

Research Article

CFD Modeling and Simulation of 10KWE Biomass Downdraft Gasifier

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Abstract

Biomass gasification is the most appropriate natural energy conversion technology for clean coal mechanism and pollution control purpose. Due to the decreasing conventional and non-renewable resources as fossil fuels and their environment impact, biomass becomes the more important CO₂-neutral fuels. In this work, CFD modeling and simulation is used for performance analysis of a 10kWe downdraft fixed bed type biomass gasifier which is installed at Department of Energy And Environment Mgt. in UTD Rajiv Gandhi Proudyogiki Vishwavidyalaya, Bhopal. The complete model is created in ANSYS MESHING and simulated in ANSYS FLUENT. The simulation work is done through the species transportation model with volumetric and particle surface reaction for calculation of gas temperature and mass fractions. In this study work on thermal, kinematic and chemical reaction analysis of gasifier view modeling and simulation on fluent.

Keywords: Biomass, downdraft-gasifier, CFD simulation, ANSYS FLUENT, air velocity, species transportation model

1. Introduction

Due to rise in energy demand and fossil fuel exhaustion the alternate resources such as the solar, wind, biomass, and fuel cell were being gradually utilized. For 20 years, the biomass is one of the most relied and sustainable renewable energy sources in the world. Biomass is organic material from agricultural and animal residues. Biomass devolatilization and gasification technique becomes most important research field for future energy generation and supply. Biomass energy has risen to 14% of the total energy consumption in the world. The energy can be released from biomass by thermal conversion processes such as combustion and gasification. Biomass gasification is an attractive technology. Gasification not only generates heat, but it also produces important intermediate chemicals such as syngas (CO + H₂), which is widely used in chemical industries (San Miguel, Domínguez *et al.* 2012). Additionally, the conversion efficiency of gasification, which can reach up to 50%, is higher than the efficiency of combustion, about 20–40% (Caputo, Palumbo *et al.* 2005).

There are many types of the gasifier in present. Gasifier mostly classified into fixed bed and fluidized bed. Downward gasifier a fixed bed technology base gasifier is essential now a day because of there is no generation of tar in the byproduct of gasification. In downdraft gasifier, the fuels enter at top of gasifier and move downward while oxidizer agent blew from the bottom/across the fuel bed.

Following reaction zone and process in the gasifier;

Devolatilization zone: Biomass → char + volatile + tar
Devolatilization reduction: Volatile → Gas₁ (CO, CO₂, H₂, CH₄ etc.)

Char Combustion: Char → Gas₂ (CO, CO₂)

There is also 10kWe downdraft gasifier available at Energy Park in Rajiv Gandhi Technical University, Bhopal (M.P.) for investigation and analysis of different woody biomass in the area of the research and development. This gasifier model shows in figure (1).



Fig.1 Downdraft gasifier at RGPV, Bhopal

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Specification of Gasifier

Gasifier model- 10kWe Cosmo-Cp-10
 Mode of operation- clean and cold gas
 Gasifier type- Downdraft gasifier
 Rated hourly consumption- up to 17 kg/hour

In past few years, remarkable progress has been attained in improving the accuracy and stability of numerical methods and algorithms. Computational fluid dynamics (CFD) has been applied as an important design tool in various industrial zones, and the CFD techniques have shown the capability to provide an accurate prediction for some chemical processes(Ahmed, Ahmad *et al.* 2012). At present-day, for CFD simulations of coal or biomass gasification, two types of techniques, the Eulerian-Lagrange approach, and the Eulerian-Eulerian approach are widely used. Mathematical and numerical methods were used to simulate the performance of gasifiers operating at various working conditions.

Zainal has been developed an equilibrium model through energy balance process to predict composition and calorific value of the syngas in equilibrium operating conditions(Zainal, Ali *et al.* 2001).

Pratik and Babu, (2009) is given the kinetic constant of the kinetic model can applied to any size and shape of the particle by the rate of pyrolysis reaction(Babu and Sheth 2006).

The theoretical kinetic equations on the non-equilibrium conditions have been developed and solved numerically with rice husk gasifier. the effect of temperature and calorific value of the producer gas has been studied by Chowdhury (Chowdhury, Bhattacharya *et al.* 1994).

Marta Muilenburg research on the CFD modeling of downdraft gasifier bed which will be implemented by the University of Iowa Oakdale power plant(Muilenburg, Shi *et al.* 2011).

2. Description of gasifier model

The schematic diagram of downdraft gasifier installed at RGPV with their dimension shown in the figure. This model is considered in this study.

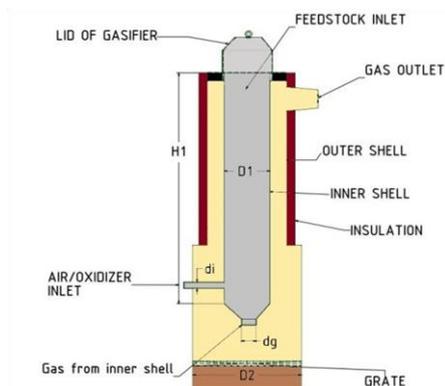


Fig.2 Downdraft gasifier installed at UIT RGPV

Dimension of downdraft gasifier is given below

Table 1 Dimension of gasifier

S.N.	Part of gasifier	Dimension
1	Inner shell diameter (D1)	22cm
2	Outer shell diameter (D2)	26cm
3	Thickness of shell	0.7cm
4	Height of gasifier (H1)	115cm
5	Insulation diameter	32cm
6	Air nozzle diameter (di)	3cm
7	Length of air nozzle	10cm
8	Gas outlet diameter at inner shell (dg)	7cm

3. Model setup

Numerical modeling using Ansys software is cost effective approach for future biomass fuel combustion and gasification application design. The important tool for CFD simulation of gasification of biomass is ANSYS FLUENT.

There five process/ phase to complete the modeling and simulation of downdraft gasifier.

- a) Geometry designing
- b) Meshing
- c) Setting up
- d) Solution
- e) Post processing

All phase of modeling and simulation is performed in ANSYS 18.0 software. In this study, 2D geometry modeling of 10kWe downdraft gasifier is done by using Design Modeler package. The meshing of geometry model is done on ANSYS Meshing package. Meshing of model is shown in the figure (3)

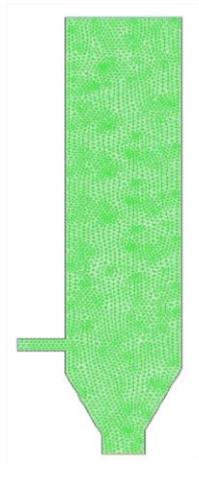


Fig.3 meshing of 2D gasifier model

Statics of meshing is
 →No. of Nodes 3713
 →No. of Elements 7096 with triangular shape
 →Quality of mesh 6.66027e-01 m orthogonal

The following were the general assumptions made in the study:

- The flow is steady and two-dimensional.
- Wall surfaces at the no-slip condition.
- The chemical reactions were faster than the time scale of the turbulence eddies.
- Discrete phase model was used, given the small particle size and compared to the reactor volume.
- The particles are spherical in shape and size 25mm has a uniform distribution.
- The inner shell of gasifier considers for all chemical reaction.
- Oxidizer considers as only pure O₂, not include N₂.

4. Governing equation

The equation for mass flow, momentum, and energy is given by following:

$$\nabla(\rho v) = S_m \quad (1)$$

$$\nabla(\rho v v) = \rho v v - \rho g + \nabla \cdot (\tau) + S_f \quad (2)$$

$$\nabla(v(\rho E + p)) = \nabla \cdot K \Delta T - \nabla \sum h_i J_i + \nabla \cdot (\tau \cdot v) \quad (3)$$

Where, the effective conductivity is K and the diffusion is J_i of species i .

4.1 Turbulence model

Most common RANS turbulence model applied to coal combustion is k-epsilon and its variants (standard and Realizable). The k-epsilon models provide a good solution without excessive computation time.

Standard k- ϵ model: - in this study k- epsilon turbulence model considered for simulation of flow. In the standard k- ϵ model, the k and ϵ can be achieved from the following transport equations as(Launder and Spalding 1972)

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (4)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} + S_\epsilon \quad (5)$$

Turbulent Viscosity The eddy viscosity, μ , is computed by combining k and ϵ as follows:

$$\mu = \rho C_\mu \frac{k^2}{\epsilon} \quad (6)$$

Where, C_μ is a constant

4.2 Radiation model

Radiation model: in this model, Radiative transfer equation (RTE) for an absorbing, emitting, and scattering medium at position r in the direction s can be given as(Habibi, Merci et al. 2007).

$$\frac{dI(\vec{r}, \vec{s})}{ds} + (\alpha + \sigma_s) I(\vec{r}, \vec{s}) = \alpha n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \Phi(\vec{r}, \vec{s}, \vec{s}') d\Omega \quad (7)$$

There are four common radiation models in Fluent

- P-1 Radiation Model
- Rosseland Model
- Discrete Ordinates Model (DOM)
- Discrete Transfer Radiation Model (DTRM)

P-1 Radiation Model is considered for this simulation process work. P-1 model is the simplest modified derivation of the P-N radiation model which is based on the expansion of the radiation intensity I into an orthogonal series of spherical harmonics and high order accuracy.

$$q_r = - \frac{1}{3(\alpha + \sigma_s) - C\sigma_s} \nabla G \quad (8)$$

$$-\nabla q_r = \alpha G - 4\alpha\sigma T^4 \quad (9)$$

Where,

q_r is the radiation heat flux,
 α is the absorption coefficient,
 G is the incident radiation,
 C is the linear-anisotropic phase function coefficient,
 σ_s is the Stefan-Boltzmann constant.

4.3 Species transport model

The species model is the best way for modeling of biomass/coal gasification. The species transport model has been chosen to model the chemical reactions inside the gasifier and to find out the composition of various species like CO, CO₂, N₂, H₂, and CH₄. the common form of the transport equation for each species is defined as(Magnussen and Hjertager 1977)

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla(\rho \vec{v} Y_i) = \nabla \cdot \vec{J}_i + R_i \quad (10)$$

Where R_i is the net rate of production of species "i" by chemical reaction

Mass diffusion \vec{J} is given as

$$\vec{J} = - \left(\rho D_{i,m} + \frac{\mu_t}{Sc_i} \right) \nabla Y_i \quad \text{for laminar flows} \quad (11)$$

and

$$\vec{J} = -\rho D_{i,m} \nabla Y_i \quad \text{For turbulent flows} \quad (12)$$

Where $D_{i,m}$ is the mass diffusion coefficient of species in the mixture, and Sc_i is the turbulent Schmidt number. The net rate of production or destruction of species i as the result of reaction r , in $R_{i,r}$ is given by

$$R_{i,r} = \nu'_{i,r} M_{i,r} A \rho \frac{\epsilon}{k} \min_g \left(\frac{Y_r}{\nu'_{i,r} M_{w,j}} \right) \quad (13)$$

and

$$R_{i,r} = \nu'_{i,r} M_{i,r} B \rho \frac{\epsilon}{k} \min_g \left(\frac{\sum_p Y_p}{\sum_j \nu''_{i,r} M_{w,j}} \right) \quad (14)$$

Where, Y_p is denoted the mass fraction of any product species, P , Y_r is denoted the mass fraction of a particular reactant, R .

This model is used for transport of reactant and product in this simulation.

4.4 Chemical reaction model

Chemical reactions in Biomass gasification model are involved following process: devolatilization of biomass, homogenous reaction and heterogeneous reaction.

a) Devolatilization

Devolatilization model for biomass is given

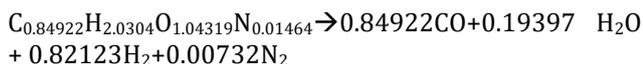
Biomass \xrightarrow{k} char(C_s)+ash + moisture + volatile (R_d) The reaction kinetic rate (k) is expressed in single-step Arrhenius fashion as

$$k = A \exp\left(-\frac{E_a}{RT}\right) \tag{15}$$

Where A pre-exponential factor and E_a is activation energy. single rate devolatilization model has very peculiar characteristics hence taken this model for this study.

b) Volatile reduction

The volatile represented by $C_xH_yO_zN_w$ is are decompose into gas component(CO , H_2O , H_2 , N_2).chemical reaction (R_g1)shown below is strictly balanced by heat and mass basis.



For formation of empirical formula of biomass and volatile is based on proximate and ultimate analysis of biomass .empirical chemical formula of volatile derived by using ANSYS (2010)developed species prediction scheme.

c) Gas phase homogeneous reactions



d) Particle surface heterogeneous reaction:



Chemical kinetics of reactions is summarized in table (1) and table (2).

Table 2 Gas phase reaction kinetics

Kinetic parameters (A_i, E_i [kJ/mol])	References
$A_d=10e8 s^{-1}$ $E_d=140$	(Chan, Kelbon <i>et al.</i> 1985)
$A_{g2}=10^{17.8}(m3/mol)^{0.75} s^{-1}$ $E_{g2}=166.28$	(Di Blasi 2000)
$A_{g3}=10e11(mol/m3)^{-1} s^{-1}$ $E_{g3}=42$	(Di Blasi 2000)
$A_{g4}=0.0265(mol/m3)^{-1} s^{-1}$ $E_{g4}=65.8$	(Di Blasi 2000)

Table 3 Particle surface reaction kinetics

Kinetic parameters (A_i, E_i [kJ/mol])	References
$A_{s1}=5.67e9(s^{-1})$ $E_{s1}=160$	(Di Blasi 2000)
$A_{s2}=7.29e4(mol/m3)^{-1} s^{-1}$ $E_{s2}=218$	(Di Blasi 2000)
$A_{s3}=7.29e4(mol/m3)^{-1} s^{-1}$ $E_{s3}=218$	(Di Blasi 2000)
$A_{s4}=7.29e4(mol/m3)^{-1} s^{-1}$ $E_{s4}=218$	(Di Blasi 2000)
$A_{s5}=7.29e4(mol/m3)^{-1} s^{-1}$ $E_{s5}=218.$	(Di Blasi 2000)

4.5 Boundary and Operating condition

The boundary and operating condition are based on previous experiment and literature of downdraft gasifier installed at UTD RGPV. Boundary and operating condition of gasifier model summarized in Table (3)

Table 4 Boundary and operating condition

Boundary and operating condition	Values
Air inlet	
Temperature (K)	400
Velocity (m/s)	3.2-7.2
Fuel inlet	
Temperature (K)	320
Mass flow rate (kg/h)	17
Combustible particle	
Temperature (K)	440
Diameter (m)	0.025
Turbulence intensity (%)	10

4.6 Feedstock fuel property

Sobabul wood (*L. leucocephala*) is selected for the gasification simulation. Ultimate and proximate analysis of *L. leucocephala* wood is given in table (4)

Table 5 Ultimate and proximate analysis of *L. leucocephala* wood (Payormhorm, Kangvansaichol *et al.* 2013)

Ultimate and proximate analysis of <i>L. leucocephala</i>	
Parameter	Ultimate analysis (%d.b.)
C	46.2
H	5.8
N	0.7
O*	47.3
Parameter	Proximate analysis (%a.r.)
Volatile matter	3.7
Fixed carbon	77.0
Moisture	3.2
Ash contain	16.1
Gross heating value, (MJ/kg)	17.94

* Determined by difference
Bulk density of wood is 619 kg/m³

5. Results

Different types of parameter which affects the gasifier performance are following:

5.1 Static Temperature

Temperature distribution within the downdraft gasifier inner shell at desired operating condition is given temperature profile contour. the maximum average temperature of gasifier achieves approx 800.3°k.

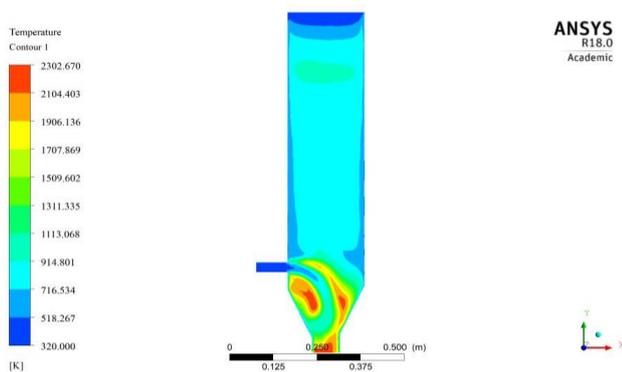
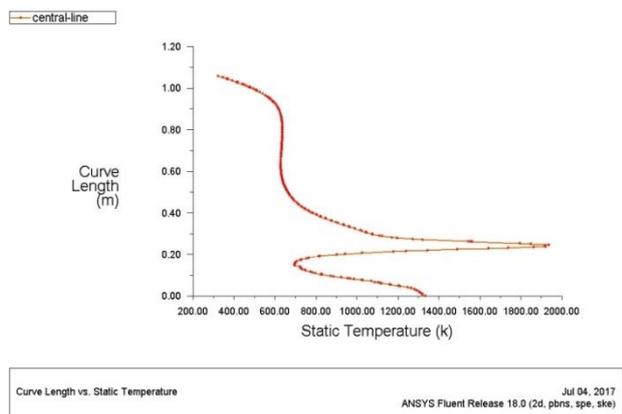


Fig.4 contour of static temperature

Temperature distribution within the gasifier due to combustion of wood at the central line of gasifier shown following graph (1).



Graph 1 central line temperature of gasifier

5.2 Pressure

Gasifier file although working at atmospheric pressure but the static pressure of the gasifier varied with a height of gasifier due to the generation of combustion gaseous products. static pressure varying between 0 Pa to 1.75Pa. with the height of gasifier.

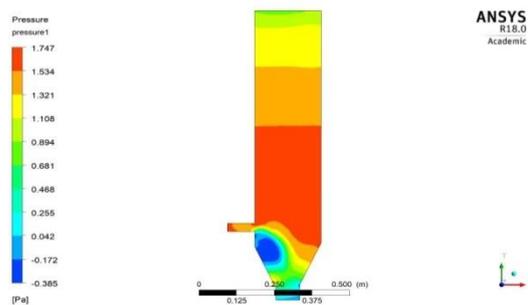
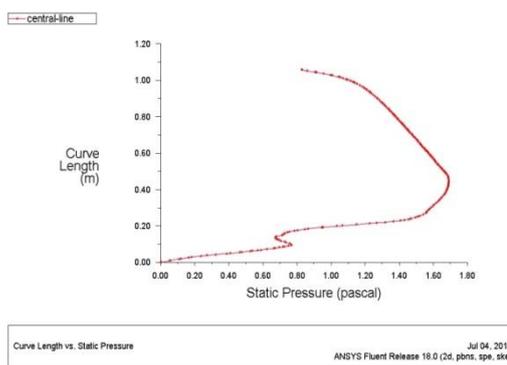
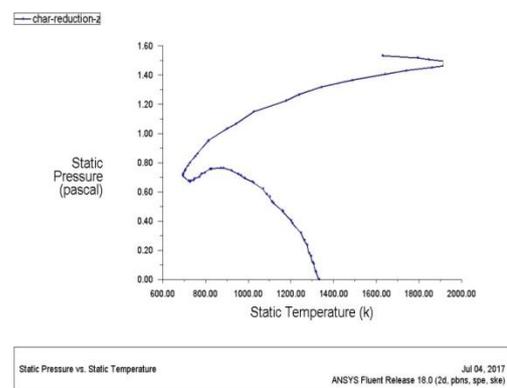


Fig.5 contours of static pressure of gasifier



Graph 2 Pressure variation inside gasifier at central line



Graph 3 temperature vs pressure at char reduction zone

5.3 Producer gas composition

production of syngas and combustion product in this modeled and simulated downdraft gasifier is given in the table (5)

Table 6 Mass fraction of output byproduct

Component	Mass fraction	% Mass
volatile	0.0575	5.75
O2	0.03168	3.168
N2	0.1364	13.64
CO2	0.13537	13.537
CO	0.5696	56.96
CH4	0.02232	2.232
H2	0.00163	0.163
H2O	0.0455	4.55

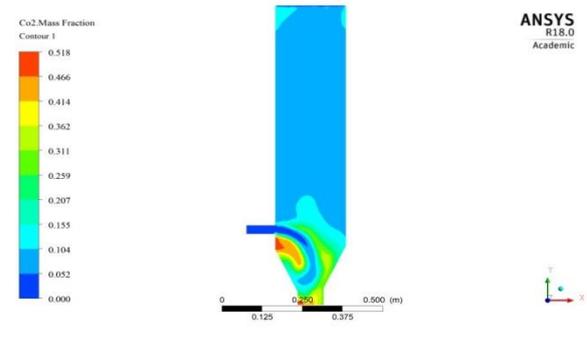
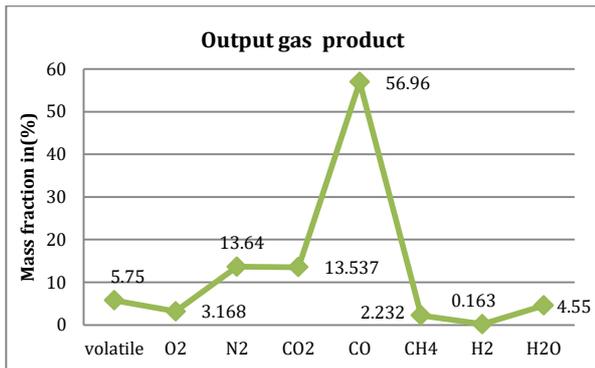


Fig.8 Contour of CO₂ mass fraction

Graph4 output gas product within gasifier

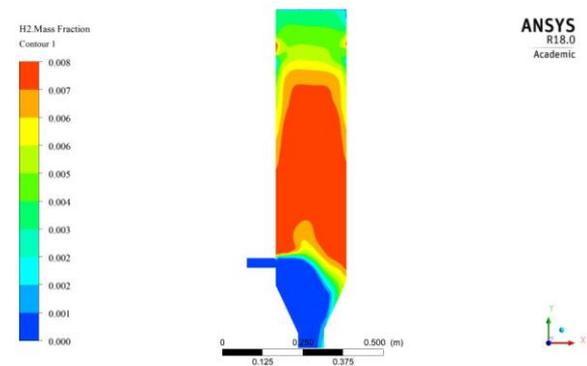
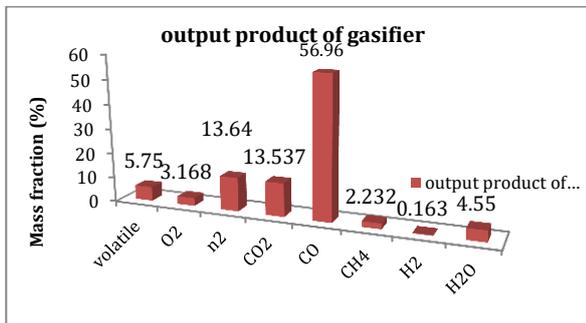


Fig.9 Contour of H₂ mass fraction

Graph 5 3D Bar graph of output gas product

the contour profile of simulated gasifier output products shown in figure no [6 to 12].

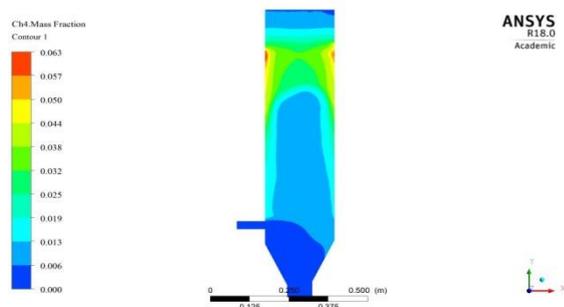


Fig.6 Contour of CH₄ mass fraction

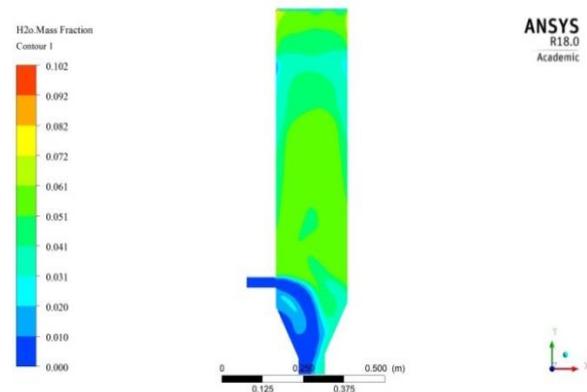


Fig.10 Contour of HO₂ mass fraction

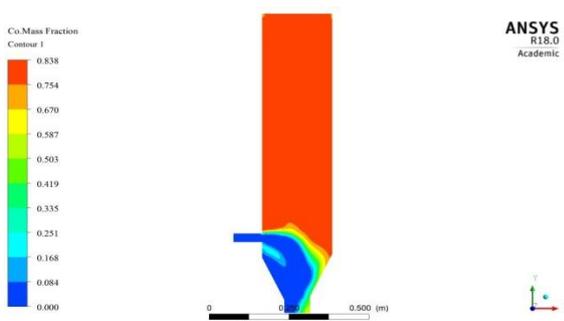


Fig.7 contour of co mass fraction

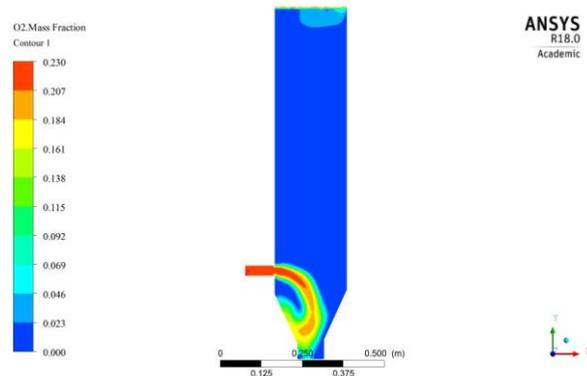


Fig.11 Contour of O₂ mass fraction

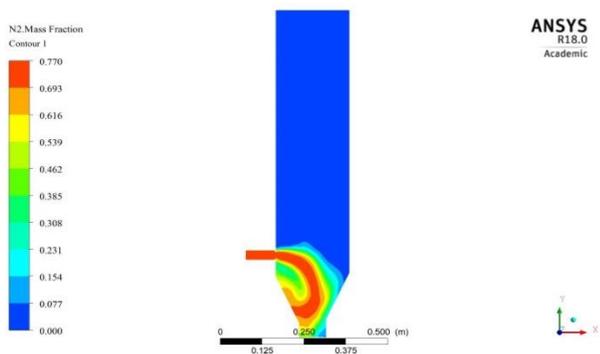


Fig.12 Contour of N2mass fraction

5.4 The Turbulence of Oxidizer

The maximum intensity of turbulence is achieved by oxidizer velocity at the reduction zone. Turbulence and flow velocity with direction shown in figure (13).

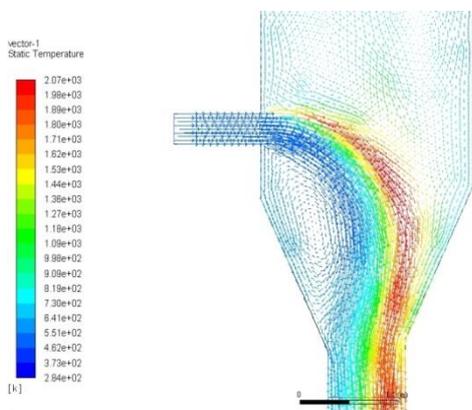


Fig.13 Velocity vector of turbulence of oxidizer and temperature

5.5 Cold Gas Efficiency of Downdraft Gasifier

$$CGE(\%) = \left(\frac{m_{out, gas}(y_{CO_2}HHV_{CO_2} + y_{CO}HHV_{CO} + y_{CH_4}HHV_{CH_4} + y_{H_2}HHV_{H_2})}{m_{in, fuel}(HHV_{fuel})} \right) \times 100$$

Mass flow rate of fuel = 0.0047 kg/s
 Mass flow rate of producer gas = 0.072511774 kg/s
 Heat value of fuel is 17.994 MJ/kg

CEG = 62.18%

Conclusion

In this CFD model of downdraft gasifier predict the composition of producer gas, temperature, pressure, and turbulence of oxidizer (air) flow. Following conclusion carried out basis on CFD gasifier model:

1) Modeling and simulation of 10 kWe laboratory scaled downdraft gasifier which is implemented by RGPV state university.

- 2) The average temperature of the gasifier is 800.3°k and maximum temperature found at char reduction zone and pressures vary with height of gasifier.
- 3) The cold gas efficiency of the gasifier is 62.18% only.
- 4) Simple and economic technique to calculate the composition of producer gas by this CFD model.
- 5) From the result obtain producer gas production in this model compares to theoretical values having less amount of error (approx. 4-6%).
- 6) This model may be use to model and simulate of laboratory scale downdraft gasifier for thermal and physical analysis which is not achieved easily like flow pattern and turbulence and zone of reactions.

References

(2010). FLUENT ANSYS 13. fluent user manual.
 Ahmed, T. Y., et al. (2012). Mathematical and computational approaches for design of biomass gasification for hydrogen production: A review. Renewable and sustainable energy reviews 16(4): 2304-2315.
 Babu, B. and P. N. Sheth (2006). Modeling and simulation of reduction zone of downdraft biomass gasifier: effect of char reactivity factor. Energy Conversion and Management 47(15): 2602-2611.
 Caputo, A. C., et al. (2005). Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. biomass and bioenergy 28(1): 35-51.
 Chan, W.-C. R., et al. (1985). Modelling and experimental verification of physical and chemical processes during pyrolysis of a large biomass particle. Fuel 64(11): 1505-1513.
 Chowdhury, R., et al. (1994). Modelling and simulation of a downdraft rice husk gasifier. International Journal of Energy Research 18(6): 581-594.
 Di Blasi, C. (2000). Dynamic behaviour of stratified downdraft gasifiers. Chemical engineering science 55(15): 2931-2944.
 Habibi, A., et al. (2007). Impact of radiation models in CFD simulations of steam cracking furnaces. Computers & chemical engineering 31(11): 1389-1406.
 Launder, B. E. and D. B. Spalding (1972). Lectures in mathematical models of turbulence.
 Magnussen, B. F. and B. H. Hjertager (1977). On mathematical modeling of turbulent combustion with special emphasis on soot formation and combustion. Symposium (international) on Combustion, Elsevier.
 Muilenburg, M., et al. (2011). Computational modeling of the combustion and gasification zones in a downdraft gasifier. ASME 2011 International Mechanical Engineering Congress and Exposition, American Society of Mechanical Engineers.
 Payormhorm, J., et al. (2013). Pt/Al 2 O 3-catalytic deoxygenation for upgrading of Leucaena leucocephala-pyrolysis oil. Bioresource technology 139: 128-135.
 San Miguel, G., et al. (2012). Characterization and potential applications of solid particles produced at a biomass gasification plant. biomass and bioenergy 47: 134-144.
 Zainal, Z., et al. (2001). Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass materials. Energy Conversion and Management 42(12): 1499-1515.