2 Temperature distribution on gasifier wall

Table 5. Grid independency test

Number of Cells	Maximum Temperature detected(K)
7.62k	1118
15.3k	1161
30.7k	1189
62.5k	1193

III. RESULTS AND DISCUSSION

In present study, numerical simulation has been carried out in Industrial operating condition as given by ceramic industry. By operating conditions we found that they are working at E.R. value 0.295. The case is validated with Industrial data of gasifier wall temperature. In actual gasifier, five thermocouples are attached at gasifier wall with 3feet distance each. While one is located near inlet of air at bottom. Fig. 2 shows that within gasifier height, temperature is continuously changing along the gasifier wall. Simulation result for temperature distribution shows good agreement with present industrial data. Also, the temperature in the gasifier has been noticed that after combustion zone it decrease in reduction and pyrolysis zone.

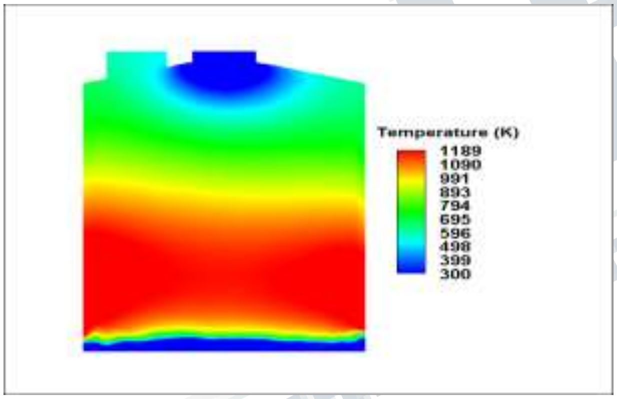


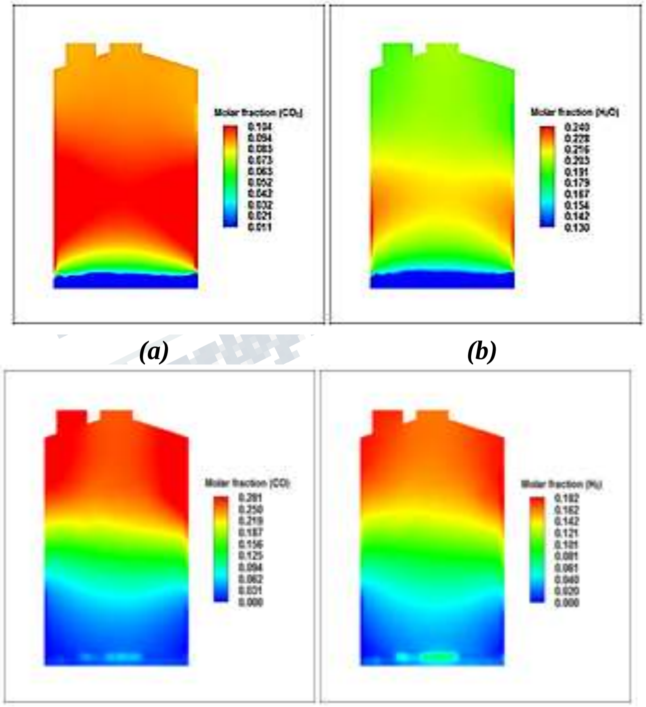
Fig.3 Temperature profile at E.R. 0.295

3.1 Gasification Process:

Fig. 3 shows temperature profile of gasifier at E.R. value 0.295. It has been noticed that high temperature is located in combustion zone just above ash zone and after oxidation zone, marching upward; temperature is reduced in reduction and pyrolysis zone. Fig. 4 shows molar fraction profile of CO2, H2O, CO, H2 respectively. We can clearly see that at bottom part in combustion zone, coal particles react with air and steam and due to complete combustion; more amount of carbon dioxide and water vapor is generated. In reduction zone that products react with oxidizers and produce carbon monoxide and hydrogen i.e. syngas. So, clearly CO2 and H2O concentration is more in oxidation zone while CO and H2 concentration is high in reduction zone. At outlet, syngas is taken at nearly 595K temperature with gas component molar fraction as CO-26.1%, CO2-8.3%, H2-16.7%, H2O-16.4%, CH4-0.2% and N2-rest. Further the gas is cleaned and water vapor, tar and other particles was separated out.

3.2 Effect of E.R.:

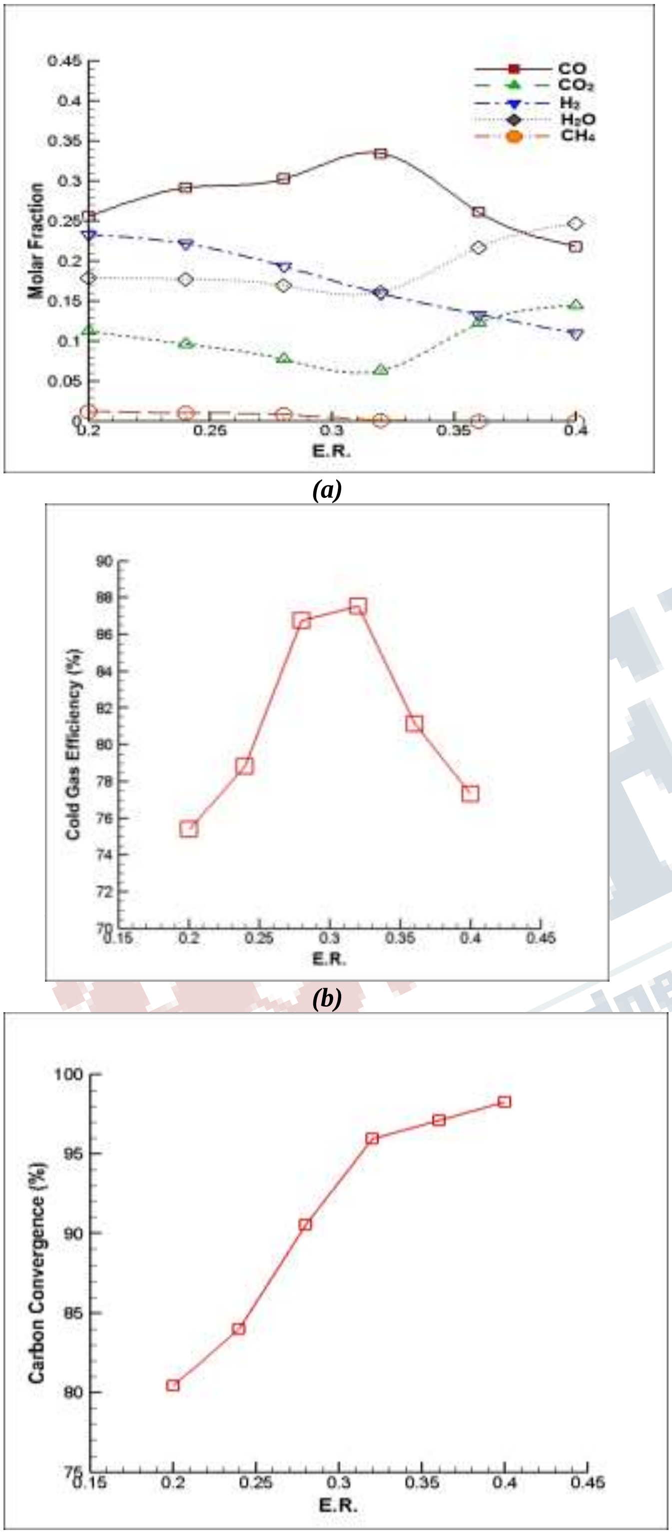
After the simulation as per experimental data, further simulations are carried out under different E.R. values with constant steam fed rate at 0.122kg/s. E.R. values are taken between 0.2 to 0.4. In Fig. 5 (a), results show molar fraction of different species in syngas at outlet of gasifier. Corresponding to E.R. value 0.2, CO molar fraction increases while CO2 molar fraction decreases. E.R. value 0.32 gives



(a) *(b)*

(c) *(d)*

Fig. 4 Molar fraction profile of (a) CO2 (b) H2O (c) CO (d) H2 at E.R. 0.295



(a)

(b)

(c)

Fig. 5 Profiles of (a) molar fraction of species (b) cold gas efficiency (c) carbon convergence at different E.R. values

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