

Equilibrium modeling and CFD simulation of oxy-enriched air gasification of wet biomass

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June, 2017

CERTIFICATE

I hereby declare that the thesis entitled, "**Equilibrium modeling and CFD simulation of oxygen-enriched air gasification of wet biomass**" is an authentic record of my work carried out as per requirements for the award of degree of **Master of Engineering in Thermal Engineering** at **Thapar University, Patiala** under the supervision of **Dr. Sandeep Kumar**, Assistant Professor, Mechanical Engineering Department, Thapar University, Patiala during July 2015 to July 2017. No part of the matter embodied in this report has been submitted to any other university or institute for the award of any other degree.

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It is certified that the above statement made by the student is correct to the best of my knowledge and belief.



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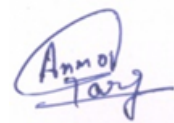
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Dedicated to
My family
My friends

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ABSTRACT

Biomass gasification, as a thermo-chemical process, is picking up the interest for converting waste biomass to energy and electricity generation using IC engine is of foremost interest. Downdraft fixed bed gasifiers are employed as better alternative for IC engine application due its low tar yield, but is restricted with the use of biomass with low moisture content only. Biomass available as agro/civic waste is generally high on moisture content. Also, the tendency of biomass to imbibe moisture during rainy days makes it energy and cost intensive for storage and pre-processing of wet biomass for use in downdraft gasification system. Endothermicity induced due to absorption of latent and sensible heat by H₂O present in wet biomass is attributed to the lower bed temperatures resulting in poor performance of downdraft gasification system. Lower bed temperature also leads to high tar yield in gasification of wet biomass. There is a need to supply high amount of oxidiser to compensate for the endothermicity through enhanced oxidation. But literature shows that the high reactant mass flux may lead to convective cooling of the reaction front where increased N₂, a inert in the gasification system, absorbs the sensible heat and reduces the local temperature of the reaction front which is undesirable. Another approach is devised in the present work to enhance the O₂ fraction in the reactant mixture (oxy-enriched air) keeping the reactant mass flux constant. This avoids the convective cooling of the reaction zone.

Present study is broadly divided into three parts.

Firstly, thermodynamic equilibrium studies are performed to evaluate the effects of oxy-enriched air gasification of wet biomass. Gasification is a heterogenous reaction system and seldom reaches equilibrium, but equilibrium studies helps in determining the amount of surplus O₂ fraction required for wet biomass gasification in order to maintain bed temperature similar to that in air gasification of dry biomass. NASA SP-273 code is used for the study of thermodynamic equilibrium under adiabatic and isothermal conditions.

Secondly, exergy analysis is performed to identify the exergy or 2nd law energy losses that arise while using wet biomass and enriched oxy-air gasification process. It helps in optimising the process towards energy efficiency.

Thirdly, CFD simulation is performed to enable analysis in more realistic conditions. The aim of this study is to stimulate the variation in temperature distribution along the bed height by changing the input air velocity. The literature supports that there is heat transfer from combustion zone to the bed above it through conduction and radiation, this heat enhances the pyrolysis process and better char conversion. The effects of air mass flux on the convective cooling and temperature distribution over the bed height is presented and analysed in detail.

Present study analyses the effects of moisture in biomass on gas composition and bed temperature distribution. Optimum fraction of O₂ enrichment is identified and effects on gas composition and system efficiencies are addressed.

TABLE OF CONTENTS

LIST OF FIGURES	viii
LIST OF TABLES	ix
NOMENCLATURE	x
ABBREVIATIONS	xi
CHAPTER 1 INTRODUCTION	1
1.1 INTRODUCTION.....	1
1.2 THEORY OF GASIFICATION	2
1.2.1 Different Zones in a Gasifier	2
1.2.2 Tar Formation and Conversion during Biomass Gasification	4
1.2.3 Applications of Gasifier.....	5
1.2.4 Different Types and Design of Gasifier	5
1.2.5 The Dependence of Tar Nature on Gasifier Type	7
1.3 COMPUTATIONAL FLUID DYNAMICS	8
1.3.1 ANSYS FLUENT Software	8
CHAPTER 2 LITERATURE SURVEY	10
2.1 OBJECTIVES	10
2.2 LITERATURE SURVEY	11
CHAPTER 3 EXPERIMENTS AND METHODOLOGY	15
3.1 BIOMASS FUEL AND CHARACTERIZATION	15
3.1.2 Elemental Mass Balance.....	16
3.2 EQUILIBRIUM ANALYSIS.....	16
3.3 ENERGY AND EXERGY EFFICIENCY.....	16
3.3.1 Energy Efficiency Evaluation Methodology	17
3.3.2 Exergy Efficiency Evaluation Methodology	17
3.4 EQUILIBRIUM ANALYSIS RESULTS	19
3.4.1 Adiabatic Analysis Results	19
3.4.2 Isothermal Analysis Results	20
3.5 SUMMARY	23
CHAPTER 4 CFD SIMULATION OF DOWNDRAFT GASIFIER	24
4.1 INTRODUCTION.....	24
4.2 BROAD VIEW OF PROBLEM STATEMENT	25

4.3	COMPUTATIONAL MODEL	25
4.3.1	Physical Characteristics of the Problem	25
4.4	COMPUTATIONAL SCHEME	26
4.4.1	Solution Methodology	26
4.5	CFD SIMULATIONS	27
4.5 (a)	CASE 1	28
4.5.1	System Description.....	28
4.5.2	Assumptions	29
4.5.3	Bed Porosity Conditions.....	29
4.5.4	Procedure for Steady State Problem.....	29
4.5.5	Experimental.....	30
4.5.6	Mesh Quality Details	32
4.5.7	Cell Zone Conditions.....	32
4.5.8	Boundary Conditions.....	33
4.5.9	Solution Controls.....	33
4.5 (b)	CASE 2.....	36
4.5.10	Geometry	36
4.5.11	Mesh Generation.....	38
4.5.12	Computational Model Parameters	39
4.5.13	Results and Discussion	40
4.5 (c)	CASE 3	43
4.6	SUMMARY	49
CHAPTER 5 CONCLUSIONS		50
REFERENCES		52

LIST OF FIGURES

Fig.1.1 Gasification Process	2
Fig.3.2 Variation in ER with moisture %	19
Fig.3.3 Variation of CV with Moisture %	20
Fig.3.4 Variation of Efficiency with Moisture %	20
Fig.3.5 Variation of CO yield at all Moisture % by varying temperature	21
Fig.3.6 Variation of H ₂ yield at all Moisture % by varying temperature.....	21
Fig.3.7 Variation of efficiency at all Moisture % by varying temperature.....	22
Fig.3.8 Variation of CV (PG/m ³) at all Moisture % by varying temperature.....	22
Fig.4.1 Modeling scheme of biomass gasification by CFD approach	25
Fig.4.1 Isometric view of Downdraft Gasifier.....	30
Fig.4.2 tetrahedral mesh generated on the downdraft gasifier bed	31
Fig.4.3 A histogram between the orthogonal quality and the number of elements	32
Fig.4.4 A histogram between element quality and the number of elements.....	32
Fig.4.5 Variation in temperature distribution along the bed height vs. input air velocity	34
Fig.4.6 Variation in pressure drop along the bed height vs. bed porosity	35
Fig.4.7 Isometric view of Downdraft Gasifier.....	37
Fig. 4.8 Front view of downdraft gasifier	38
Fig.4.9 Variation in temperature along the bed height with the increase in O ₂ fraction in input reactant.....	40
Fig.4.10 Variation in CO mole fraction along the bed height with the increase in O ₂ fraction in input reactant.....	41
Fig.4.11 Variation in H ₂ mole fraction along the bed height with the increase in O ₂ fraction in input reactant.....	42
Fig.4.12 Variation in H ₂ O mole fraction along the bed height with the increase in moisture content in biomass.....	43
Fig.4.13 Variation in H ₂ O mole fraction along the bed height with the increase in moisture content in biomass.....	44

Fig.4.14 Variation in H ₂ mole fraction along the bed height with the increase in moisture content in biomass.....	45
Fig.4.15 Variation in H ₂ mole fraction along the bed height with the increase in moisture content in biomass.....	46
Fig.4.16 Variation in CO mole fraction along the bed height with the increase in moisture content in biomass.....	47
Fig.4.17 Variation in CO mole fraction along the bed height with the increase in moisture content in biomass.....	48

LIST OF TABLES

Table1.1 Relative advantages and disadvantages of different types of gasifier	6
Table3.1 Properties of biomass fuel used for experiments	15
Table4.1 Correlations for the prediction of pressure drop.....	29
Table4.2 Geometry design parameter details.....	30
Table4.3 Meshing Details	31
Table4.4 Gasifier bed conditions	32
Table4.5 Viscous resistance and inertial resistance values.....	33
Table4.6 Correlations used to determine geometry of downdraft gasifier	36
Table4.7 Meshing details	38
Table4.8 Details of model settings, boundary conditions and solvers.....	39

NOMENCLATURE

E_{in}	Input exergy (kJ/kg)
E_{out}	Output exergy (kJ/kg)
I	Irreversibility (kJ/kg)
EX_{ch}	Chemical exergy (kJ/mol)
EX_{ph}	Physical exergy (kJ/mol)
h_i	Enthalpy of i^{th} specie (kJ/mol)
s_i	Entropy of i^{th} specie (kJ/kmol K)
$h_{i,0}$	Standard enthalpy of i^{th} specie (kJ/mol)
$S_{i,0}$	Standard entropy of i^{th} specie (kJ/Kmol K)
$\epsilon_{i,0}$	standard chemical exergy of i^{th} specie (kJ/mol)
T_0	reference temperature (K)
x_i	mole fraction of i^{th} specie
f_{pore}	friction factor
Re_{pore}	pore Reynolds number
μ	Viscosity (kg/m-s)
V_{∞}	Free stream velocity (m/s)
D_p	Mean Particle Diameter (m)
E	Void Fraction
L	bed depth (m)
A	Permeability Coefficient
C	Inertia loss coefficient
D	Diameter of gasifier (m)
H	Height of gasifier (m)
T	Length of operating time (hours)
P	Density of feed Material (kg/m ³)
η	Efficiency

ABBREVIATIONS

ER	Equivalence Ratio
FVM	Finite Volume Method
HCV	Higher Calorific Value (MJ/kg)
LCV	Lower Calorific Value (MJ/kg)
CFD	Computational Fluid Dynamics
DNS	Direct Numerical Simulation
LES	Large Eddy Simulation
RANS	Reynolds Averaged Navier Stokes
FCR	Fuel Consumption Rate (kg/s)
SGR	Specific Gasification Rate (kg/hr.m ²)
ICE	Internal Combustion Engine
RPS	Rotational Particle Separator
FSI	Fluid Structure Interface

1.1 INTRODUCTION

Modern agriculture practices are quite energy consuming. The advent of green revolution and the high outputs from the agricultural industry has been achieved due to the extensive amount of energy inputs provided by fossil fuels. Increase in the price and the limited availability of these fuels have resulted in a shift towards the use of alternative sources of energy like solar, wind, geothermal, etc. Fossil fuels, however, have not proven to be a financially feasible solution for agriculture related applications (Rajvanshi, 1986).

Wood/biomass gasification has proven to be quite successful and was reliably used during the Second World War for transportation and use on agricultural farms (Dzombo, 2014).

Biomass gasification involves incomplete combustion of biomass resulting in production of combustible gases comprising of Carbon monoxide (CO), Hydrogen (H₂) and traces of Methane (CH₄). The resulting mixture is called producer gas. Producer gas can be used as fuel in both S.I. and C.I internal combustion engines. It can also be used as a replacement for furnace oil in direct heating applications. It also presents a financially feasible method to manufacture methanol, which is very attractive for its use in the chemical industry as well as a fuel for engines (Reed, 1982). Due to the fact that any biomass material can readily be used for gasification, this process is much more advantageous than the production of ethanol or biogas which can only be manufactured from select biomass materials.

Moreover, the real world problem remains that the solid wastes found on the farms are rarely ever in the form that they can be utilized efficiently/economically. For example, the hog fuel boiler utilizes wood wastes as its fuel but due to the high equipment cost, energy recovery is small. Hence, the conversion of these wastes into readily usable producer gas is the most advantageous strategy. Here lies the charm of gasification.

In the present scenario, economic conditions seem to provide the strongest argument in favour of gasification (Eggen, July). In those countries, where crude oil prices are high and supply is scarce, biomass gasification can prove to be a cost effective system as long as the required biomass stock is available at hand (like in agricultural systems).

1.2 THEORY OF GASIFICATION

Gasification is a thermo-chemical process by which carbonaceous (hydrocarbon) materials (coal, petroleum coke, biomass, etc.) can be converted to a synthesis gas (syngas) or producer gas by means of partial oxidation with air, oxygen, and/or steam. The device which performs this work is known as gasifier. Gasifier is a chemical reactor where various complex chemical and physical processes take place. A hydrocarbon feedstock (biomass) is fed into a high-pressure, high temperature chemical reactor (gasifier) containing steam and a limited amount of oxygen. As biomass flows through the reactor it gets dried, heated, pyrolysed, partially oxidized and reduced. Under these “reducing” conditions, the chemical bonds in the feedstock are severed by the extreme heat and pressure and producer gas is formed. The main constituents of producer gas are hydrogen (H₂) and carbon monoxide (CO). In short, the task of gasifier is to pyrolyze the biomass to produce volatile matter, gas and carbon and to convert the volatile matter into permanent gases, CO, H₂ and CH₄ as shown in fig.1.1.

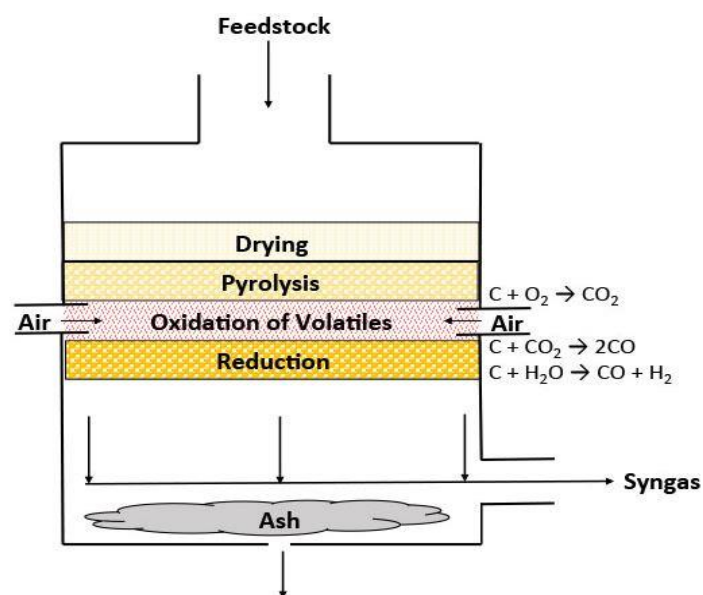


Fig.1.1 Gasification Process

1.2.1 Different Zones in a Gasifier

The various zones present in the gasifier are:

Drying zone

Pyrolysis zone

Combustion zone

Reduction zone

Drying zone: The chief process that occurs in this zone is drying of wood. Moisture content of the wood at the inlet to the gasifier is about 10-30%. Tests under varying conditions on different gasifiers have shown that the average amount of condensate formed is about 6-10 wt% of gasified wood. Some organic acids are also produced as a by-product of the drying process. These acids subsequently result in the corrosion of gasifiers.

Pyrolysis Zone: Due to the complex nature of the wood pyrolysis process, a complete understanding of it still doesn't exist. The resulting products depend upon temperature, pressure, residence time and heat losses.

When the temperature reaches upto 200°C, water is heaved out. When the temperature increases from 200°C to 290°C CO₂, acetic acid and water are heaved out. Large quantities of tar and CO₂ containing gases are produced when the temperature reaches between 290°C to 500°C. These are the real pyrolysis products.

Combustion Zone: Carbon, hydrogen and oxygen are the main combustible constituents of the solid fuel. Carbon dioxide and water are the main products of the complete combustion formed from carbon and hydrogen in fuel respectively. The combustion reaction is exothermic and yields a theoretical oxidation temperature of 1450°C. The main reactions, therefore, are:



Reduction Zone: Partial combustion leads to the formation of water, carbon dioxide and other pyrolysis products which are partially cracked. These products then pass through a red-hot charcoal bed where the following reduction reactions take place.

Water gas reaction:



Boudouard reaction:



Water shift reaction:



Methane reaction:



Reactions (3) and (4) are main reduction reactions. These reactions are endothermic in nature and have the capacity of reducing gas temperature. Therefore, the temperatures in the reduction zone are normally in the range of 800-1000°C. It has been observed that lower is the reduction zone temperature (~ 700-800°C), lower is the calorific value of the resulting producer gas (Goswami et al. 1986).

1.2.2 Tar Formation and Conversion during Biomass Gasification

“Tars are the organics, produced under thermal or partial-oxidation regimes (gasification) of any organic material. They are usually considered to be largely aromatic.”

One of the barriers to the use of producer gas in heat engines applications is the presence of tar (M., 2014). Tar is present in the vapour phase in the producer gas. It is bituminous oil that is tedious to remove via simple condensation or cleaning. The cause being that it tends to clog filters and valves and also causes the corrosion of metallic components (Anis S, 2011). On account of these problems, various methods for the reduction of tar have been developed to improve gasification system. The gasification technology, design, operating conditions and the use of bed additives or catalysts are all parts of the techniques developed for gasification improvement (Ahrenfeldt J, 2012; Mayerhofer M, 2014). Tar-cracker reactors and mechanical gas filtration setups are used to produce tar-free producer gas (Tuomi S, 2014) (Qin YH, 2010). Depending upon the suitable use of producer gas in prime movers, the tar content varies. High tar content producer gas can be used in the internal combustion engine than the gas turbine. For naturally aspirated internal combustion engines, the acceptable tar content is 100mgNm^{-3} , whereas for turbocharged engines and gas turbines it is 5mgNm^{-3} for (Milne TA, 1998). Even though high tar content is not a problem in solid oxide fuel cells, it is generally preferred that producer gas should have low tar content. Also, the effect of impurities in fuel gas on the functioning of the fuel cells is not well studied. (Hofmann P, 2009). Apart from the evaluation of tar content, the compounds that are crucial for the operation of the system must also be determined. As in the case of internal combustion engines, heavy tar usually accumulates in the engine manifolds and on the cylinder walls. Pollutants in the engine exhaust like polycyclic aromatic hydrocarbon (PAH) compounds may not get accumulated inside the engines but are harmful to the environment. Similar problem exists with wastewater from the gas conditioning units. Depending on the gasifier design, (Milne TA, 1998) laid down a thumb rule for the formation of tar. For updraft gasifiers, the tar limit is 100gNm^{-3} . Similarly for fluidised bed gasifiers the limit is 10gNm^{-3} and downdraft gasifiers with less than 1gNm^{-3} .

1.2.2.1 Chemical compound classes found in tar

The tar concentration is dependent on various factors such as temperature, pressure, moisture/size/ash content of the feedstock, gasifying medium, catalyst and additives, equivalence ratio (ER) and residence time.

Tar may be categorised into four major product groups: primary, secondary, alkyl tertiary, and condensed tertiary (Milne TA, 1998). These are briefly summarised below:

Primary tar is a product of primary pyrolysis. It is made up of oxygenated, primary organic, condensable molecules. Primary products form directly from the breakdown of the cellulose, hemicellulose, and lignin components of biomass. It contains a large number of compounds of acids, alcohols, ketones, aldehydes etc.

When the gasifier's temperature rises above 500°C, the primary tar formed in the gasifier begins to rearrange, leading to the formation of more non-condensable gases and heavier molecules called secondary tar. Secondary tar consists of phenols and olefins.

Condensed tertiary aromatics constitute poly-nuclear aromatic hydrocarbon (PAH) series without substituents. The secondary and tertiary tar products are derived from the primary tar. The primary products are consumed before the tertiary products are formed (Milne TA, 1998).

Temperature is regarded as a crucial variable for the production and maturation of tar. Overall tar yield falls when higher operating temperatures are used.

1.2.3 Applications of Gasifier

Gasifier can be used in the direct or indirect thermal applications. Direct thermal applications are process heat, chemicals, etc. and the indirect thermal application is motive power generation to produce electrical or mechanical energy etc. When the gasifier is used in direct thermal application for example process heat, there is no requirement of after treatment of producer gas, but when gasifier is used in motive power generation, after treatment of producer gas is very essential because producer gas contain CO₂, tar, oxide of sulphur, soot and dust particle which can be proof harmful for the engine and can reduce engine life by corroding engine components. Hence, better cooling and cleaning of producer gas is required before feeding the producer gas in motive power generation.

1.2.4 Different Types and Design of Gasifier

There are different types of gasifiers based on the movement of fuel and reactants. Gasification reactor can be run at atmospheric or increased pressure for thermo-chemical conversion of solid biomass.

Gasifier can be classified into the five main categories- fixed-bed updraft, fixed-bed downdraft, fixed-bed cross-draft, bubbling fluidized bed, and circulating fluidized bed

gasifiers. These gasifiers differ from each other only in the way the biomass is supported in the reactor vessel, the mode of fuel, flow of reactant and how heat is supplied to the reactor. Fixed bed gasifiers are mainly categorised as updraft, downdraft and cross draft. This classification is made on the direction of air and fuel flow. These are typically simpler in design, economical, and produce gas with lower calorific value, whereas fluidized bed gasifiers have a complex construction, produce large quantity of tar, are costly and yield a higher heating value gas. The removal of tar from the producer gas is a major hurdle in gas cleaning. Tar laden gas in internal combustion engines will subsequently block the valve and lead to a shutdown stoppage of the engine. The extent of damage is so critical that the entire engine assembly has to be opened and cleaned. In the future, gasifier designs that enable maximum conversion of tar to gas will be the front runners in the development of gasifier. For running an internal combustion engine, downdraft gasifier have been used and air moves downwards which under normal operating conditions have a small capacity to generate tar. Table 1.1 compares the advantages and limitations of the different type of gasifier design.

Table 1.1 Relative advantages and disadvantages of different types of gasifier

Gasifier type	Advantages	Disadvantages
Updraft fixed bed	<ul style="list-style-type: none"> • Used for small scale industries • Can be used for wet biomass • No content of carbon in ash 	<ul style="list-style-type: none"> • Cannot use large feed size • Tar production is high • Cannot use for large scales • Calorific value of gas is low
Downdraft fixed bed	<ul style="list-style-type: none"> • Used by small scale industries • Low tar production • This gas can be used in IC engines 	<ul style="list-style-type: none"> • Cannot use large feed size • Cannot use for large scales • Calorific value of gas is low • Cannot use wet biomass
Bubbling fluid bed	<ul style="list-style-type: none"> • Used by large scale industries • Higher calorific value gas is produced 	<ul style="list-style-type: none"> • Tar production is greater than downdraft gasifier • Particle loading is high

Circulating fluid bed	<ul style="list-style-type: none"> • Used by large scale industries • Higher calorific value gas is produced 	<ul style="list-style-type: none"> • Tar production is greater than downdraft gasifier • Particle loading is high
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The reactor design used until recently was the closed top, where the upper portion of the reactor acts as a storage bin for the fuel and air is allowed to enter at the lower part that generally contains charcoal. The developmental effort at the IISc on wood gasifier has resulted in a design (Mukunda, 1994) with an open top where air enters both at the top and at the air nozzles. This feature has resulted in a design that can handle wood chips of higher moisture content up to 25% and generates gas with lower tar levels (< 30ppm) (Mukunda, 1994). The low tar levels are due to the stratification of flame front into the fuel bed helping in maintaining large bed volume at high temperature. In steady operation, the heat from the combustion zone is transferred by radiation and convection upwards causing wood chips to pyrolysis and loses 70-80% of its weight. The pyrolysed gases burn with air to form CO₂ and H₂O raising the temperature to 1300-1400 K. The product gas from the combustion zone further undergoes the reduction reactions with char, to generate combustible products like CO, H₂ and CH₄.

1.2.5 The Dependence of Tar Nature on Gasifier Type

In updraft gasification, all forms of tar are present in the final gas. The dominant constituent is usually primary tar which is around 10-20%. Gases produced from updraft gasification can be burned at a high temperature. Although, the large amounts of tar present in it makes it tedious for application in IC engine applications. In downdraft gasifier the gas produce has low tar content which makes it appropriate for use in IC engines where clean gas is desirable. Fluidised bed gasification is similar to downdraft gasification in the way that some of the oxidants come in contact with biomass and burn the tar. But some of the oxidants come in the contact with charcoal as in an updraft gasifier. Hence the tar content lies in between that of updraft and downdraft gasification, usually 1-5%.

In the present work, downdraft gasifier is used for producer gas generation, because it produces less tar compared to updraft gasifier. Since the gasifier has to couple with diesel engine for performance and emission and combustion test hence producer gas from gasifier must content as less tar as possible because higher tar content fuel gives rise to corrosion effect which is a major cause of damage to engine components like piston, valve and fuel

pipe lines etc. Hence downdraft gasifier is the most appropriate for the above application. The influence of O₂ enriched air on the temperature profile and gas quality has been studied while gasifying wet woody biomass. In air gasification, it was found that nitrogen in air acted as a diluting agent for the calorific value of the gases produced during gasification and hence enriched air was used to sustain the latent heat of moisture present in wet biomass and for any increase in heating value of the produced gases.

1.3 Computational Fluid Dynamics

Laws for the conservation of mass, momentum, energy are used to govern the fluid flows in all applications. These conservation laws are mathematically represented by partial differential equations (PDE). Computational Fluid Dynamics (CFD) involves the use of computers to solve these PDEs. The approach involves replacing the system of PDEs with a set of algebraic equations. These algebraic equations are then solved by numerical methods. The basic procedure starts with dividing the domain into geometrically similar elements (cells). The conservation laws are then discretized and then represented for each cell. The solution is obtained in an iterative manner till the desired convergence criteria is achieved.

CFD simulation method is widely used to analyze the fluid flow behavior, heat and mass transfer processes and chemical reactions. Improvements in computational power and development of advanced numerical techniques have enabled the means of simulating complex physical and chemical phenomenon in the biomass driven reactors under different operating conditions. The results of such simulations can be used to optimize the design, operating conditions and the actual working inside such reactors. This CFD approach is quickly making its way in various sectors including the thermo chemical conversion of biomass, like in gasifiers.

1.3.1 ANSYS FLUENT Software

Structures of ANSYS FLUENT software are as follows:

MESH GENERATION: ANSYS FLUENT's native mesh generator is capable of a number of different meshing techniques. It allows the user to generate both structured and unstructured meshes on the domain. Various types of meshing elements like 2D (quads, triangles) and 3D (tetrahedron, hexahedron, prisms, etc.) can be generated. Mesh refinement features are also quite flexible.

MULTIPHASE FLOW: Flows involving two or more components (solid, liquid or gas) can be modeled using the various in-built multiphase models.

REACTION FLOW: Thermo chemical processes such as combustion, surface chemistry etc. can also be modeled in FLUENT.

TURBULENCE: A wide variety of turbulence models are built into FLUENT and can be used for the variety of applications.

DYNAMICS AND MOVING MESH: Mesh motion can also be defined by the user which allows different meshes to move relative to each other.

POST-PROCESSING AND DATA EXPORT: FLUENT offers additional packages like CFD-Post which enables the user to process their data visually and make contours, vector plots, etc.

2.1 OBJECTIVES

Industry which employs air gasification process for power production faces issue during the monsoon season with wet biomass. Literature doesn't show any work to address this issue apart from energy intense drying and storage process. The use of wet biomass for producer gas production is proposed in this report. Experiments will be conducted with air as the gasification medium and the excess O₂ will be supplied i.e. enriched air will be used. In order to found stable operating conditions various sets of experiments will be carried out. With varying moisture content %, O₂ % will be varied and optimum O₂ supply will be formulated for efficient working. From the literature collection, it was understood that nobody has carried out this work with wet biomass.

The present work focuses on understanding the science underlying the heterogeneous reaction based O₂ enriched air gasification of wet biomass through modelling studies.

In gasification process to assess the working, economics and sustainability of the technology for the use in IC engine various analysis has be done are:

Equilibrium modelling to predict the gasification process in a downdraft gasifier. To study the effect of process parameters like temperature, moisture % present in biomass, and equivalence ratio (ER) on the gas composition.

Present study also focuses on the energy and exergy analysis of the O₂ enriched air gasification. Then, it has to be compared with air gasification to optimize the H₂ yield, CO yield, efficiency (η) and producer gas energy density.

To study the effect of O₂ enriched air on the temperature profile and gas quality while gasifying wet woody biomass. Since the gasifier has to couple with diesel engine for performance and emission and combustion test hence producer gas from gasifier must content as less tar as possible. So the effect of increase in O₂ % on the formation of tar will be studied.

The various aspects of gasification processes have to be investigated for down-draft gasifier using simulation in FLUENT software. The present work also focuses on developing a fluid flow and heat transfer model for the reactive, porous bed of the biomass gasifier to stimulate the effect of various parameters on the bed temperature profile and pressure drop through the gasifier.

2.2 LITERATURE SURVEY

REVIEW OF PREVIOUS RESEARCH WORK:

A number of studies have been carried out on the field of biomass gasification. A brief overview of some of the works is presented below.

[**Bo Zhang et al. 2015**] utilized biomass with a novel sorbent in steam gasification and examined the hydrogen production. The biomass sample used was *Ficus lacor* leaves (moisture fraction of 35 wt.%, fixed carbon fraction 10.2wt.%, ash fraction 2.7wt.% and volatile fraction 52.3wt.%). The sorbent was prepared by heating the mixture of pre calcined dolomite, limestone and water at 850°C for 3 h. They investigated the feasibility of hydrogen production from steam gasification using wet biomass and sorbent in a fixed bed system. They observed that higher temperature complimented hydrogen yield and carbon dioxide generation. At temperature of 850°C, hydrogen yield of 204.6 ml/g-biomass was reported to be maximum For the different temperature studied. At higher temperature, the heating value of gas decreases, so at 650°C CO₂ concentration was found lower with hydrogen yield of 118.8 ml/g-biomass. The effect of steam/biomass (wt. 0 to 2.5) on the hydrogen yield was also studied. Highest hydrogen yield of 140.3 ml/g-biomass was found at steam/biomass ratio of 2.5.

[**Siva Sankar Thanapal et al. 2012**] studied the yield of producer gas from diary biomass by fixed bed gasification under varying air blend enrichments, equivalence ratio and steam/biomass ratio. It was reported that with reduction in carbon monoxide and increment in oxygen content in the input gasification medium, the peak temperature and carbon dioxide yield increased. It was observed that by decreasing oxygen concentration input, HHV of the gases also reduces. It was also noticed that the gases produced had a higher HHV when the carbon dioxide and oxygen mixture was utilized rather when air or enriched air gasification was used.

[**Hu Guoxin et al. 2009**] investigated the gasification of wet biomass along with CO₂ absorption for the production of hydrogen rich fuel gas. Pine tree sawdust (particle size: <0.15 mm, moisture content of 7.9 wt.%, fixed carbon content 10.8wt.%, ash content 1.1wt.% and volatile content 80.2wt.%) was used as a biomass sample. The experiment was conducted under controlled environment temperature. They varied the moisture (M) from 0.09 to 1.31 and their results showed that M has an effect on the H₂ yield and gas composition. They found that with the increase of M from 0.09 to 0.90, it can be found that the H₂ yield was increased by 51.5%. By the test data of varying M, it was found that the

direct use of wet biomass will produce two different outcomes. Firstly, a fall in temperature and yield of gas and H₂ was observed due to the drying step consuming more heat. It was reported that the H₂ yield increases significantly in the presence of the sorbent. The effect of the reactor temperature on the H₂ yield and the amount of absorbed CO₂ was also examined. The H₂ yield increased at a constant rate, while the amount of absorbed CO₂ decreased slowly. The variation of H₂ yield was linked to the higher extent of volatiles cracking that occurs at higher temperatures.

[**Sandeep Kumar et al. 2009**] conducted experiments in a modified and smaller model of open-top downdraft gasifier. They conducted the experiments with wet biomass and O₂ amounting to an ER of 0.3. They injected the extra moisture in biomass under controlled condition. On molar basis, the variation of moisture to biomass ratio (0.5 to 0.75) was studied. Fractions of methane and tar increases by increasing moisture content. This was attributed to the fact that average bed temperature was reduced. Small fraction (10-15% of total O₂ supply) of O₂ was passed from the bottom nozzle that lead to partial combustion of char providing higher bed temperature. It helped them in reducing the methane and tar level and subsequent increased in H₂ content. They accomplished the H₂ yield of 70 g/kg of biomass with moisture to biomass ratio of 1.4 and ER value of 0.37 with average bed temperature of 875 K. They entered O₂ from the bottom nozzle which helped them in maintaining higher bed temperature providing higher residence time at higher temperature with lower CH₄ and tar level and yielding more H₂.

[**Wang and Yanet et al. 2008**] reviewed the various studies on the CFD modeling of thermo chemical biomass conversion. These studies included gasification and combustion processes in different devices like fixed beds, furnaces, fluidized beds and wood stoves. Euler-Lagrange approaches were used in most of the commercial CFD commercial codes. He concluded that CFD modeling can be effectively used to evaluate biomass thermo chemical processes as well as to design thermo chemical reactors. The results predicted by the CFD model were found to be accurate and were in accordance with the experimental data in many cases.

[**Gerun et al. 2008**] constructed a CFD model for the oxidation zone of two-stage downdraft gasifier. They simulated temperature pattern and tar content and were found in agreement with experimental data. The simulations had shown the temperature profile in the reactor and predicted that the heat of reaction was released mainly close to the injector. The stream function and also the gas path lines were shown in the reactor. They found that gas path mainly depended on the primary departure point.

[**Yiqun and Lifeng et al. 2008**] did a 3D CFD simulation of a fluidized bed gasifier that utilized sewage sludge as input for the production of producer gas. The model also takes into account the intricate physical and chemical phenomenon in the gasifier by incorporating turbulent flow, heat and mass transfer, and chemical reactions. Standard $k - \epsilon$ turbulence model was used for the gas phase. While, the Eulerian approach was used for the gas phase and for sludge particles, the Lagrangian approach (discrete phase model) was used. For the simulation of chemical reactions, the non-premixed combustion model was used. The simulation predicted the variation in temperature distribution and gas composition inside and at the outlet of the gasifier. Significant amount of effect was noticed on the producer gas by varying equivalence ratio and temperature.

[**A.G. Bhawe et al. 2008**] developed a system to clean the producer gas i.e. to reduce tar as it is essential for the efficient functioning of the engine. For this purpose, they manufactured a system that produced a clean gas with tar amount under the limit of 150 mg/nm^3 provided the inlet gas had a tar content of under 600 mg/nm^3 . The system was coupled with a dual fuel engine to work out any problems during the running phase. The maintenance requirements were analysed and an effort was made to raise the duration of continuous use of the sand filter without any user attention. The system was specifically designed keeping in mind small scale gasifier–engine systems. It can also be applied on a bigger scale by increasing the cross-sectional areas of the different beds and increasing the water flow rate in ratio to the increase in the producer gas flow rate.

[**Luc Gerun et al. 2007**] conducted a 2D CFD simulation depicting the oxidation zone of a two-stage downdraft gasifier. An axisymmetric geometry of the gasifier was used for the simulation. The simulation helped to analyse the critical points in the gasification process. It was found that the composition of gas during the pyrolysis stage greatly affected the process. Also, the air injector design was found to be critical for gasification as the air velocity and the air/fuel ratio significantly affected the process. Critical injection velocity of approx. 34 m/s was found to change the pattern of flow drastically.

[**Pengmei Lv et al. 2007**] proposed that for low energy input based hydrogen gas production, biomass oxygen/steam gasification in a downdraft gasifier was a suitable system. The biomass oxygen/steam gasification was found to give higher yield of hydrogen and also approximately twice the heating value of fuel gas as compared to biomass air gasification. The LHV of fuel gas and hydrogen yield was found to be the highest - 11.11 MJ/N m^3 and $45.16 \text{ g H}_2/\text{kg biomass}$ respectively for biomass oxygen/steam gasification.

[Avdhesh Kr. Sharma 2007] proposed a model for the reactive, porous bed type of gasifier. The model incorporated fluid flow and heat transfer within the gasifier to predict pressure drop, flow rates and temperature variations across the bed. It was found that gas flow rate and heat generation in oxidation zone significantly affected the temperature variation across the bed. Also, high temperature in the bed, gas flow rate and smaller feedstock particle size led to appreciable increase in pressure drop across the gasifier. Temperature profiles in the downstream zones were affected intensely than the upstream zones due to the heat generation in the bed. Based on the analysis, it was suggested that the preheating zone should go as far as the pyrolysis zone to help improve the preheating of the input air.

[Hasler et al. 1999] reported in his work that the producer gas used for IC engine applications should be free from tar and particles. The study was conducted for fixed bed biomass gasifiers with capacities from 100 kW up to 5000 kW. He evaluated the tar and particle removal efficiencies of a variety of devices and techniques like tar adsorption on coke. It was reported in the findings that such gas cleaning techniques could not yield the producer gas that would be suitable for use in IC engines. It was also found that the gas cleaning systems can only be used for those units in which catalytic crackers were used or where the gases had high tar content.

CHAPTER 3 EXPERIMENTS AND METHODOLOGY

This chapter focuses on the methodology adopted towards conducting experiments and analysis using an open top downdraft reactor for enriched air gasification towards generating syngas production. This chapter also discusses the thermodynamic equilibrium analysis on a preliminary basis to determine the effect of various process parameters like temperature, moisture percentage, ER on the H₂ yield, CO yield and cold gas efficiency.

3.1 BIOMASS FUEL AND CHARACTERIZATION

Eucalyptus Sawdust was used as a fuel for gasification. Saw dust was dried in an electric oven at 378K (105°C) to bring down the moisture to less than 1%. The results of the proximate analysis and ultimate analysis of dried eucalyptus sawdust sample are presented in Table 3.1.

Table3.1 Properties of biomass fuel used for experiments

Sample Biomass	Particle density (kg/m³)
Eucalyptus sawdust	600 ± 10

Proximate Analysis	Mass fraction (% , dry basis)
Fixed carbon	19.6% ± 0.2
Volatile matter	79% ± 1.5
Ash content	0.4% ± 0.05

Calorific value	MJ/kg (Air Dried Basis)
HCV	19.274
LCV	18.091

Ultimate Analysis	Mass fraction (% , dry basis)
Carbon	46.25
Hydrogen	5.82
Nitrogen	4.54
Oxygen	43.39
Chemical Composition	CH1.5O0.7
Molecular weight	24.7kg/kmol

3.1.2 Elemental Mass Balance

To arrive at the overall mass balance, elemental mass balance method was implemented. Wet biomass along with air/enriched air were the inputs and their respective flow rates were calculated during the experiments. Gas composition was determined on a dry basis.

3.2 EQUILIBRIUM ANALYSIS

Thermodynamics analysis was done using NASA-SP 273 code (Gordon and McBride, 1976) for chemical equilibrium analysis. The purpose of this analysis was to determine the theoretical limits for enriched air gasification of wet biomass before conducting the experimental trials. Analysis has been done to study the influence of process parameters like temperature, moisture % present in biomass, and equivalence ratio (ER).

Adiabatic analysis is performed to find out the suitable ER or extra oxygen required in order to reach same adiabatic temperature in the system with increasing moisture content as acquired in air gasification of dry biomass.

Isothermal analysis is performed to simulate the conditions of reduction zone at different temperatures and to identify the product gas composition and the variation in the cold gas efficiency in downdraft gasifier. Thermodynamic equilibrium analysis also provides input towards arriving at experimental operating conditions.

3.3 ENERGY AND EXERGY EFFICIENCY

The first law of thermodynamics conserves the total energy in the gasification process i.e. during the transformation of solid fuel. While, the second law of thermodynamics puts limits on the amount of energy available (exergy) that can be converted to useful form. Production of gaseous species during the gasification process leads to the generation of entropy and causes irreversibility in the overall thermo-chemical conversion process. The conversion of chemical energy of the solid fuel to thermal energy in the form of sensible heat does not convert to chemical enthalpy in the gaseous species. Energy efficiency is calculated based on the ratio of energy output to the energy input and the energy losses from the system to the surroundings are found out. This method may not be enough while calculating the combined process and device as one unit. Recognizing the energy losses due to the irreversibility is crucial in analysing any energy transformation process and is quite useful in optimizing the system elements.

The following section provides an in-depth analysis of energy and exergy exchanges and transformation during the gasification process.

3.3.1 Energy Efficiency Evaluation Methodology

Energy efficiency is defined as the fraction of output to the input energy. An attempt has been made here to arrive at near realistic estimation of input and output energy components. Output energy is recognized as the heating value of producer gas and the energy present in remaining carbon (char) which can be further used. The input energy is determined as the total of energy content of biomass, energy inputs of secondary units of gasifier like water pumps, scrubber, etc., enthalpy required to generate steam and energy required in separation of oxygen from the air. (Sandeep & Dasappa, 2009) Sandeep & Dasappa, 2009 used oxygen cylinder for their gasification experimentations but the total energy used in the oxygen separation from air is based on the oxygen utilized is used in the present analysis. To calculate the energy efficiency following equation has been used:

$$\text{Energy efficiency } (\eta_{en}) = \frac{LHV_{SYNGAS} + LHV_{CHAR}}{LHV_{BIOMASS} + E_{O_2\text{SEPARATION}} + E_{AUXILLARY_UNIT} + Q_{STEAM}}$$

Energy requirement for O₂ separation and auxiliary units of the gasifier is evaluated on the basis of energy spent per unit mass of the biomass (fuel) gasified.

3.3.2 Exergy Efficiency Evaluation Methodology

Exergy balance of the biomass gasification can be expressed as:

$$\Sigma E_{in} = \Sigma E_{out} + I \quad (3.1)$$

where, E_{in} and E_{out} represent the input exergy and output exergy, and *I* represent the irreversibility brought during the conversion process.

Biomass, oxygen, steam or air is considered as input terms for exergy analysis. Hot syngas composition (compared with elemental mass balance) and residual carbon (char) are used to evaluate the output exergy.

By adding chemical and physical exergy gives the total exergy or available energy of the gaseous species (equation 3.2). Physical exergy outlines the energy involved in raising the enthalpy of specific gaseous species from standard state to the set pressure and temperature and also cause loss in entropy in the process (equation 3.3). Chemical exergy of the mixture is the exergy due to mixing of all the constituents (1st term in equation 3.4) and the reduction in entropy due to mixing of different species of gases (2nd term in equation 3.4).

$$Ex = Ex_{ch} + Ex_{ph} \quad (3.2)$$

$$Ex_{ph} = \Sigma((h - h_0) - T_0(s - s_0)) \quad (3.3)$$

$$Ex_{ch} = \Sigma (x_i \cdot \varepsilon_{i,0} + RT_0(x_i \cdot \ln x_i)) \quad (3.4)$$

where, Ex_{ch} = chemical exergy, kJ/mol

Ex_{ph} = physical exergy, kJ/mol

h_i = enthalpy of i^{th} specie, kJ/mol

x_i = mole fraction of i^{th} specie

s_i = entropy of i^{th} specie, kJ/(kmol K)

$h_{i,0}$ = standard enthalpy of i^{th} specie at 1 bar 298 K, kJ/mol

$S_{i,0}$ = standard entropy of i^{th} specie at 1 bar 298 K, kJ/(Kmol K)

$\varepsilon_{i,0}$ = standard chemical exergy of i^{th} specie at 1 bar 298 K, kJ/mol

T_0 = reference temperature, 298 K

Summation of chemical exergy of the mixture is always lower than of the sum of standard chemical exergy of the specific species as by the blending of gases, higher irreversibility is produced (2^{nd} term in the equation (3.4)).

The following equation has been used to evaluate exergy efficiency for further calculation, using equation (3.2-3.4)

$$\begin{aligned} \text{Exergy efficiency} &= \frac{Ex_{SYNGAS} + Ex_{CHAR}}{Ex_{BIOMASS} + Ex_{O2SEPARATION} + Ex_{STEAM}} \\ &= \frac{(Ex_{ph} + Ex_{ch})_{SYNGAS} + Ex_{CHAR}}{Ex_{BIOMASS} + Ex_{O2SEPARATION} + (Ex_{ph} + Ex_{ch})_{STEAM}} \\ &= \\ &= \frac{\Sigma(x_i \cdot Ex_0 + RT_0(x_i \cdot \ln x_i)) + \Sigma(x_i(h-h_0) - x_i T_0(s-s_0)) + Ex_{char}}{Ex_{BIOMASS} + Ex_{O2SEPARATION} + \Sigma_{O2, H2O}(x_i \cdot Ex_0 + RT_0(x_i \cdot \ln x_i)) + \Sigma(x_i(h-h_0) - x_i T_0(s-s_0))} \quad (3.5) \end{aligned}$$

Each term in the numerator and denominator in the equation (3.5) will be analysed separately from the experimental results to study the influence of the change in moisture content on efficiency and to relate efficiencies of air and enriched air gasification process.

3.4 EQUILIBRIUM ANALYSIS RESULTS

3.4.1 Adiabatic Analysis Results

Moisture % in biomass vs. Equivalence ratio (ER)

To find out the suitable ER or extra oxygen required in order to reach same adiabatic temperature in the system with increasing moisture content as acquired in air gasification of dry biomass. Fig. 3.2 shows the variation in ER with the increase in moisture content in biomass at 2074 K.

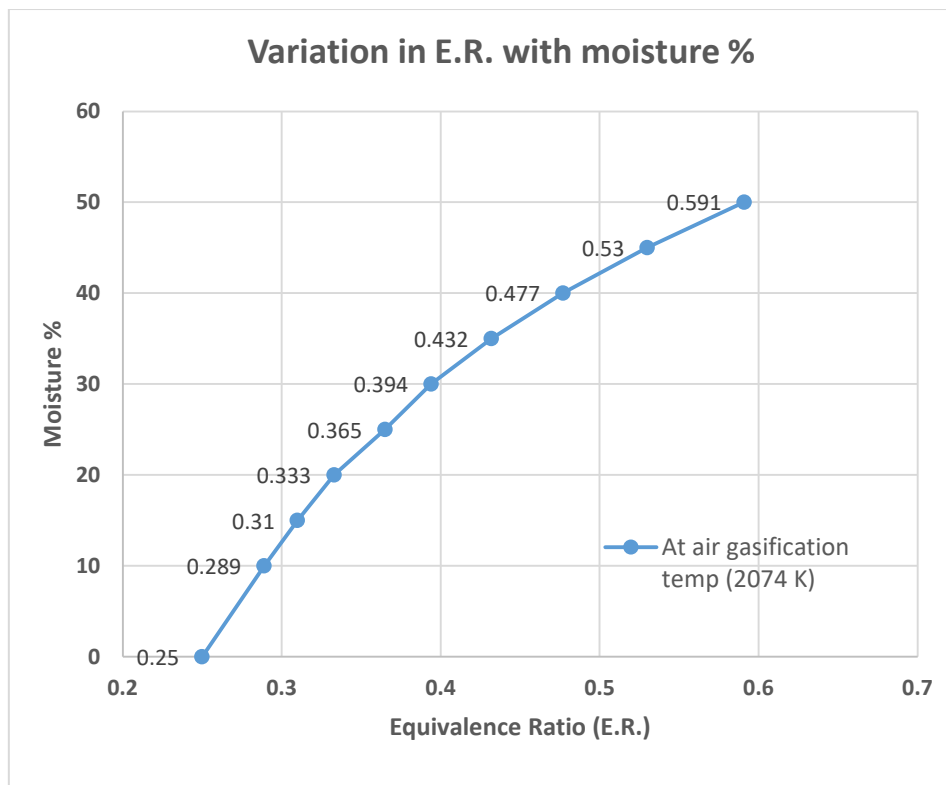


Fig.3.2 Variation in ER with moisture %

Effect of ER on efficiency and Calorific Value

The variation in efficiency and calorific value with the ER is shown in fig.3.3 and fig.3.4. As with the increase in O₂% in input, we are increasing the ER and moving from gasification towards combustion. To sustain the latent heat of H₂O present in wet biomass, extra heat is required. This extra heat is compensated by combustion of H₂/CO, thus leading to a reduction in cold gas efficiency and calorific value.

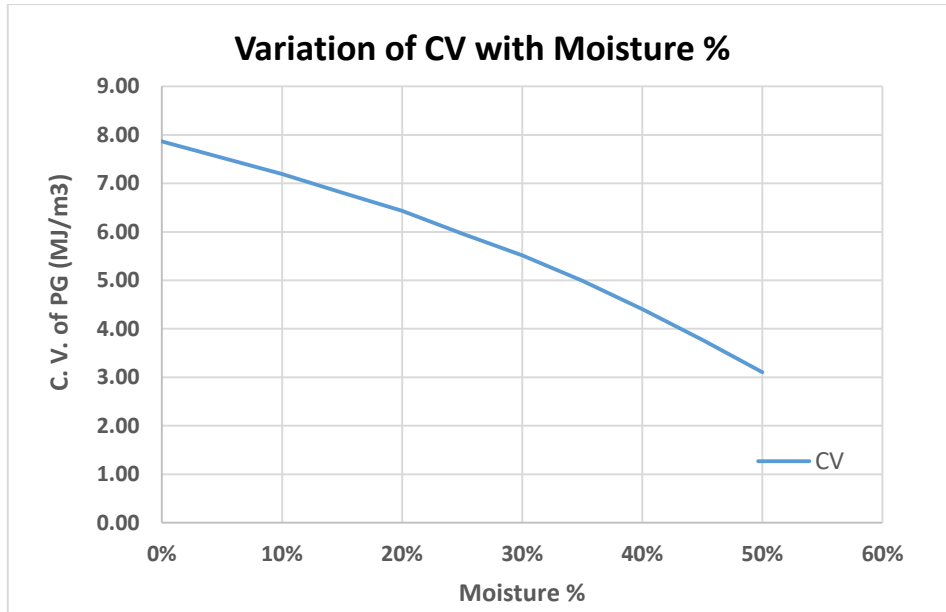


Fig.3.3 Variation of CV with Moisture %

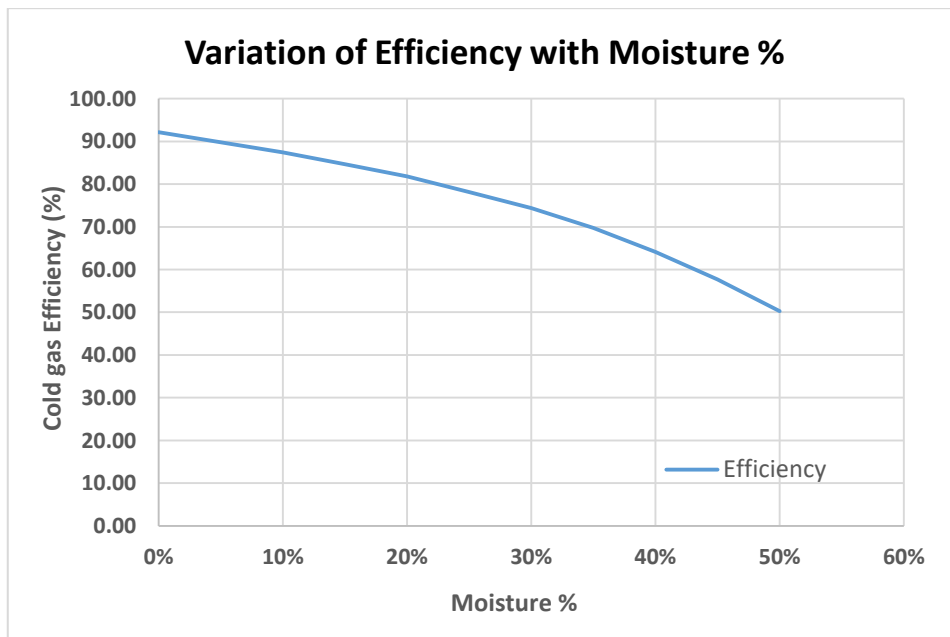


Fig.3.4 Variation of Efficiency with Moisture %

3.4.2 Isothermal Analysis Results

Effect of Moisture content on CO yield by varying temperature

The effect of moisture content on CO yield by varying temperature is shown in fig.3.5. It is noticed that with the increase in temperature, CO (yield) increases and with the increase in the moisture content, CO yield decreases which matches with experimental results by

(Sandeep & Dasappa, 2009). As we increase the temperature, the endothermic reactions (i.e. water gas and boudouard reaction) are favoured to yield more fuel gas.

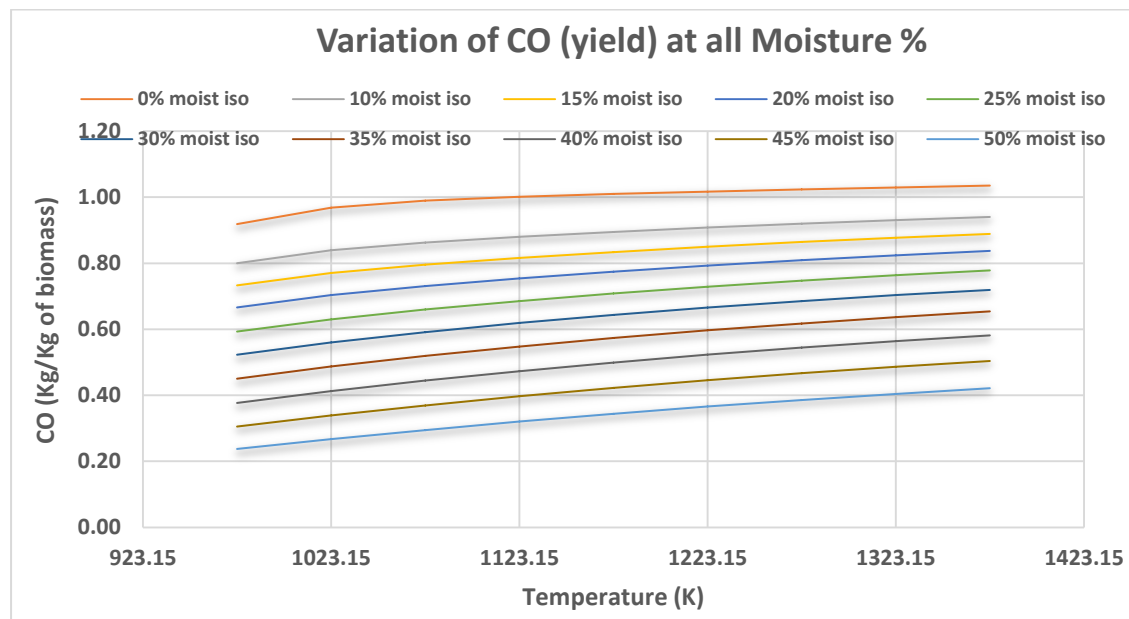


Fig 3.5 Variation of CO yield at all Moisture % by varying temperature

Effect of Moisture content on H₂ yield by varying temperature

The effect of moisture content on H₂ yield by varying temperature is shown in fig.3.6. It is noticed that with the rise in temperature, H₂ (yield) reduces which does not verified with the experimental results of (Sandeep & Dasappa, 2009). This is because beyond 850 K, all biomass is converted to gas in chemical equilibrium model. But this is not the case with real experimental system as we get 5-10 % char residue as reported by (Sandeep & Dasappa, 2009). This char residue favoured water shift and water gas reaction, hence more H₂ yield than theoretical model.

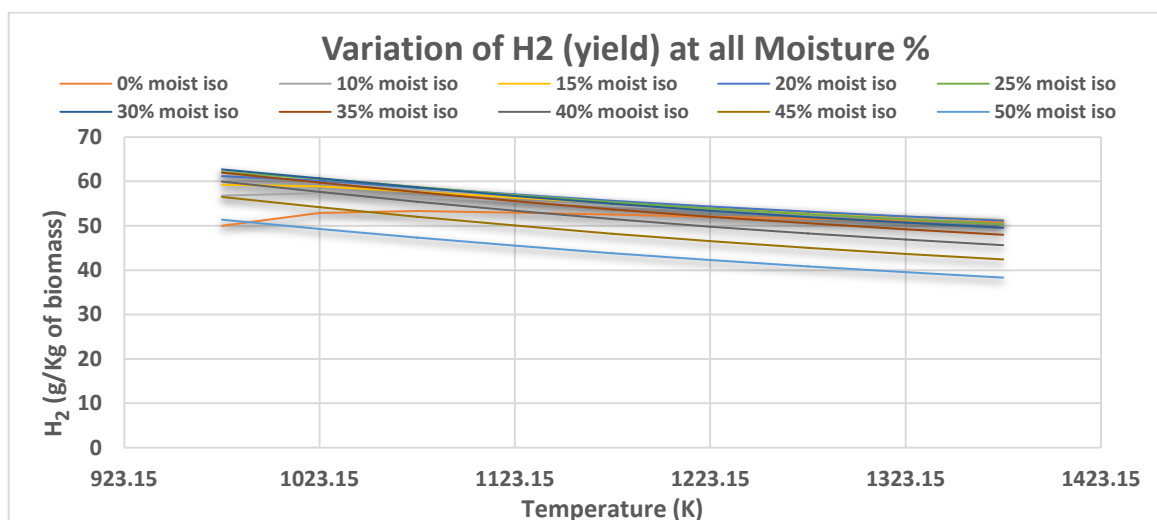


Fig 3.6 Variation of H₂ yield at all Moisture % by varying temperature

Effect of Moisture content on Efficiency and Calorific Value of Producer gas by varying temperature

The effect of moisture content on efficiency and calorific value by varying temperature is shown in fig.3.7 and fig.3.8. It is observed that with the increase in temperature, there is slightly increase in efficiency and calorific value and with the increase in moisture %, to sustain the latent heat of H₂O present in wet biomass, extra heat is required. This extra heat is compensated by combustion of H₂/CO, thus leading to reduction in cold gas efficiency and calorific value.

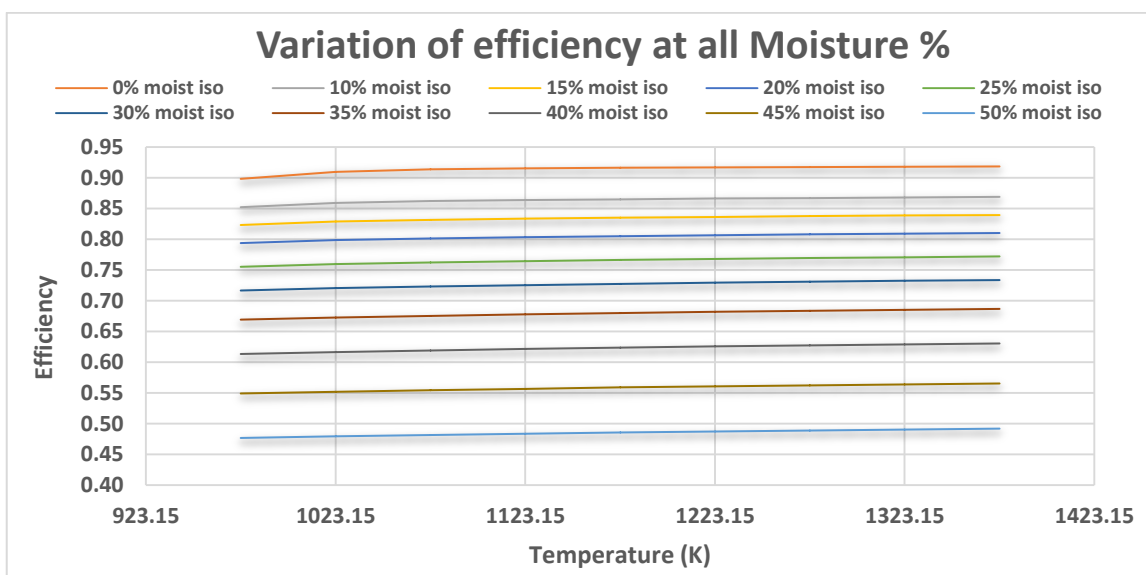


Fig 3.7 Variation of efficiency at all Moisture % by varying temperature

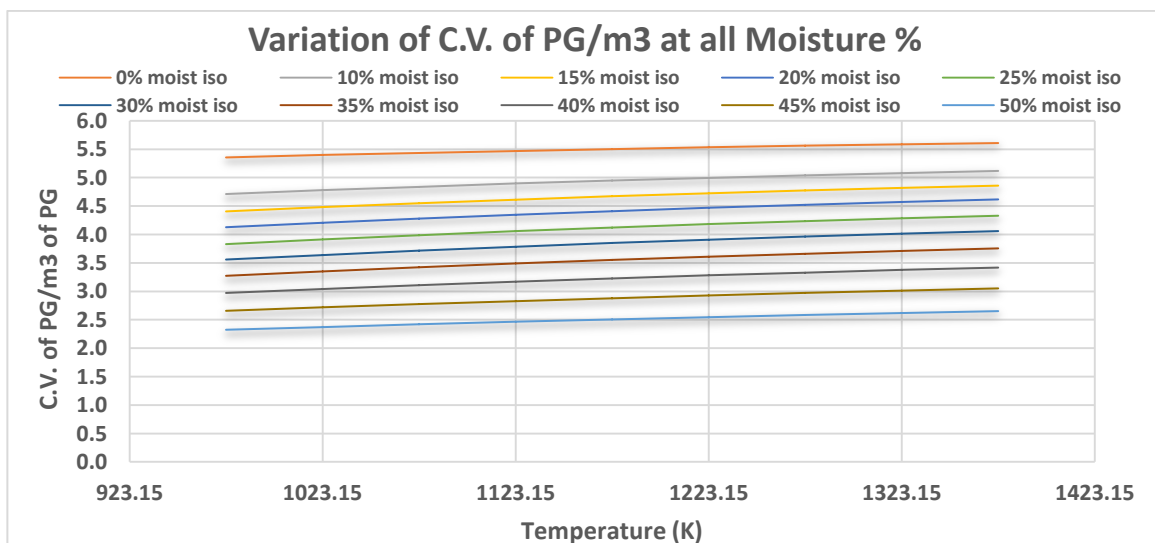


Fig 3.8 Variation of CV (PG/m³) at all Moisture % by varying temperature

3.5 SUMMARY

Thermodynamic equilibrium analysis has been performed. Adiabatic analysis gives us the input for the O₂ fraction to be maintained with varying moisture level in biomass. Isothermal analysis provides us the insight on the influence of bed temperature on gas composition and efficiency. Increase in O₂ fraction leading to higher ER is found to be accountable for the decrease in energy efficiency as the process shifts from gasification towards combustion.

Methodology for the energy and exergy analysis has been discussed. The exergy analysis helps in identifying the factors which influence the efficiency most towards better design and optimisation of process parameters.

CHAPTER 4 CFD SIMULATION OF DOWNDRAFT GASIFIER

4.1 INTRODUCTION

CFD is prevailing software for the forecasting of the fluid dynamics and heat transfer in many types of systems which gives us a prudish design of numerous systems. The accessibility of reasonable high performance computing hardware and the outlining of user-friendly interfaces are the main developers of CFD packages suitable for both research and commercial purposes. In the field of fluidization, in particular, the use of CFD has pushed the frontier of basic understanding of FSI and has assisted the accurate theoretical estimation of many classical phenomena come across in fixed beds. Most of packages like CFX, FLUENT are based on the FVM that are employed to solve fluid flow and heat and mass transfer problems.

FVM is a prominent technique used for the solution of governing equations of heat and mass transfer and fluid flow problems. The main features of the FVM are that the resultant solution satisfying the conservation of mass, momentum, energy and species transfer. In the FVM, the solution domain is sectioned into cells or control volumes where the variable of interest is positioned at the centroid of the control volume making a grid. The next step is to integrate the differential form of the governing equations over each control volume. Assumptions of interpolation profiles are taken to describe the deviation of the concerned variables between cell centroids. Central differencing, upwind differencing, power law differencing and quadratic upwind differencing schemes are few methods for discretization of governing equations. The resulting equations are called discretized equations. In this way, the discretized equation manifests the conservation principle for the variable inside the control volume. This variable forms a set of algebraic equations which are solved all together using algorithm.

CFD plays an vital role in modeling of both fluidized-bed gasifier and fixed downdraft gasifier. A CFD model connects a solution of conservation of mass, momentum of species, energy flow, hydrodynamics and turbulence over a definite section. Solutions of such complex approach can be attained with commercial software such as ANSYS, ASPEN, Fluent (Basu, 2010). CFD appears to be cost-effective options to discover the various configurations and operating conditions at any scale to detect the optimum configuration

depending on the project requirement (P. Pepiot, 2010). Many sub-models are unified within the CFD model as shown in fig. 4.1.

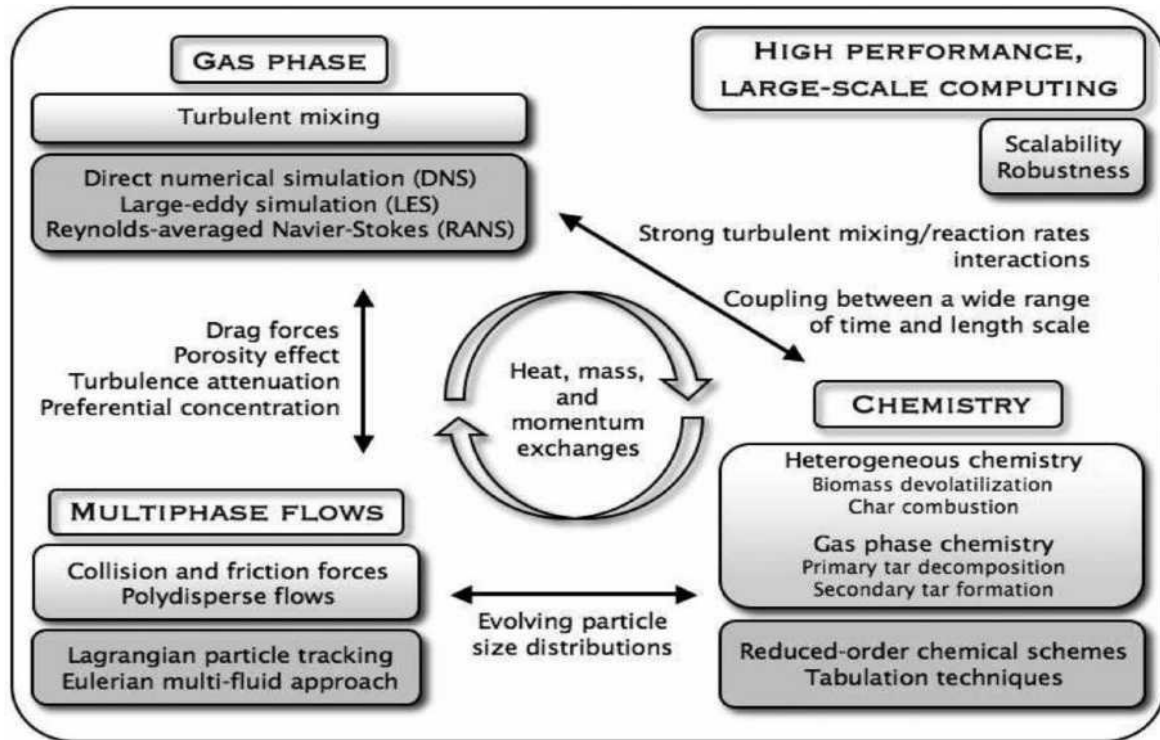


Fig.4.1 Modeling scheme of biomass gasification by CFD approach (P. Pepiot, 2010)

4.2 BROAD VIEW OF PROBLEM STATEMENT

Computational Fluid Dynamics simulation is an efficient tool to analyse biomass gasification in fixed bed gasifier. This study will investigate the bed porosity, injected particle flow, thermal-flow and effect of moisture content in biomass in a downdraft gasifier. Biomass gasification is a multiphase problem between biomass particles and gases. Gasification includes homogeneous reactions among gases and heterogeneous reactions between biomass particles and gases. The problem has been solved using Euler-Lagrangian method. Homogeneous (gas-gas) reaction and heterogeneous (gas-solid) reactions are simulated simultaneously in this study.

4.3 COMPUTATIONAL MODEL

4.3.1 Physical Characteristics of the Problem

The physical features of the problem are modeled as follows:

- The flow inside the domain is three dimensional, incompressible, and turbulent.
- Gravitational force is considered.

- Gas species involved in this study are Newtonian fluids with variable properties as function of temperature. Piecewise polynomial method is used to evaluate the variable properties.
- Mass-weighted mixing-law for specific heat and incompressible-ideal gas for density is used for gas species mixture.
- The walls are impermeable and convective.
- The flow is steady.
- No-slip condition (zero velocity) is imposed on wall surfaces.

4.4 COMPUTATIONAL SCHEME

4.4.1 Solution Methodology

There are three major steps for solving a CFD problem. These are

- Pre-processing
- Solver
- Post-processing

➤ **Pre-processing**

Pre-processing is the initial step for solving any CFD problem. Designing and building domains are the chief functions of pre-processing. The functional steps are listed below:

- To construct the geometry of the computational region.
- In grid generation, the computational domain is subdivided into small size sub domains. These sub domains may of any type like control volumes or elements but these must be non-overlapping.
- Fluid properties of the domain are defined.
- Suitable boundary conditions are specified at the cells which coincide with or touch the boundary.

For a flow problem, the solution is described at each node in every cell. The number of cells in computational domain regulates the precision of the CFD solution. By increasing the number of cells, the accuracy of the CFD solution also increases. SOLIDWORKS software is used to make the geometry of downdraft gasifier. Tetrahedron meshes are used in the simplified 3-D domain. After meshing the computational domain, suitable models and boundary conditions are set by using commercial CFD code in ANSYS FLUENT 15.0.

➤ **Solver**

In the proceeding step, flow calculations are carried out on the meshed geometry. To get the results of the governing equations many calculations has to be performed. Many CFD solvers are used for the flow calculations like FLUENT, CFX, POLYFLOW, etc. To get the desired result, quite a lot of iterations are performed till the solution is converged. Before the start of initialization, under relaxation factors have to be set as this helps in the solution convergence. If under relaxation factors are not set correctly, the solution might diverge. Initialization of the solution is important before the start of iterations as it supports the solver to guess some initial values which are essential in solving governing equations.

➤ **Post processing**

Iterations are performed until the desired convergence is achieved. Then the post processing of the results is performed. It includes the organization and interpretation of the expected flow data. Animations and contours can also be made under post processing. There are many charts and schemes to visualise and understand the physics of the solution. For the present study, contours are plotted to understand the effect of moisture on gasification process (e.g. temperature contours, CO and H₂ fraction contours).

4.5 CFD SIMULATIONS

In the present thesis three cases were studied as follows-

Case 1. To stimulate the variation in temperature distribution along the bed height by changing the input air velocity. Also, to study the variation in pressure drop along the bed height with the change in bed porosity.

Case 2. To stimulate the variation in temperature, CO fraction and H₂ fraction in producer gas by changing the O₂ fraction in input air reactant.

Case 3. To stimulate the variation in temperature, CO fraction and H₂ fraction in producer gas by increasing moisture percentage in input reactant.

4.5 (a) Case 1

To stimulate the variation in temperature distribution along the bed height by changing the input air velocity. Also, to study the variation in pressure drop along the bed height with the change in bed porosity.

There is huge importance in countless practical applications of flow of fluids through porous media, counting the drying the wet biomass particles, the gasification of biomass or coal, ground water movement, surface catalysis of chemical reactions etc. In all these instances it is essential to calculate design parameters such as pressure drop, friction factor, heat transfer coefficients in order to forecast optimal operating conditions, size and design of equipment. The pressure gradient through the porous bed is a function of system geometry, medium porosity, permeability and relationship among velocity versus pressure drop or Reynolds number versus friction factor.

(Ergun, 1952), (Ranz, 1952), (Brownell, 1956), (Comiti, 2000) developed non-dimensional method to establish the link in frictional factor and Reynolds number to define the fluid transport through porous media as

$$f_{pore} = \alpha / Re_{pore} + \beta / Re_{pore}^n + \lambda$$

$$Re_{pore} [= qv_0 dp / \mu(1 - \epsilon_{bed})]$$

Here, Re_{pore} is the pore Reynolds number, f_{pore} is the friction factor. α , β and λ are the constants. Darcy law deviates as fluid velocity increases, since inertial contribution starts dominating. (Ergun, 1952) combined the Carman–Kozeny equation (Kozeny, 1927), and Blake–Plummer equation in form of Forchheimer equation.

4.5.1 System Description

The open top downdraft biomass gasifier has been chosen for this case study. In this system air enters from the top and exists from the bottom of the reactor. For simplicity, the gasifier is divided into three zones, each one corresponding to a dominant phenomenon as: pyrolysis zone (upper bed), oxidation zone (oxidation bed), and char reduction zone (lower bed).

4.5.2 Assumptions

The porous bed is assumed to be isotropic, within each zone, the particle size, bed porosity is assumed to be uniform.

4.5.3 Bed Porosity Conditions

The Darcy's law for flow through different types of porous media is valid for $Re_{Dp} \leq 1$, when $Re_{Dp} \geq 1$, the inertial effects needs to be accounted for in the momentum balance. Thus, the correlations of (Ergun, 1952) and (Kozeny, 1927) as given in Table 4.1 are used in the present work for comparative analysis of the pressure drop through granular bed of gasifier.

Table 4.1 Correlations for the prediction of pressure drop

S.no.	Correlations	Reference
1.	$\frac{\Delta P}{L} = \frac{150\mu}{D_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} V_\infty + \frac{1.75\rho}{D_p} \frac{(1-\varepsilon)}{\varepsilon^2} V_\infty^2$	(Ergun, 1952)
2.	$\frac{\Delta P}{L} = \frac{150\mu}{D_p^2} \frac{(1-\varepsilon)^2}{\varepsilon^3} V_\infty$	(Kozeny, 1927)

Where,

μ = viscosity/

D_p = mean particle diameter

ε = void fraction = $\frac{\text{Volume of voids}}{\text{Volume of packed bed region}}$

L = bed depth

4.5.4 Procedure for Steady State Problem

1. Model the geometry using a CAD modeller like Solid-works.
2. Import the geometry into FLUENT and generate a mesh.
3. Choose a model for the continuous flow like viscous – laminar.
4. For heat transfer problem, 'ON' the energy equation.
5. Set up the cell zone conditions of the geometry.
6. Set up boundary conditions for the problem.
7. Initialize the problem and run it till the solution converges.
8. Analyse the result in post processing.

4.5.5 Experimental

Geometry

Fig.4.1 shows the fixed bed downdraft gasifier geometry that has been designed for the problem. The geometry was created in SOLIDWORKS.

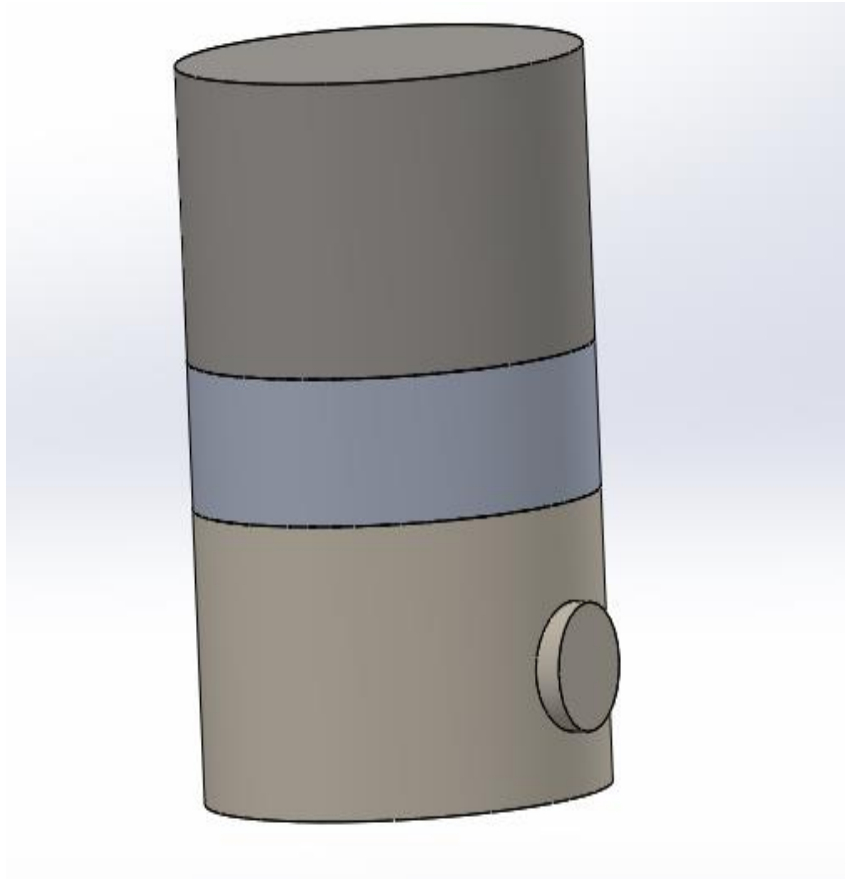


Fig.4.1 Isometric view of Downdraft Gasifier

Geometry Design Parameters

The details of the geometry design parameters are listed in Table.4.2

Table 4.2 Geometry design parameter details

Inlet air duct diameter	10cm	Combustion bed length	3cm
Inlet air duct diameter	10cm	Lower bed diameter	10cm
Upper bed length	6cm	Lower bed length	6cm

Combustion bed diameter	10cm	Outlet duct diameter	2cm
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Mesh Generation

A tetrahedral mesh was generated using ANSYS FLUENT's native mesh generator (Fig.4.2). The cells on the outlet duct were also refined. The details of the mesh generated are listed in Table.4.3.

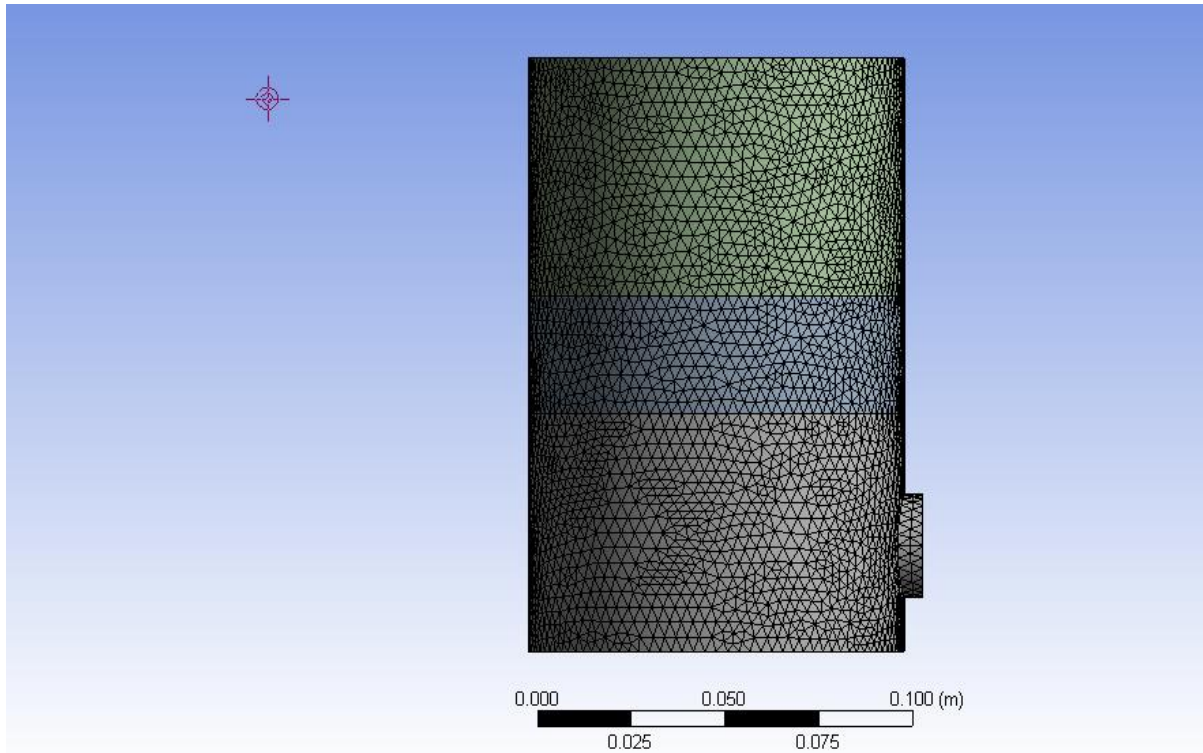


Fig.4.2 tetrahedral mesh generated on the downdraft gasifier bed

Table 4.3 Meshing Details

Elements used	Tetrahedrons
Relevance Centre	Fine
Smoothing	High
Minimum edge length	$6.747e^{-3}m$
Nodes	35777
Elements	181397

4.5.6 Mesh Quality Details

Orthogonal quality - Min. 0.274677 Max. 0.99388 Average 0.855531

The mesh has a good element quality (close to 0.9) as seen in Fig.4.3.

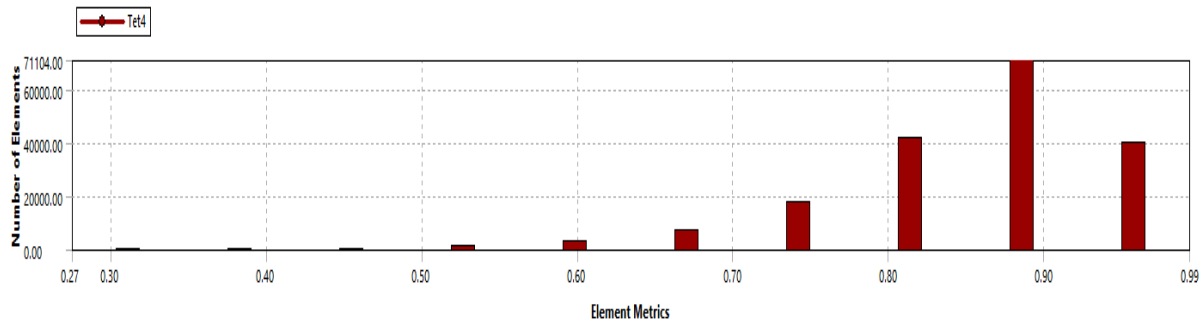


Fig.4.3 A histogram between the orthogonal quality and the number of elements

Element quality - Min. 0.29131 Max. 0.99968 Average 0.83303

The mesh has a good element quality (close to 0.9) as seen in Fig.4.4.

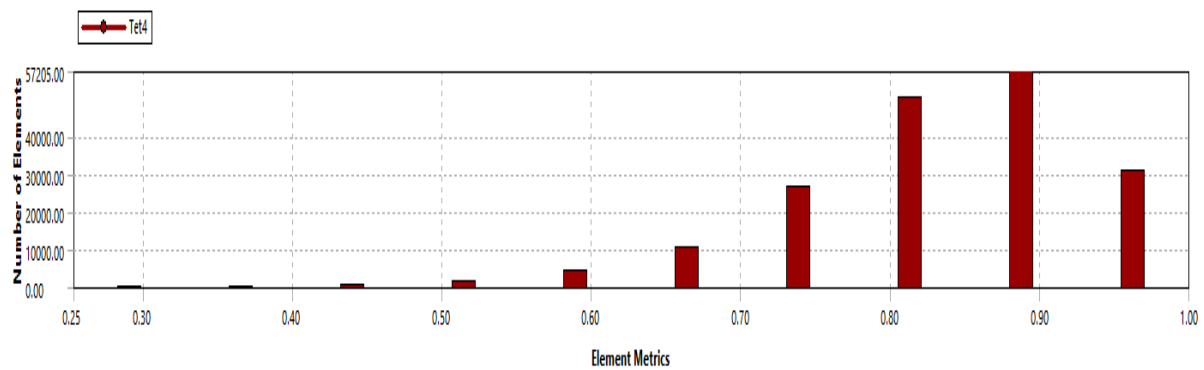


Fig.4.4 A histogram between element quality and the number of elements

4.5.7 Cell Zone Conditions

In 'Cell zone conditions' the material is set to air.

The bed condition details are listed in the Table 4.4.

Table 4.4 Gasifier Bed Conditions

Upper Bed		Combustion Bed		Lower Bed	
Porous Zone		Porous Zone		Non Porous Zone	
Void Fraction	0.4	Void Fraction	0.3	Void Fraction	--

For different values of bed porosity (void fraction), permeability coefficient and inertia loss coefficient values are calculated and listed in the table.

$$\text{Permeability coefficient} \\ \alpha = \frac{D_p^2}{150} \frac{\epsilon^3}{(1 - \epsilon)^2}$$

$$\text{Inertia loss coefficient} \\ c = \frac{3.5(1 - \epsilon)}{D_p \epsilon^3}$$

$$\frac{1}{\text{permeability coefficient}} = \text{Viscous resistance}$$

Table 4.5 Viscous resistance and inertial resistance values

Void fraction	Viscous resistance	inertial resistance
0.9	5144	24
0.8	29296.9	68.36
0.4	3750000	1640.625
0.3	6805000	4537
0.25	13500000	8400

4.5.8 Boundary Conditions

At Inlet, Velocity magnitude varies from 0.5 to 2.5 mm/s, Initial gauge pressure- 1000Pa.

At Outlet, Gauge pressure - 0Pa.

Bed wall thermal conditions are given as:

Upper bed wall – Convective heat transfer to surroundings ($h = 25 \text{ W/m}^2\text{k}$)

Combustion bed wall – At constant temperature of 2000 k

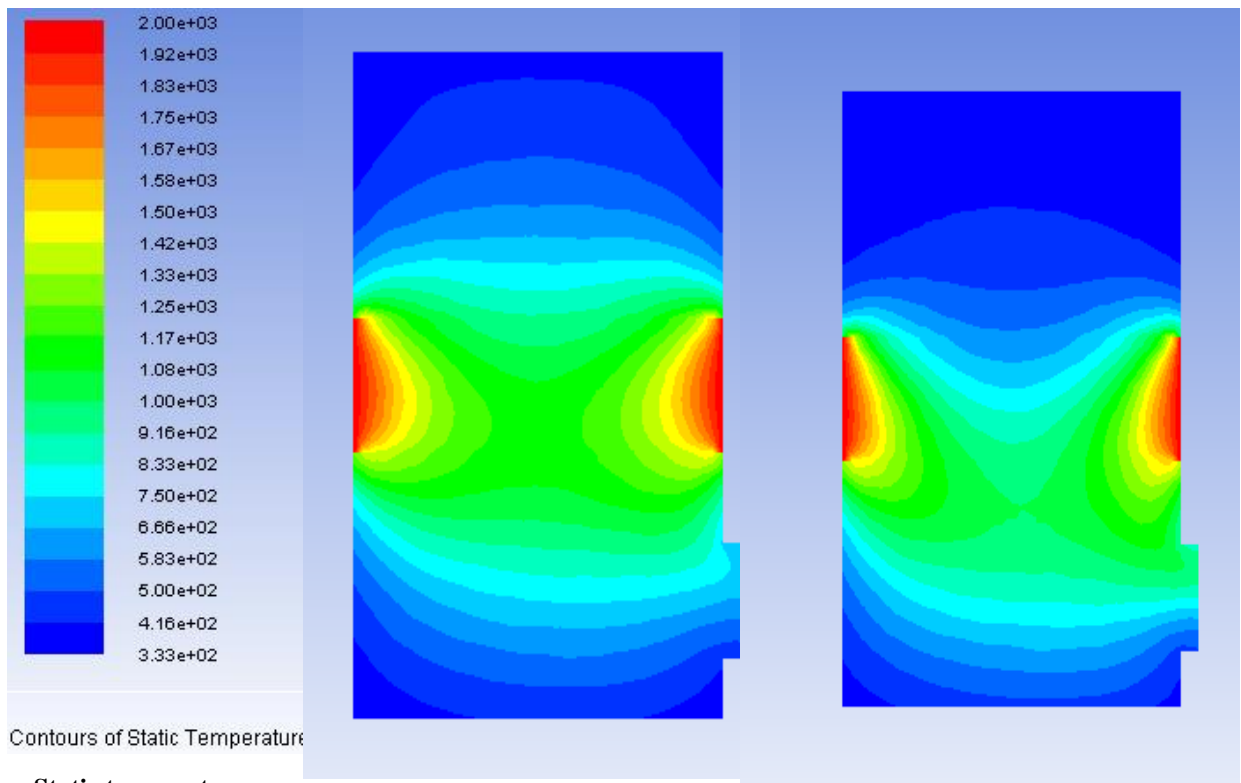
Lower bed wall – Convective heat transfer to surroundings ($h = 25 \text{ W/m}^2\text{k}$)

4.5.9 Solution Controls

Normal relaxation factor – Pressure – 0.3 and Momentum – 0.7

Convergence criterion - Energy equation converges at 10^{-06} and rest all at 10^{-03}

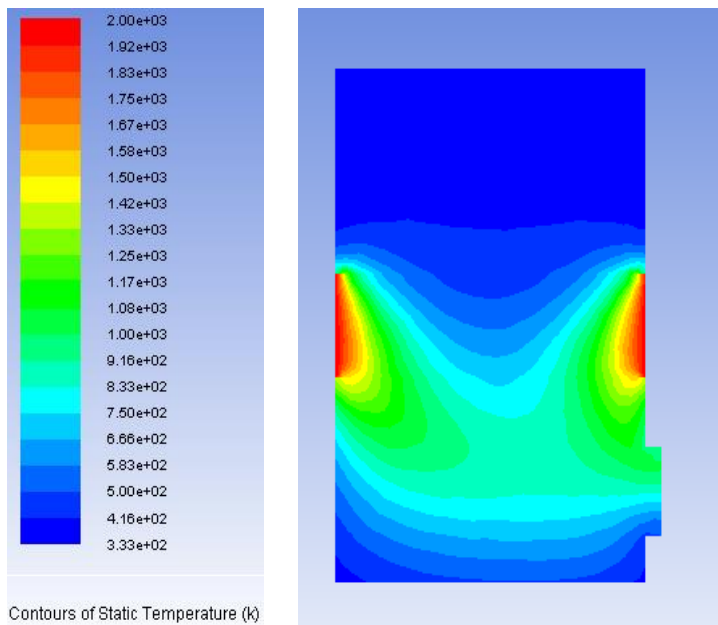
Fig.4.5 shows the simulation of variation in temperature distribution along the bed height vs. input air velocity. Temperature profile is found to be very sensitive to air flow rate. It is observed that with the increase in air inlet velocity, the temperature near the pyrolysis zone (upper bed) decreases.



Static temperature scale

Temperature distribution at 0.5mm/s air velocity

Temperature distribution at 1.5mm/s air velocity



Static temperature scale

Temperature distribution at 2.5mm/s air velocity

Fig.4.5 Variation in temperature distribution along the bed height vs. input air velocity

Fig.4.6 shows the simulation of variation in pressure drop along the bed height vs. bed porosity. The reduction in feedstock particle size (i.e. decrease in porosity of bed) are found to cause a marked increase in pressure drop through the gasifier.

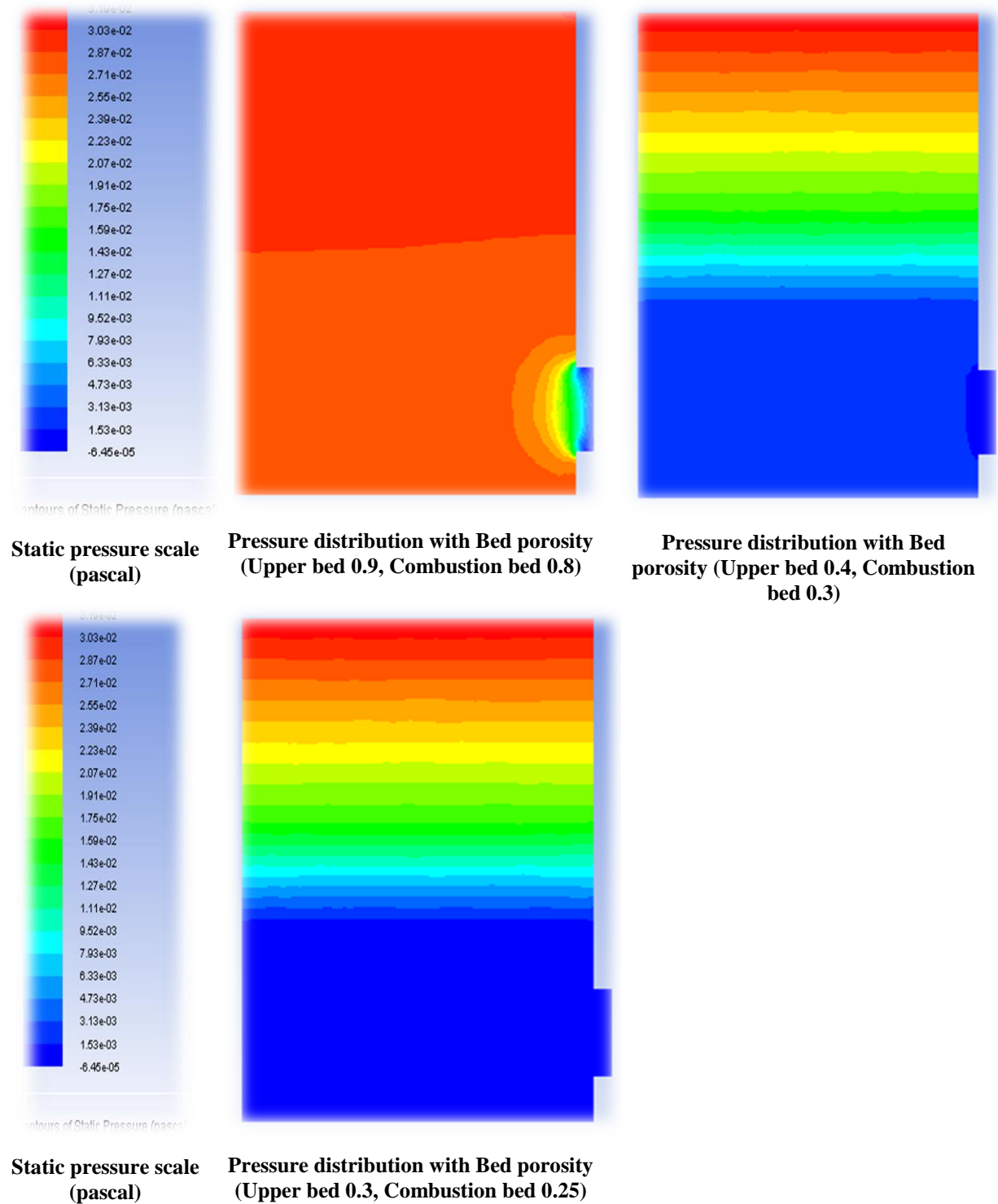


Fig.4.6 Variation in pressure drop along the bed height vs. bed porosity

4.5 (b) CASE 2

To stimulate the variation in temperature, CO fraction and H₂ fraction in producer gas by changing the O₂ fraction in input air reactant.

4.5.10 Geometry

To determine the geometry of the model, following correlations are used as mentioned in table 4.6:

Table 4.6 Correlations used to determine geometry of downdraft gasifier

S.no	Correlations	Reference
1.	$D = \left(\frac{1.27 * FCR}{SGR} \right)^{0.5}$	(Belonio, 2005)
2.	$H = \left(\frac{SGR * t}{\rho} \right)$	(Belonio, 2005)

Where,

D = diameter of gasifier (m)

H = height of gasifier (m)

SGR = Specific Gasification Rate (kg/hr.m²)

FCR = Fuel Consumption Rate (kg/s)

‘ρ’ = density of feed material (kg/m³)

‘t’ = length of operating time (hours)

Following procedure is followed for the steady state problem:

- Model the geometry using a CAD modeller like Solid-works.
- Import the geometry into FLUENT and generate a mesh.
- Choose a model for the continuous flow like viscous – laminar.
- For heat transfer problem, ‘ON’ the energy equation.
- Set up the cell zone conditions of the geometry.
- Set up boundary conditions for the problem.
- Initialize the problem and run it till the solution converges.
- Analyse the result in post processing.

Fig.4.7 and 4.8 shows the fixed bed downdraft gasifier geometry that has been designed for the problem. The geometry was created in SOLIDWORKS. After creating geometry, a uniform mesh has been generated.

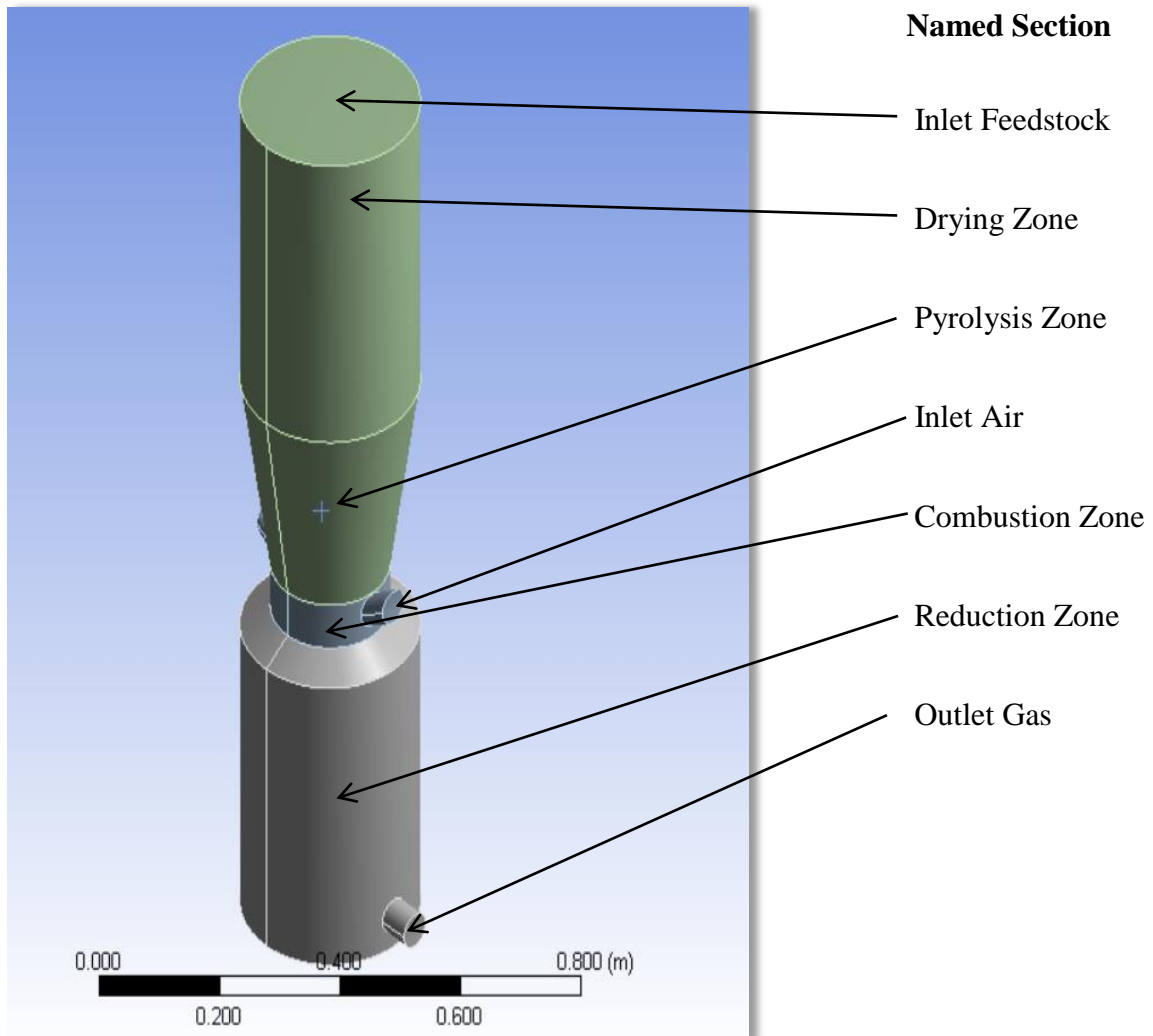


Fig.4.7 Isometric view of Downdraft Gasifier

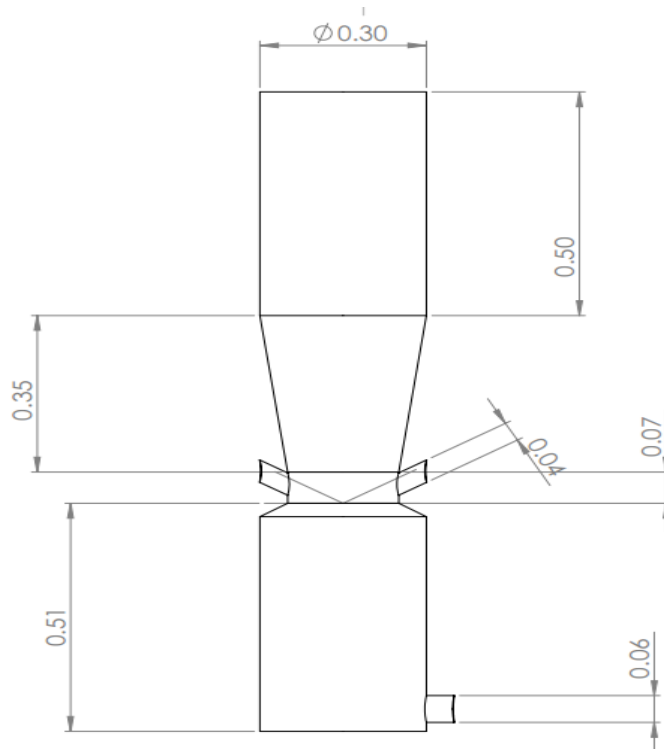


Fig. 4.8 Front view of downdraft gasifier (all dimensions in meters)

4.5.11 Mesh Generation

A tetrahedral mesh was generated using ANSYS FLUENT's native mesh generator. The cells on the outlet duct were also refined. The details of the mesh generated are listed in Table.4.7.

Table 4.7 Meshing Details

Elements used	Tetrahedrons
Relevance Centre	Fine
Smoothing	High
Minimum edge length	$1.345e^{-03}$ m
Nodes	68465
Elements	294207

4.5.12 Computational Model Parameters

Details of model settings, boundary conditions and solvers used are described in Table 4.8 below:

Table 4.8 Details of model settings, boundary conditions and solvers

	MODEL	SETTINGS	INFORMATION
Model Settings	Space	3-D	-
	Time	Steady	-
	Viscous	Realizable k-epsilon turbulence model	Turbulence intensity = 5%
	Wall Treatment	Standard Function	Wall -
	Heat Transfer	Enabled	-
	Species Transport	Non – Premixed	-
	Discrete phase	Surface Injection	-
		NAME	TYPE
Boundary Conditions	Fluid	Fluid	Air (21% of O ₂)
	Outlet-syngas	Exhaust fan	-
	Inlet-air	Mass-flow-inlet	15gm/s
	Inlet-feedstock	Mass-flow-inlet	20gm/s
	Drying	Wall (mixed)	Convection and Radiation
	Pyrolysis	Wall (mixed)	Convection and Radiation
	Oxidation	Wall (mixed)	Convection and Radiation
	Reduction	Wall (mixed)	Convection and Radiation
	VARIABLE	DISCRETIZATION SCHEME	INFORMATION
	Pressure	PRESTO!	-
	Momentum	Second Order Upwind	-

Solvers	Turbulent Kinetic Energy	Second Order Upwind	-
	Turbulent Dissipation Rate	Second Order Upwind	-
	Energy	Second Order Upwind	-

4.5.13 Results and Discussion

Fig.4.9 shows the contour plots of temperature distribution along the bed height with the increase in O₂ fraction in input reactant. The temperature in the reduction zone is found to be increasing with increase in O₂ fraction in input reactant. The high temperature in the reduction zone enhances tar cracking and better char conversion (driving endothermic C+CO₂ and C+H₂O reactions).

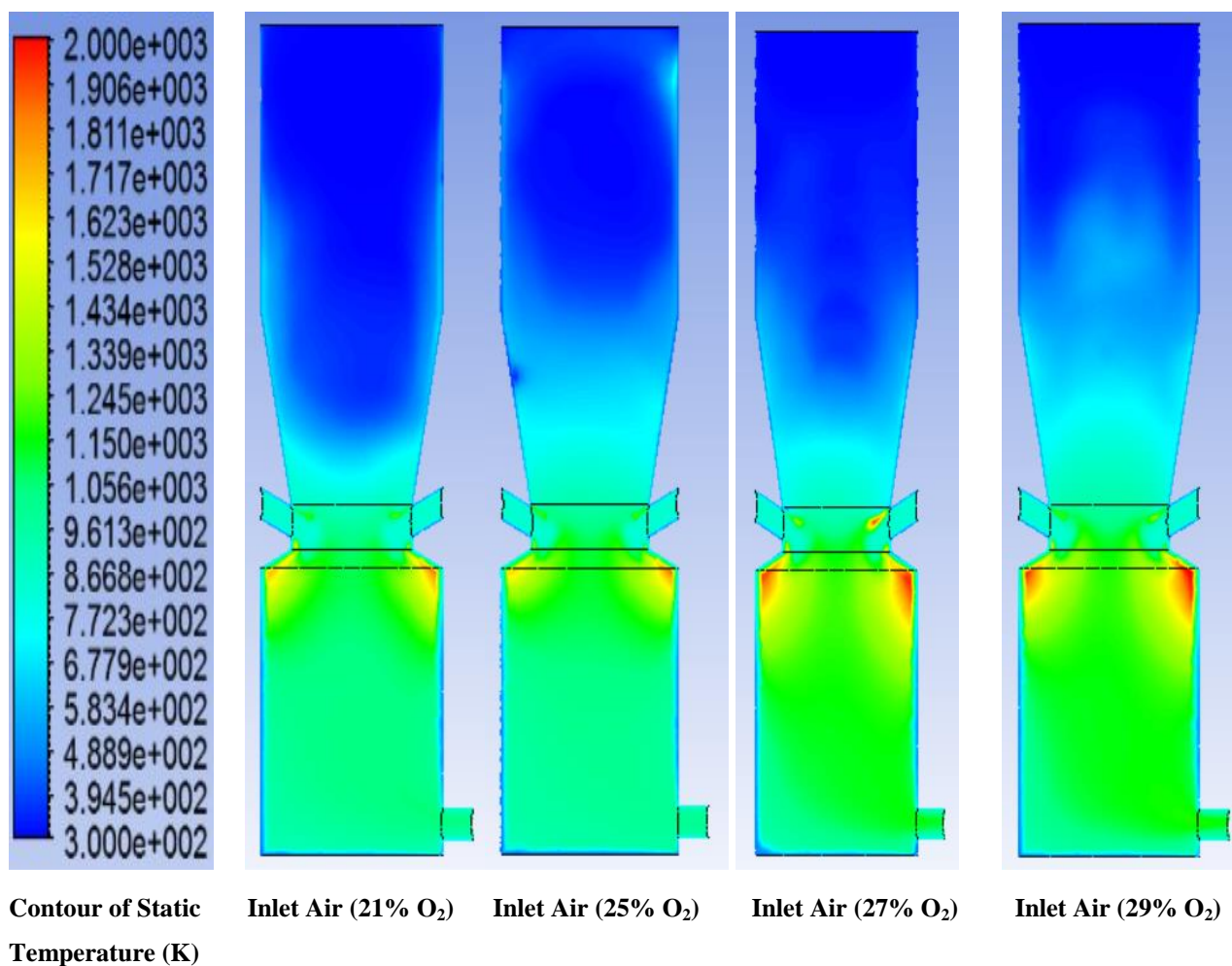


Fig.4.9 Variation in temperature along the bed height with the increase in O₂ fraction in input reactant

Fig.4.10 shows the contour plots of CO mole fraction in producer gas composition with the increase in O₂ fraction in input reactant. The temperature achieved with O₂ fraction enhances the CO fraction in product gas which directly suggests the higher char reduction reactions.

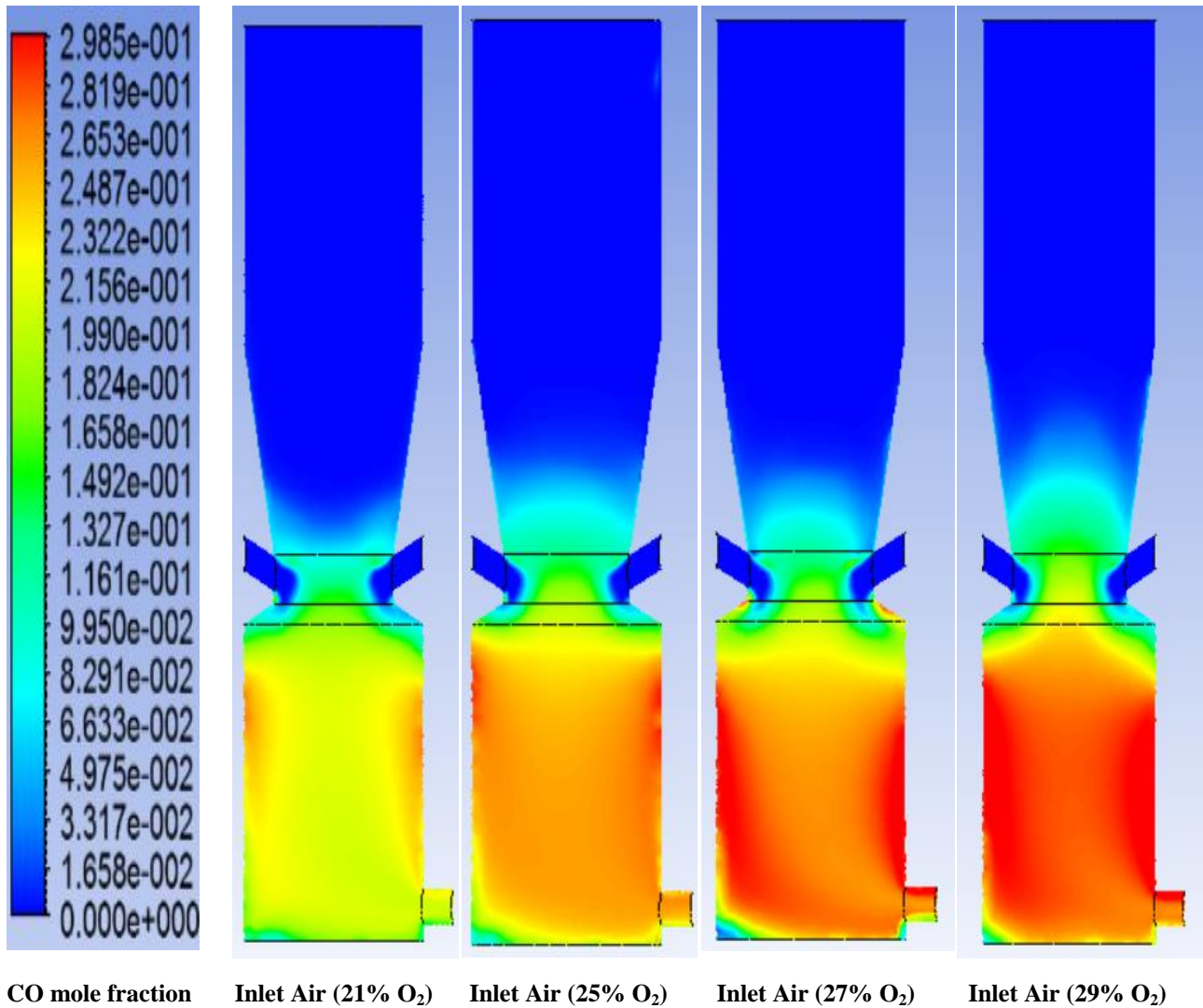
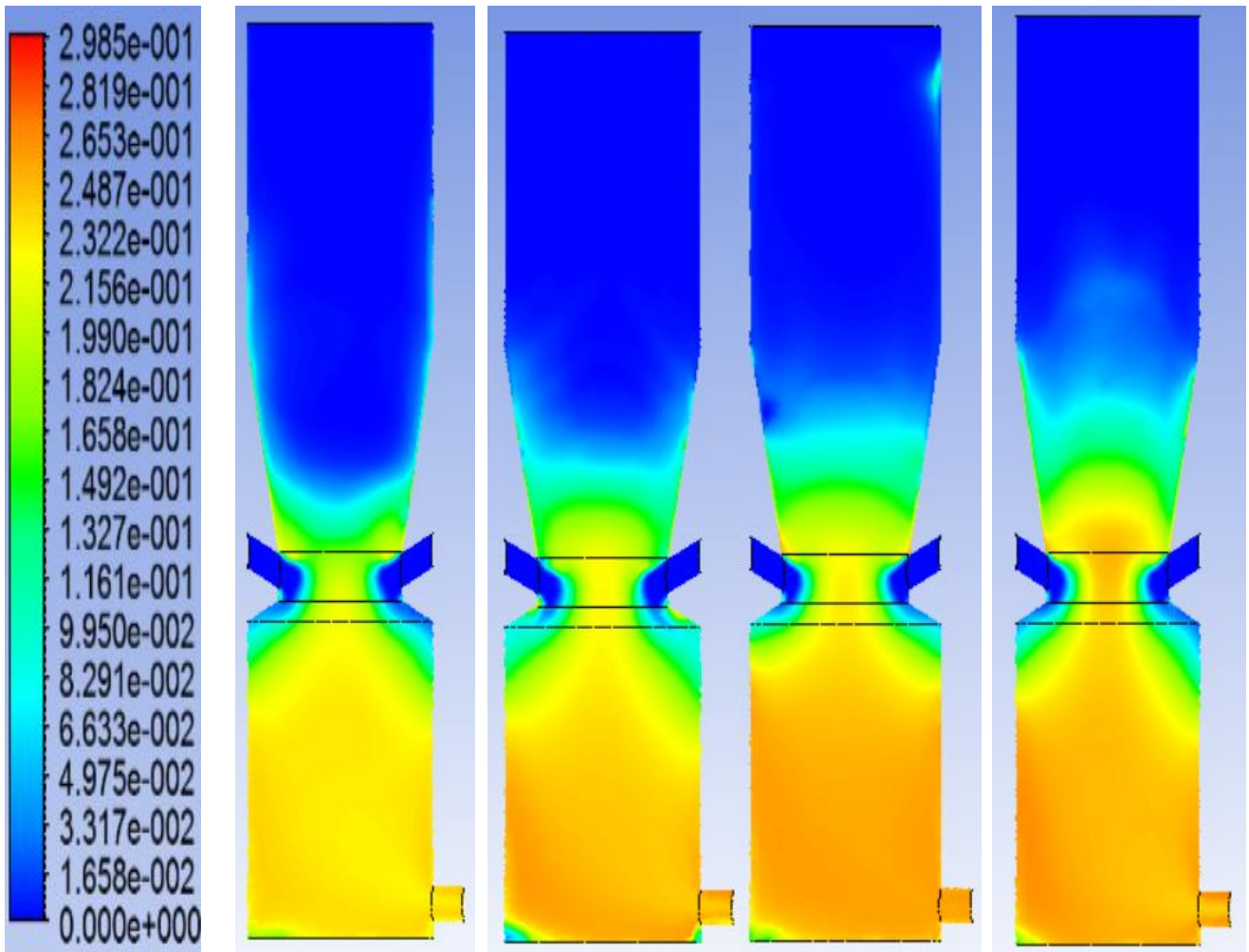


Fig.4.10 Variation in CO mole fraction along the bed height with the increase in O₂ fraction in input reactant

Fig.4.11 shows the contour plots of H₂ mole fraction in producer gas composition with the increase in O₂ fraction in input reactant. It can be seen that with the increase in temperature, H₂ fraction in producer gas increases which further also suggests the higher char reduction reactions.



H₂ mole fraction Inlet Air (21% O₂) Inlet Air (25% O₂) Inlet Air (27% O₂) Inlet Air (29% O₂)

Fig.4.11 Variation in H₂ mole fraction along the bed height with the increase in O₂ fraction in input reactant

4.5 (c) CASE 3

To stimulate the variation in temperature, CO fraction and H₂ fraction in producer gas by increasing moisture percentage in input reactant.

As we **increase the Moisture content** in biomass, **extra O₂** has to be supplied to achieve same adiabatic temperature as of gasification of dry biomass.

Fig. 4.12 and 4.13 show the variation in H₂O mole fraction along the bed height with the increase in moisture content in biomass.

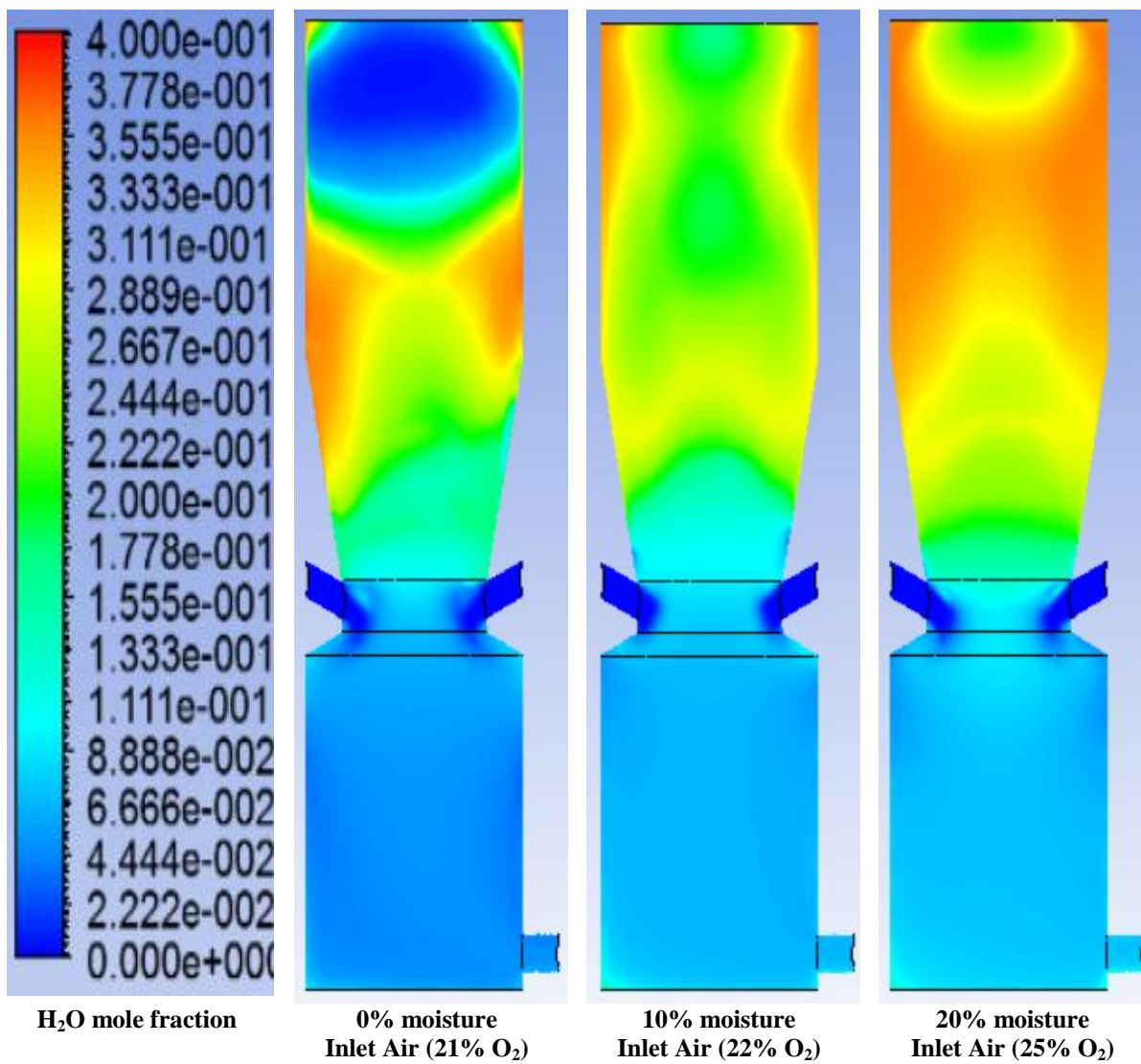


Fig.4.12 Variation in H₂O mole fraction along the bed height with the increase in moisture content in biomass

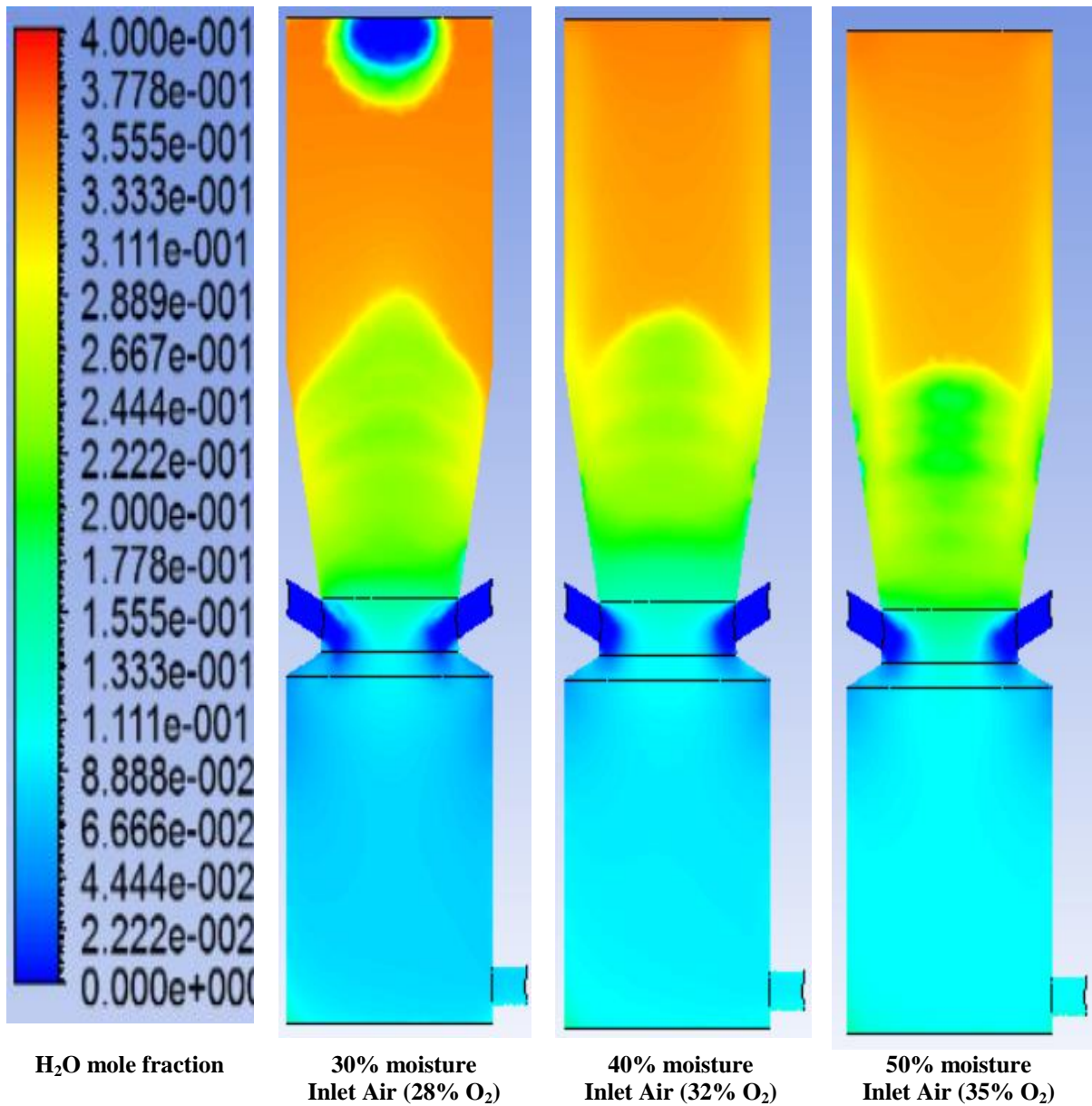


Fig.4.13 Variation in H₂O mole fraction along the bed height with the increase in moisture content in biomass

The contour plots show that with the increase in the moisture in biomass, the H₂O mole fraction in the upper bed increases.

Fig. 4.14 and 4.15 show the variation in H₂ mole fraction along the bed height with the increase in moisture content in biomass.

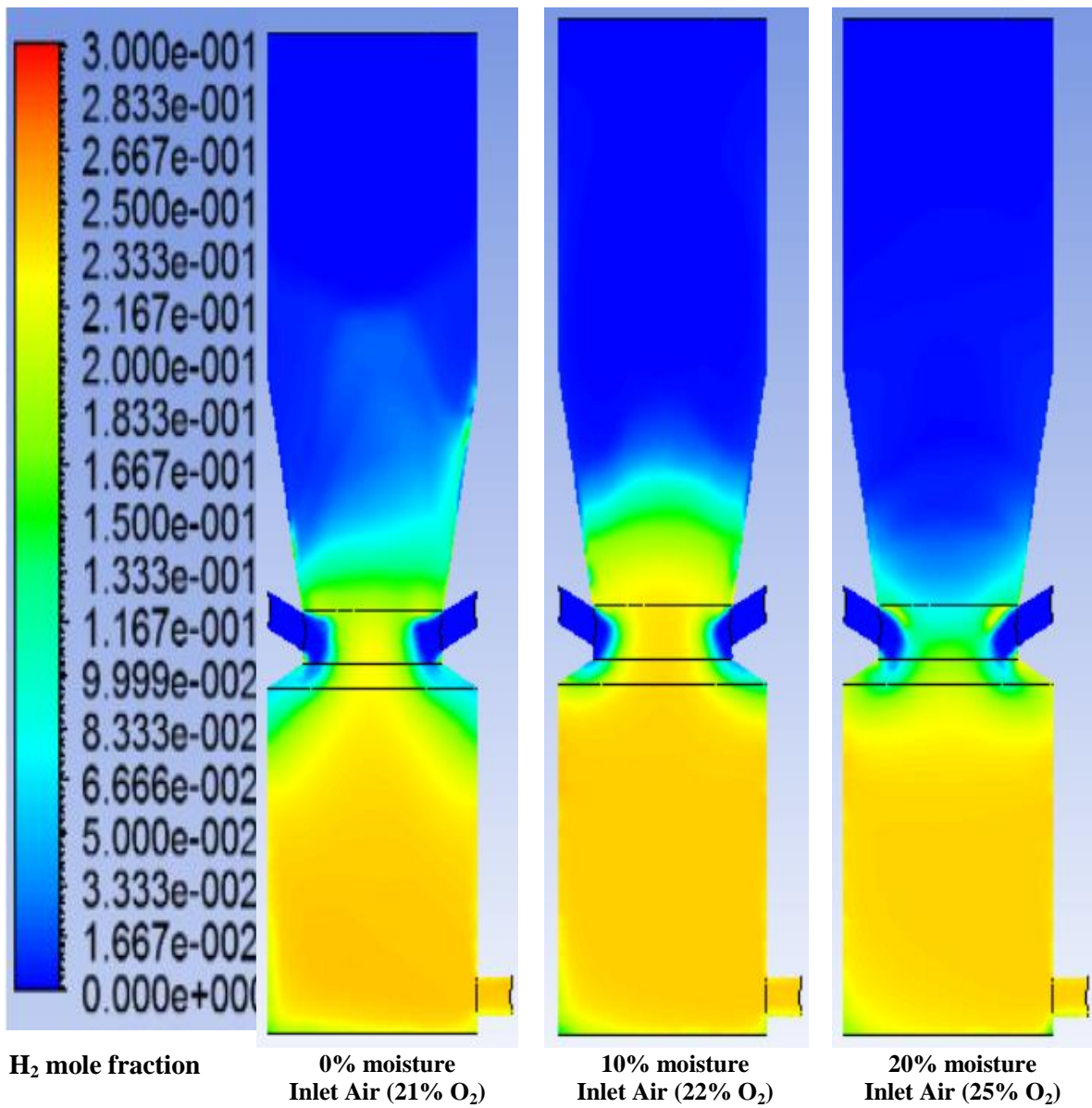


Fig.4.14 Variation in H₂ mole fraction along the bed height with the increase in moisture content in biomass

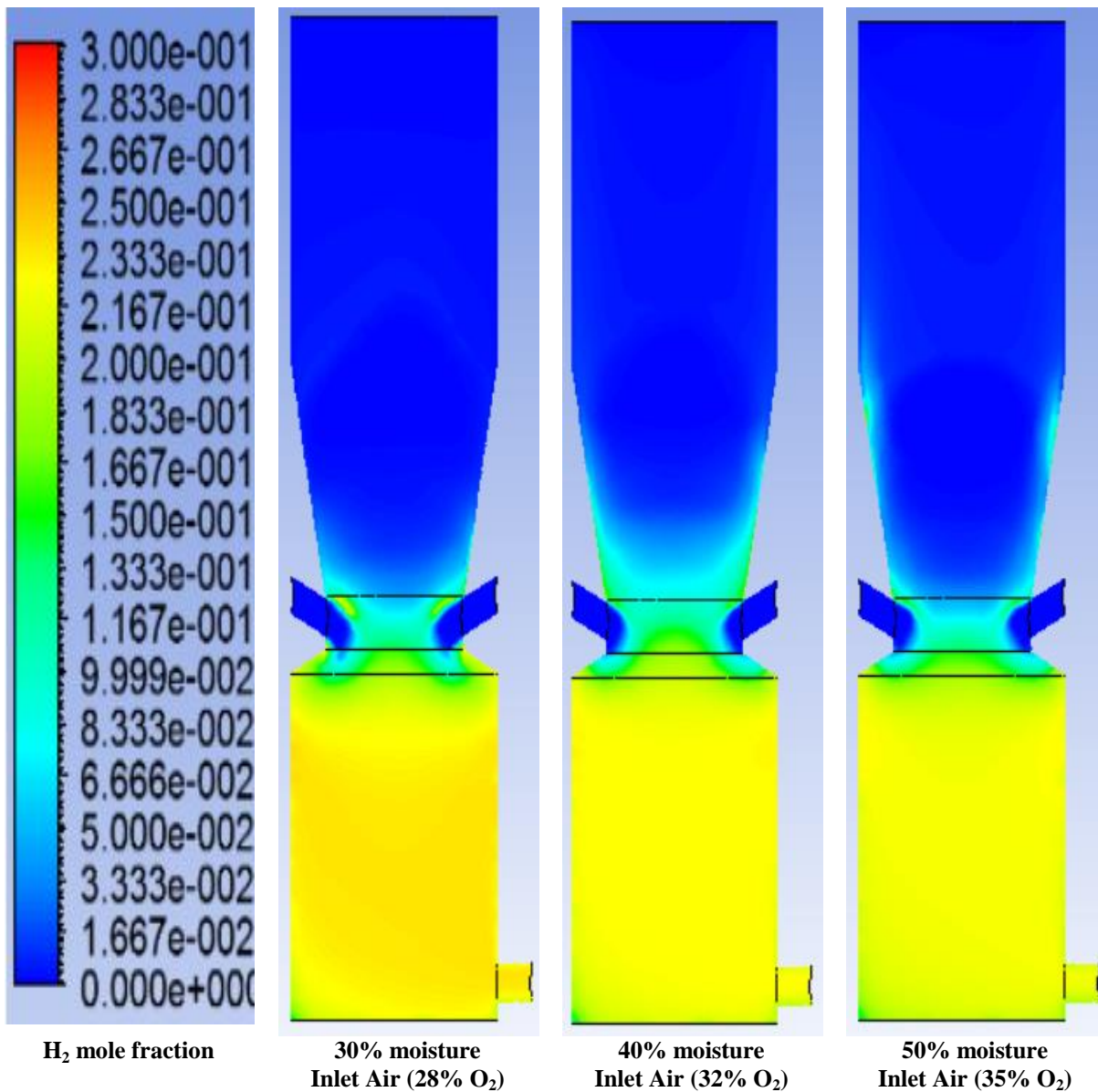


Fig.4.15 Variation in H₂ mole fraction along the bed height with the increase in moisture content in biomass

The contour plots show that with the increase in the moisture in biomass, the H₂ mole fraction in the lower bed decreases. There is reduction of H₂ in producer gas.

Fig. 4.16 and 4.17 show the variation in CO mole fraction along the bed height with the increase in moisture content in biomass.

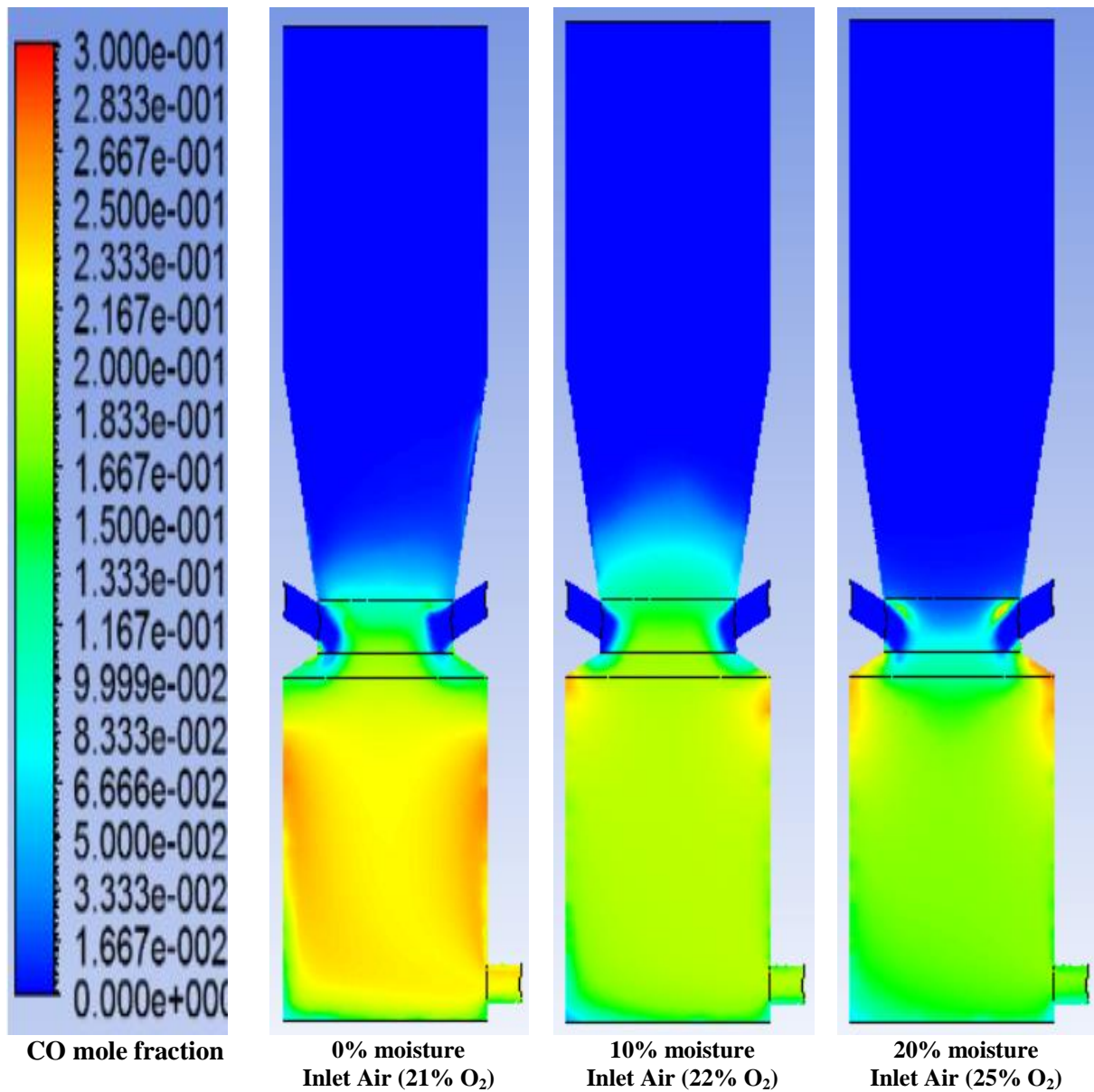


Fig.4.16 Variation in CO mole fraction along the bed height with the increase in moisture content in biomass

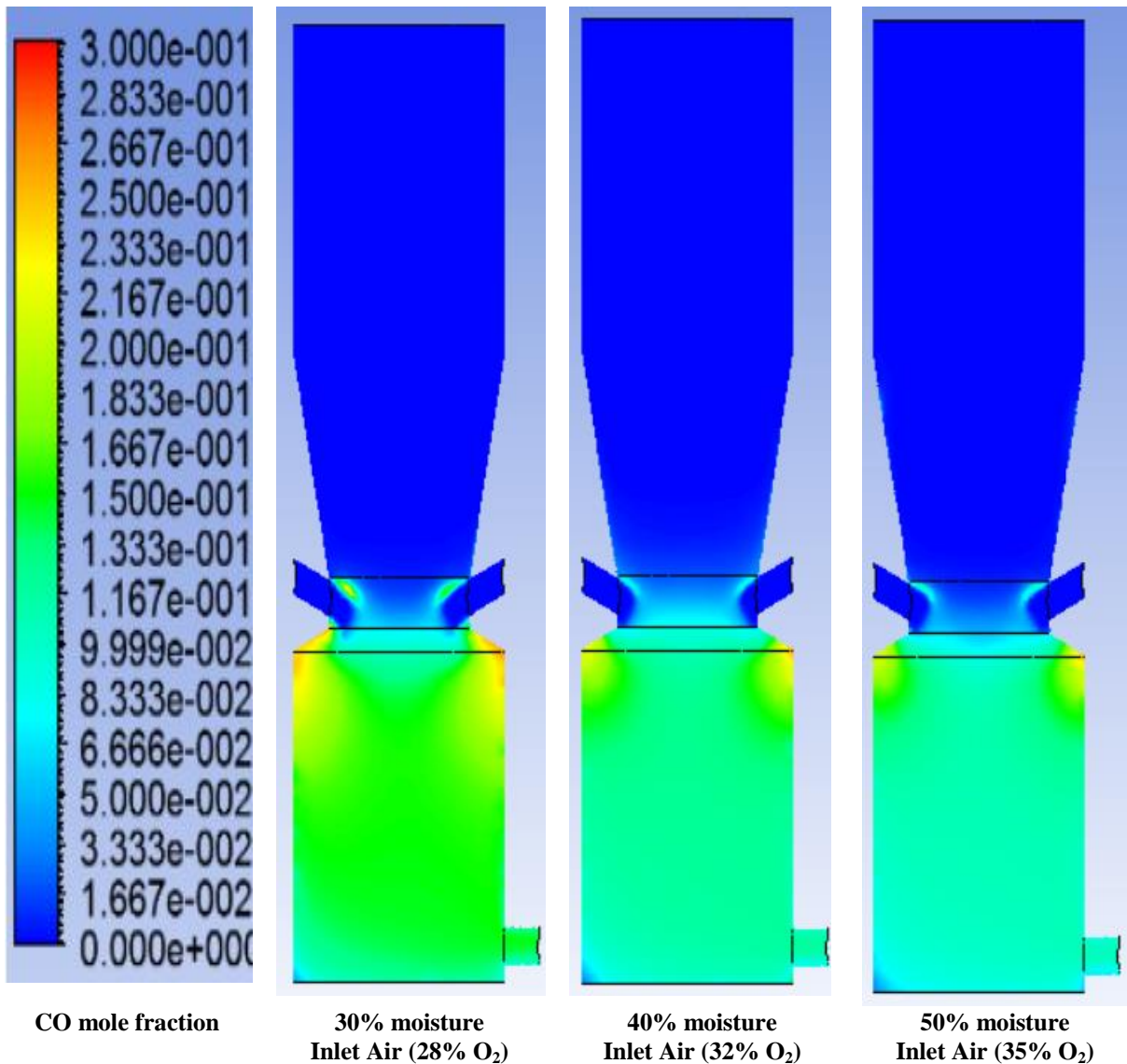


Fig.4.17 Variation in CO mole fraction along the bed height with the increase in moisture content in biomass

As evident from the figures above, the excess moisture in biomass affects the performance of gasifier. The bed temperature drops with the increase in moisture content as significant heat in pyrolysis zone is consumed for phase change of H₂O in biomass. Subsequently, the processes downstream are also affected with dilution of air with extra H₂O in combustion zone which reduces the oxidation reaction rates. The extra fraction of H₂O in char reduction zone helps in enhanced char reaction but is affected by the reduced bed temperature. The lower bed temperature in combustion zone leads to lower bed temperature in reduction zone as well and char reaction rates are reduced which is evident from the reduced CO and H₂ fraction in product gas. Enriching the air with O₂ will help in maintaining the required fraction of O₂ in combustion zone and maintain bed temperature and gas quality during gasification of wet biomass.

4.6 SUMMARY

CFD simulation of Fixed Bed Downdraft Gasifier is carried out, variation in temperature distribution along the bed height vs. input air velocity and variation in pressure drop along the bed height vs. bed porosity are obtained.

Temperature profile is found to be very sensitive to air mass flux. It is observed that with the increase in air inlet velocity or air mass flux, the temperature near the pyrolysis zone (upper bed) decreases. Simulation results indicates that with the increase in air input velocity there is a significant heat loss in pyrolysis zone through convective cooling to by incoming flux of air which dominates over the heat transfer through radiation from the lower oxidation/combustion zone. At very high air mass flux, if the convective cooling effect is more than the heat gain from the combustion zone through radiation, the gasifier will quench.

The temperature variation with change in air mass flux also influences the gas composition. Endothermic char reduction reactions are favoured at higher bed temperature and hence the better gas quality. Also, high pyrolysis rate at higher pyrolysis zone temperature leads to higher biomass consumption at given air mass flux which leads to thermochemical conversion at lower ER and high fuel gases in product gas mixture. On the other hand, lower bed temperature in pyrolysis zone at higher air mass flux not only reduces the pyrolysis or biomass conversion rate but also increases the ER due to higher oxidiser availability and lower biomass conversion. It leads to lower fuel gases in product gas mixture.

Effects of moisture fraction in biomass has been identified to reduce the bed temperature and hence gas composition.

The reduction in feedstock particle size are found to cause a marked increase in pressure drop through the gasifier. Simulation results also indicates that with the decrease in bed porosity, there is pressure drop along the bed height which will lead to more resistance time further leading to complete char conversion to gas.

In the present work, downdraft gasifier is used for producer gas generation, because it produces less tar compared to updraft gasifier. Since the gasifier has to couple with IC engine for performance and emission and combustion test hence producer gas from gasifier must contain as less tar as possible because higher tar content fuel gives rise to corrosion effect which is a major cause of damage to engine components like piston, valve and fuel pipe lines etc. Hence downdraft gasifier is the most appropriate for the above application. The effect of O₂ enriched air on the temperature profile and gas quality has been studied while gasifying wet woody biomass. Enriched air mixture has higher oxygen concentration compared to that of air. In air gasification, it was found that nitrogen in air acted as a diluting agent for the heating value of the gases produced during gasification and hence enriched air was used to sustain the latent heat of moisture present in wet biomass and for any increase in heating value of the produced gases.

Thermodynamic equilibrium analysis has been performed. Adiabatic analysis gives us the input for the O₂ fraction to be maintained with varying moisture level in biomass. Isothermal analysis provides us the insight on the influence of bed temperature on gas composition and efficiency. Increase in O₂ fraction leading to higher ER is found to be responsible for the reduction in energy efficiency as the process shifts from gasification towards combustion.

Methodology for the energy and exergy analysis has been discussed. The exergy analysis helps in identifying the factors which influence the efficiency most towards better design and optimisation of process parameters.

Tar reduction is one of the objective of the present work and chapter 3 describes the methodology for the tar analysis and the setup for the same.

CFD simulation of Fixed Bed Downdraft Gasifier is carried out, variation in temperature distribution along the bed height vs. input air velocity and variation in pressure drop along the bed height vs. bed porosity are obtained.

Temperature profile is found to be very sensitive to air flow rate. It is observed that with the increase in air inlet velocity, the temperature near the pyrolysis zone (upper bed) decreases. Simulation results indicate that with the increase in air input velocity there is a significant decrease in heat transfer from combustion zone (through radiation/conduction) to biomass bed above (needed to initiate pyrolysis). If the heat loss by convective cooling to

ambient air from pyrolysis zone increases, than the heat gain from the combustion zone, then the gasifier will quench.

The temperature variation with change in air mass flux also influences the gas composition. Endothermic char reduction reactions are favoured at higher bed temperature and hence the better gas quality. Also, high pyrolysis rate at higher pyrolysis zone temperature leads to higher biomass consumption at given air mass flux which leads to thermochemical conversion at lower ER and high fuel gases in product gas mixture. On the other hand, lower bed temperature in pyrolysis zone at higher air mass flux not only reduces the pyrolysis or biomass conversion rate but also increases the ER due to higher oxidizer availability and lower biomass conversion. It leads to lower fuel gases in product gas mixture.

Effects of moisture fraction in biomass have been identified to reduce the bed temperature and hence gas composition.

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