



*MODELLING OF DOWNDRAFT GASIFIER USING
COMPUTATIONAL FLUID DYNAMICS SOFTWARE-
FLUENT*

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Energy Systems & Environment

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ABSTRACT

Biomass energy combined with computational fluid dynamics (CFD) software have been described in some detail in the following study. The aspect of biomass gasifier has been investigated with regard to the potential of designing future gasifier using simulation in FLUENT software.

The project is about the modelling of fluid flow of biomass fuel inside biomass downdraft gasifier using FLUENT software. Using the typical design of gasifier, the model is produced in 2-Dimensional for easier iterations and simulations.

Two types of gasifier are measured; pressurised and atmospheric gasifier. The gasifier's model is set to have initial temperature at 800° C for both types of gasifier and 5.0 MPa for pressurised gasifier.

After iterations in FLUENT software with first-order discretization, the results obtained are convergent and show that using second-order discretization is not suitable for 2-Dimensional model.

Finally, future investigations are also suggested in this study for more accurate result using computational fluid dynamic (CFD) software.

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Chapter 1 – Introduction

1.1 Biomass Resources

The use of biomass fuels is rapidly increasing in northern, mid and Eastern Europe. According to European Commission in the white papers' community strategy & action plan in the policies of the European Union (EU), biomass is expected to play a major role as a renewable energy source¹ (Ronald, 2001).

According to F. Dumbleton, in the UK there are about 14 000 000 tonnes/year of straw that can be obtained from the production of wheat, barley, oats, oilseeds rape and linseed. From this amount, it is estimated that 4 000 000 tonnes/year could be use for producing energy. Apart from that 1 000 000 tonnes/year of forest residue are produced and it is raised up to 2 000 000 tonnes/year in the next 20 years. For woods it is estimated about 960 000 tonnes/year as logs².

Many advantages can be obtained from biomass energy such as clean burning fuel that contributes significantly to the world energy supply. The potential for greenhouse gases production is also reduced using the biomass energy. Using gasifier as a medium for the production of syngas from biomass makes lots of benefit for people, as the sources are abundance.

It can be made available in a variety of shapes like logs, chips, bales, charcoal, sludge, fluids, straw, powders and etc. Woodchips is one of the sources of biomass renewable energy that can produce gas from gasification. It has the greatest potential of any renewable energy option for base-load electric power production for electricity generator and also heating.

Recently, there are considerable interest has been shown in the gasification of wood and its use. However, the gas produce from the wood gasification is low in calorific value³. Therefore, in order to increase the efficiency several studies can be carried out. For example perhaps enlarge the gas turbine combustor, or enlarge the gasifier. As for this dissertation, the effect of pressurised downdraft gasifier is being

¹ Ronald, V.S. (2002) *How European Waste Will Contribute to Renewable Energy*. Vol. 30 pp. 471-475.

² Dumbleton, F. (2001) *Standardisation of Solid Biofuels in the UK*, AEA Technology Environment, Report 1, ESTA 32192001.

³ McIlveen, W. et al. (2001), *Bioresource Technology, A re-appraisal of wood-fired combustion*, Vol. 76, pp 183-190

studied and the results are compared with the atmospheric gasifier for optimum efficiency.

1.2 Significance of current work

There are several types of gasifier that are normally used for converting biomass fuel to get power. For example, updraft gasifier, downdraft gasifier and fluidised bed gasifier. (Refer Appendix 1.1 for an explanation of each gasifier)

In the dissertation, wood chips gasifier is modelled in downdraft gasifier which is based on experimental set-up data from pilot scale downdraft gasifier study that have been done by Dogru et al (2002). Instead of wood chips, the hazelnut shell⁴ was used for the fuel in the gasifier. This study has shown that the quality of the product gas is found to be dependent on the smooth flow of the fuel and the uniformity of the pyrolysis process.

They also suggested that gasification of shell waste products is a clean alternative to fossil fuels and this product gas can be directly used in internal gas combustion engines. Therefore, warranting further investment by authorities to exploit this valuable resource of renewable energy. This pilot gasification system that was constructed in Mechanical Engineering Lab in New Castle University provide reasonable base like input data for pressure or temperature and also the dimension of the downdraft gasifier which can be a core for the modelling using the computer software.

As expected, the model can provide useful predictions of operating other downdraft gasifier using diverse biomass feeds as fuel. There is consideration that has to put in mind about the environmental impact, from indirect and direct emissions release from the combustion process. For this dissertation, universal emission-releasing gas model based on biomass fuel is not evaluated although it is very necessary to analyse the product gas from the combustion process. This is because each case-dependent emissions associated with biomass gasification practice is quite tedious and time-consuming. Thus, it is necessary in future to model the pollutants

⁴ Dogru, M. and et al (2002), The International Journal, *Gasification of hazelnut shells in a downdraft gasifier* Vol. 27 pp 415-427.

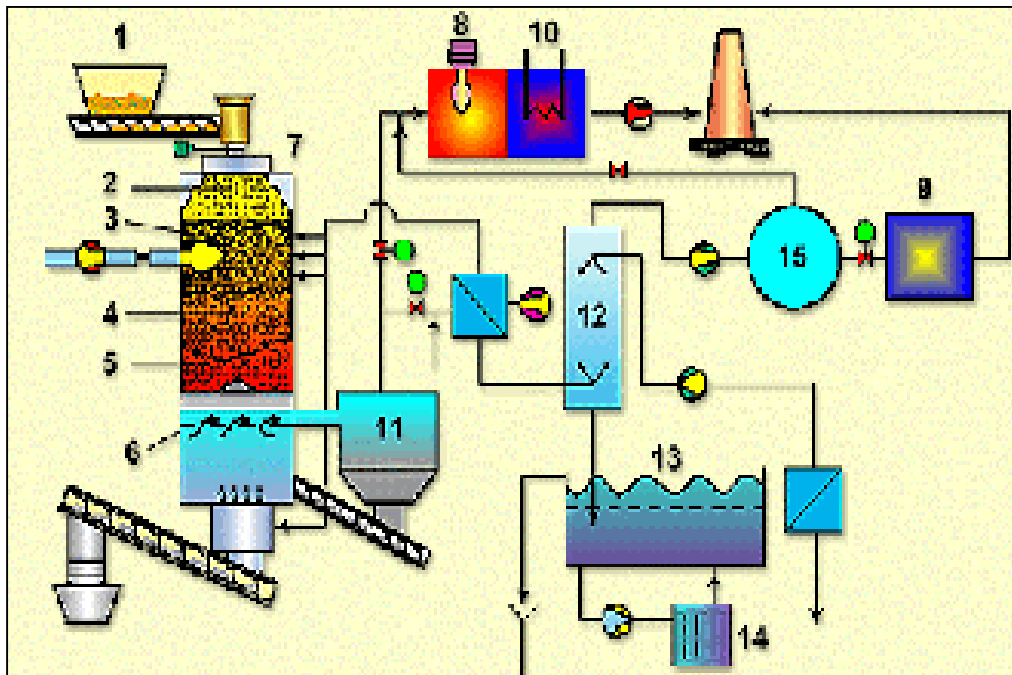
gas so that it can be used as reference when any gasifier are to be built on local community or society. So that they can be modelled based on simulation and can be evaluated in advance, as the result can be demonstrated from modelling using computational fluid dynamic software.

1.3 Biomass Gasifier

There are many types of gasifier's reactor that can be used to generate heat from the chemical process to get the gas for power generation. For example, the fixed bed reactor. This reactor is used with downdraft gasifier. Downdraft gasifier has four reaction zones which are drying, pyrolysis, oxidation, and reduction zone from top to bottom of the gasifier, respectively. This type of gasifier is operated when air is being drawn from biomass feedstock or hopper at the bottom of the gasifier to the drying zone.

In the *drying zone*, biomass fuel descends into the gasifier and moisture is removed using heat generated in the zones below by evaporating. After that, the next zone is *pyrolysis*. In this zone irreversible thermal degradation of dried biomass fuel descended from the drying zone takes place using the thermal energy released by the partial oxidation of the pyrolysis products.

In *oxidation zone*, the volatile products of pyrolysis are partially oxidised in the exothermic reactions resulting in a rapid rise of temperature up to 1200°C in the throat region. The heat generated is used to drive the gasification reactions. In the *reduction zone* often refer as gasification zone, the char is converted to the producer gas by reaction with the hot gases from upper zones. The gases are reduced to form a greater proportion of H₂, CO, CH₄. While leaving the gasifier at the temperature between 200 and 300°C, the produced gases carry over some dust, pyrolytics products (tar), and water vapour.



Picture 1.1 Fixed bed gasification reactor.

- | | |
|---------------------------------|--------------------|
| 1. Wood feeding | 9. Gas engine |
| 2. Supply zone-Drying zone | 10. Furnace |
| 3. Pyrolysis zone | 11. Dust separator |
| 4. Gasification zone | 12. Wet scrubber |
| 5. Cracking zone | 13. Settler |
| 6. Fluid bed after gasification | 14. Water filter |
| 7. Gasifier | 15. Gas tank |
| 8. Cyclone burner | |

The picture above shows an example of gasification system that using fixed bed reactor type that is finally connected to gas tank for next technology such as production of electricity or heat.

In a downdraft gasifier, the fuel and the producer gas flow downwards through the reactor enabling the pyrolysis gases to pass through a throated hot bed of char which is around 1100°C. Thus it will crack most of the tars into light chain hydrocarbon and water vapours. In addition, the air or oxygen is usually admitted to the fuel bed through intake nozzles from throat causing pyrolysis to charcoal and

volatile that partially burn as they are produced. The gaseous products of this ‘flaming pyrolytic combustion’ then consume the charcoal, produced during the pyrolysis and are converted into combustible gases⁵ (Dogru et al, 2002).

1.4 Overview of project topic

Nowadays, lots of computational fluid dynamics (CFD) simulations were conducted to study the effects of moisture in biomass, particle injection location, the burnout of different biomass particle sizes and many others characteristics of the biomass so that the prediction of the biomass combustion can be made.

This dissertation is useful for future in designing gasifier. A study of fluid flow inside the gasifier using computational software is done because experiences with computer simulation are quite insufficient and furthermore the know-how in this field is almost blank. Most of previous studies are done for coal as for fuel. Definitely coal gasifier and biomass gasifier are different things as coal char in gasification reactivity is significantly different from biomass reactivity.

Most manufacturers of gasifier of the actual size are small or medium sized enterprises with very small resources for the development of new products, up till now mainly been based on trial and error methods. But existing software is now so powerful that they can be useful tools in the development of new and environmentally friendly combustors.

This study which is based on experimental study, the gasifier is modelled using computational fluid dynamic software, FLUENT 5.5[®] and the results are compared with computational simulations.

⁵ Dogru, M et al. (2002), Fuel Processing Technology, *Gasification of sewage sludge using throated downdraft gasifier and uncertainty analysis*, Vol. 75, pp. 55-82.

1.5 Concise project definition: motivation for current work

Product gas from biomass gasification can be used in many applications such as in industrial or residential area. Most of this energy production application are decentralised and coupled with gas turbine or engine and also boiler. A solid fuel fired for gas turbine combustor should have a high intensity and produce complete carbon utilisation. Besides that it should maintain fine fly ash particle size and also have low pressure drop and good turndown.

The technologies for primary conversion of biomass for electricity combustion involve these processes which are direct combustion, gasification and pyrolysis. In direct combustion, the oxidation of biomass takes place with excess air. It will produce hot flue gases which are used to produce steam in the heat exchange sections of boilers. The steams produce from the combustion is used to produce electricity in a Rankine Cycle. Normally, only electricity is produced in a condensing steam cycle while electricity and steam are co generated in an extracting steam cycle.

As for gasification cycles, biomass is partially oxidised by stoichiometric amounts of oxygen normally with the present of steam. Then it will provide energy for thermal conversion of the remaining biomass to gases and organic vapours. For power production, the cleaned gasification product gases will be led directly to a boiler or the combustion section of an industrial or turbine.

As for pyrolysis, it uses indirect heat to convert solid organic materials, into gases and liquids. Conversion is carried out in a reaction chamber where air (oxygen) is excluded. The material within the reaction chamber is heated to temperatures of between 400 - 800°C usually by combusting a portion of the gaseous or liquid products. The resultant products of the pyrolysis process always include gas, liquid and solid char. Operating conditions and reactor design can be selected to control the relative proportions produced from the process.

According to Richard et al (1996) in indirect gasification cycles external heat source is used instead of oxygen, that provides the energy for high-temperature steam gasification of the organic fraction of biomass to vapours and gases⁶. Therefore, temperature is very important as the sources of the combustion engine from the product gas.

⁶ Richard, L.B. (1996), Biomass-Fired Power Generation in *National Renewable Energy Laboratory Conference*, New York: Engineering Foundation.

1.6 Aim and objectives of the study

The research objective of this study is to develop a 2-Dimensional Gasifier Model for Biomass Gasification using FLUENT 5.5[®] Computational Fluid Dynamics. The overall aim is to study the validity of two types of wood gasifier and the different profile between pressurised gasifier and non-pressurised gasifier.

The numerical simulation model presented in this study is aimed at direct combustion in biomass gasifier. This gasifier offers a number of characteristics when such as intense burning, enhanced heat transfer, capability of improving pressure and in addition, some potential for improvements to effectiveness and efficiency especially in gas turbine for power production.

Using the CFD commercial software, FLUENT 5.5[®], the study will continue to seek to understand the combustion mechanism of biomass fuel particularly woodchips in gasifier and then use this at larger scale to advantage for devices where fast accurate hot gas stream are needed in industrial and home appliances. In particular, to seek the fluid dynamics of the flow which is heavily dependent on the outlet channel characteristics.

In the simulation part of the project, a model of downdraft gasifier consistent with main observed phenomena is proposed. To adapt the model for numerical analysis, two methods are presented. In the first method, as a preliminary approach, the combustion process of laminar and steady state of partly hot-wall in the gasifier is simulated. In the second method, the same geometry but different boundary conditions for pressurised gasifier, of laminar and steady state combustion process is simulated and analysed.

Some results obtained from both numerical methods are compared with the experimental work carried out by M. Dogru et al (2002) and D.J. Purnomo (1990). On this basis, the validity of proposed model is being discussed.

Chapter 2 – Theory and Literature Review

2.1 Introduction

In this chapter, basic theory on biomass gasifier is explained and approaches that have been used previously on gasifier are also discussed.

2.2 Theory of biomass gasification

2.2.1 Concept of gasification & pyrolysis

The history of gasification begins long time ago during Second World War where people used gasifiers to operate cars, trucks, boats, trains and electricity generators in Europe. It was approximately about one million of gasifier were employed but recent technology performed better designs of this gasifier.

Pioneering work on coal fired downdraft furnaces was done in the late 1940's. After that, downdraft combustion of wood-chips has been investigated by Aerts & Ragland (1989) and then biomass gasifier has been reviewed by Reed & Das (1988)⁷. According to Xiu et al (2002) since 1960's there has been extensive development and deployment of fixed bed gasifier generator set which have grown in size from 60 to 200 kWe output⁸.

Basically for biomass gasifier, the processes involved are gasification and pyrolysis processes. Gasification is a partial oxidation process in which organic materials in biomass are converted to a mixture of gas phase, energetic compounds, such as carbon monoxide, hydrogen and methane. Carbon is rejected to form char which is oxidised within the process to produce additional gases, an ash residue and the heat energy necessary to drive the reactions. It is achieved by thermally degrading organic materials in the absence of adequate air to support full combustion⁹. (Heermann et al, 2000).

Apart from that, pyrolysis is another process that occurs in the absence of oxygen. It is a thermal degradation of carbonaceous materials at temperature between 400 and 800°C either in the complete absence of oxygen, or with such a limited

⁷ Purnomo, D.J.A & Ragland, K.W. (1990), Twenty-Third Symposium (International) on Combustion, *Pressurised combustion of woodchips*, pp 1025-1032.

⁸ Xiu, L.Y. et al (2002), *Biomass & Bioenergy*, Design and operation of CFB gasification and power generation system for rice husk, Vol. 23, pp 181-187.

⁹Heermann, C et al. (2000) *Pyrolysis & Gasification of Waste*. 2nd ed. Juniper Consultancy Services Ltd.

supply that gasification does not occur to any appreciable extent. Such processes devolatilise and decompose solid organic materials by heat; consequently, no combustion is possible.

Pyrolysis mechanisms typically include a superposition of kinetic mechanism for the individual component of the biomass material. The validity and the development of these mechanisms were being investigated¹⁰ by Miller and Bellan (1997). This is because a reliable description of the global kinetics biomass pyrolysis is very significant in the developing of biomass thermo chemical conversion systems that used high temperature chemistry.

These accurate chemical models of biomass gasification and combustion can be used as input in systems analysis models to adjust engineering parameters such as gas velocities, particles residence times, and heat transfer rates to optimise the design and performance of developing technologies.

Purnomo and Ragland (1990) have done a study on pressurised downdraft combustion of woodchips¹¹ by experimental approaches. They used 2 cm of yellow poplar chips. They found that pressure drop was about 10% in the gasifier bed and they found that good agreement between numerical and experimental result at 1-5 atm of the pressure. Therefore these ranges of data were inserted during simulation setting in order to validate the result.

¹⁰ Miller, R.S & Bellan, J. (1997), *Combustion Science Technology, A generalised biomass pyrolysis model based on superimposed cellulose, hemicellulose and lignin kinetics*, No. 126, pp 97-137.

¹¹ Purnomo, D.J.A & Ragland, K.W. (1990), *Twenty-Third Symposium (International) on Combustion, Pressurised combustion of woodchips*, pp 1025-1032.

2.2.2 Gasification Equation

Biomass is composed of carbon, hydrogen and oxygen, and also nitrogen and sulphur (refer Table 2.2). Carbon dioxide is obtained from complete combustion of carbon, and water is obtained from hydrogen. As for oxygen, it is incorporate into combustion products. In the combustion zone of the gasifier, heat is generated to drive the gasification reactions as can be illustrated from the equation below.

Wood is burnt from direct combustion with insignificantly amount of oxygen inside the gasifier. By the conservation of mass, the mass flow remains constant which means total mass of products equals total mass of reactants. This reactant are chemically different the product and the products leave at a higher temperature¹².



Equation 1 and 2 are the main reactions on the reduction stage and require heat. Equation 3 is called water-gas equilibrium reaction. Changes in temperature will drive the equilibrium in either direction. It is by controlling this reaction that the product gases may be maintained at a constant. Equation 4 and 5 shows the production of methane gas.

¹² Eastop, T.D and McConkey, A. (1998) *Applied Thermodynamics for Engineering Technologist*, 5th ed, Addison Wesley Longman Limited.

2.3 Model

2.3.1 Characteristics of biomass gasifier

Gasification for power production involves the de-volatilisation of biomass in an atmosphere of steam or air or both to produce medium or low calorific value gas. The syngas which is useful for electricity generation from either turbine, or engine produced from pyrolysis, is usually a medium heating value (MHV) fuel gas around 14-18 MJ/Nm³ depending on the feed and processing conditions.

Table 2.1 shows different amount of energy produces from biomass fuel which gives high value of calorific for fuel with less moisture content. The MHV gas contains a high level of hydrocarbons including uncondensed pyrolysis liquids, and saturated and unsaturated hydrocarbons, particularly methane, produced by complex thermal degradation process.

By these calorific values in the table above, all types of biomass fuel are suitable for feeding to gasifier. Thus, woodchips may also be used in gasification systems to produce low calorific value combustible gas for clean energy production.

Biomass Fuel	Net calorific value in dry matter MJ/kg	Net calorific value as received MJ/kg
Sofwood bark	18.5-20	6-9
Birch bark	21-23	7-11
Wood residue chips	18.5-20	6-15
Saw residue chips	18.5-20	6-10
Sawdust	19-19.2	6-10
Cutter chips	19-19.2	13-16
Grinding dust	19-19.2	15-17
Pellets	19.2	16.8

Table 2.1: Energy produces from different types of biomass fuel¹³

But for this modelling, the effect of the absolute and bulk density, the size and shape of the particles, moisture content and chemical composition which is proximate and ultimate analysis and higher heating value play an important role in determining the fluid flow profile inside the gasifier. Thus, the wood residue chips are being selected as the availability of density data.

¹³ LIOR International LV. (2002), *Biomass Combustion Technology (7) Wood Lower Calorific Value* <http://www.lior-int.com/FORMULA/rp7.as>

2.3.2 Gas production from gasifier

The production of useful gas from the gasifier are then becoming awareness, as the green house gasses are releases to the environment. Coal is used as fuel in boilers as it is very plentiful and cheap but the resources are non-renewable energy. Studies showed that there are many issues related to the coal and biomass fuel co-firing. But biomass is more promising energy to the environment as it gives less impact to the environment.

Figure 2.2 shows the typical ultimate analyses of wood chips and straw compare with different types of coal. It shows that coal has more production of carbon dioxide because high content of carbon. As for biomass fuels it has significantly less content of sulphur thus no amount of sulphur gas releases (Robinson, 1998).

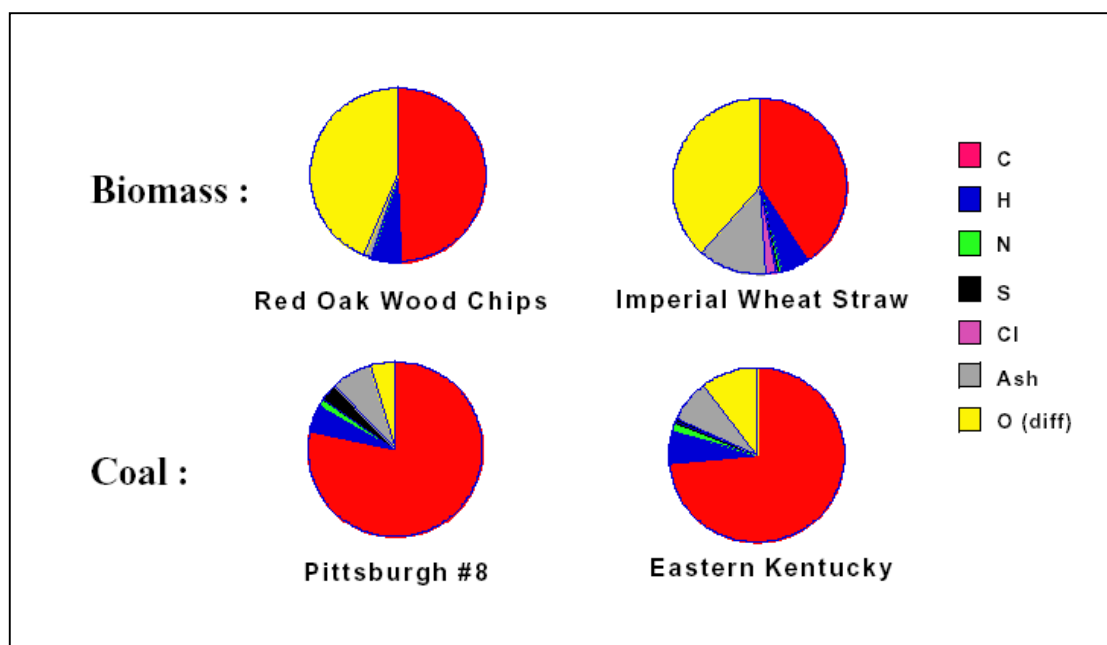


Figure 2.2: The ultimate analysis of biomass and coal fuels¹⁴

Wood offer advantages over fossil fuel with regards to gas emission where the sulphur content of wood is minimal, therefore sulphur dioxide emission are negligible. As for nitrogen, if temperature of the combustion is being controlled to avoid the oxidation of the nitrogen from the air, it will not affect the nitrogen dioxide emission because nitrogen in wood is not temperature dependence. So, the overall

¹⁴ Robinson, A et al. (1998) Fireside Issues Associated with Coal-Biomass Co-firing, in *Conference on BioEnergy '98*, United State: National Renewable Energy Laboratory

nitrogen dioxide will also be low¹⁵ (McIlveen et al, 2001). Here are examples of ultimate analyses of different types of biomass fuel. They have very low value of sulphur and also low carbon that are more favourable from coal.

Fuel	Carbon	Hydrogen	Nitrogen	Sulphur	Oxygen
Straw	0.45-0.494	0.06	0.004-0.066	0.0012	0.43-0.442
Wood without bark	0.47	0.063	0.0016	0.0002	0.46
Bark	0.47	0.054	0.004	0.0006	0.4
Wood with bark	0.47	0.06	0.003	0.0002	0.44
Oak wood	0.494	0.063			0.445
Pines wood	0.499	0.063			0.438
Triticale	0.434	0.063	0.0131	0.0022	0.4779
Miscanthus	0.46	0.06	0.007	0.002	0.44

Table 2.3: Ultimate analysis of biomass fuels (dry)

It is shown that in the table above, the composition of wood without bark has low carbon, nitrogen and sulphur which indicate low emission of these gases when combustion occur.

¹⁵ McIlveen, W. et al. (2001), Bioresource Technology, *A re-appraisal of wood-fired combustion*, Vol. 76, pp 183-190

2.4 Combustion reaction mechanisms

Nevertheless, the present computational fluid dynamic models are unable to solve such complex reaction mechanisms due to its complexity. Employing detailed reaction mechanisms in the CFD calculations will generate a numerically inflexible problem that it will be difficult to reach converged solution with the present of the solver in the CFD commercial software.

Brink et al (2001)¹⁶ created a model for biomass combustion using single-step mechanics and turbulence-chemistry interaction with eddy dissipation combustion model as the air distribution were injected around the bottom of the model. Therefore, the use of much simple or single-step reaction mechanisms is preferred rather than the global reaction mechanism.

In this model several number of simplifying assumptions has been employed for ease of the discussion. Theoretically, the combustible gas is expected to distribute uniformly throughout the space into the downdraft gasifier.

Several number of simplifying assumptions has been employed for ease of the discussion. The main assumptions of the model are as follow:

- Low Mach number for the combustion approximation
- Single-phase gaseous flow of ideal gas
- Neglect the electromagnetic radiation
- Simplified chemistry i.e. single step, Arrhenius
- Newtonian fluid flow; Fourier's and Fick's law for the diffusion heat and mass transfer

The assumption of the low Mach number implies that the ambient flow speeds are low that the heat release rate is not so strong i.e. no blast waves. The density variations are due to the differences of the density of the reaction species and the chemically reaction heat release rate. With the assumptions made, the mathematical model becomes as illustrated below:

¹⁶ Brink, A et al. (2001), IFRF Combustion Journal, Modelling Nitrogen Chemistry in the Freeboard of Biomass-FBC, pp 1-14.

- Conservation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} \rho v_i = 0 \quad (2.3)$$

- Conservation of momentum

$$\frac{\partial}{\partial t} \rho v_i + \frac{\partial}{\partial x_i} \rho v_i v_j = -\frac{\partial p_i}{\partial x_i} + \frac{1}{\text{Re}} \frac{\partial}{\partial x_j} \tau_{ij} \quad (2.4)$$

- Conservation of energy

$$\frac{\partial}{\partial t} \rho h + \frac{\partial}{\partial x_k} \rho h v_k = \frac{\partial}{\partial x_k} \left[\frac{\mu}{\sigma} \frac{\partial h}{\partial x_k} + \mu \sum_{\alpha=1}^N \left(\frac{1}{Sc_\alpha} - \frac{1}{\sigma} \right) h_\alpha \frac{\partial Y_\alpha}{\partial x_k} \right] \quad (2.5)$$

- Conservation of state

$$p_0 = \frac{\rho R_0 T}{W} = \rho R_0 T \sum_{\alpha=1}^N \frac{Y_\alpha}{W_\alpha} = \text{uniform in space} \quad (2.6)$$

- Conservation of species

$$\frac{\partial}{\partial t} \rho Y_\alpha + \frac{\partial}{\partial x_k} \rho Y_\alpha v_k = \dot{\omega}_\alpha + \frac{\partial}{\partial x_k} \left(\rho D_\alpha \frac{\partial}{\partial x_k} \right) \quad (2.7)$$

2.5 Theoretical considerations on CFD

The CFD codes are arranged by the numerical algorithm accordingly, so that the fluid flow problem can be tackled. There are three main elements of CFD codes in the CFD packages which consist of *pre-processor*, *solver* and *post-processor*¹⁷.

2.5.1 Pre-processor

The pre-processor contains all the fluid flow inputs for a flow problem. It can be seen as a user-friendly interface and a conversion of all the input into the solver in CFD program. In this stage, quite a lot of activities are carried out before the problem is being solved. These stages are listed as below:

1. *Definition of the geometry*
 - The region of interests which is the computational domain.
2. *Grid generation*
 - The subdivision of the domain into a number of smaller and non-overlapping domains. The grid mesh of cells is carried out for the geometry.
3. *Selection of the physical and chemical properties*
 - The geometry to be modelled.
4. *Definition of the fluid properties*
5. *Specifications of correct boundary conditions*
 - This is done at model's cells.

The solution of the flow problem such as temperature, velocity, pressure etc. is defined at the nodes insides each cell. The accuracy of the CFD solution governed by the number of cells in the grid and is dependent on the fineness of the grid.

¹⁷ Anderson, J. D (1995), Computational Fluid Dynamics, *The Basic With Application*, International Editions, McGraw-Hill

2.5.2 Solver

In the numerical solution technique, there are three different streams that form the basis of the solver. There are *finite differences*, *finite element* and *finite volume methods*. The differences between them are the way in which the flow variables are approximated and the discretization processes are done.

1. *Finite difference element, FDM*

- Describes the unknown flow variables of the flow problem by means of point samples at node points of a grid coordinate. By FDM, the Taylor's expansion is usually used to generate finite differences approximation.

2. *Finite element method, FEM*

- Use the simple piecewise functions valid on elements to describe the local variations of unknown flow variables. Governing equation is precisely satisfied by the exact solution of flow variables. In FEM, residuals are used to measure the errors.

3. *Finite volume method, FVM*

- It was originally developed as a special finite difference formulation. The main computational commercial CFD codes packages using the FVM approaches involves PHOENICS, FLUENT, FLOW 3D and STAR-CD. Basically, the numerical algorithm in these CFD commercial packages involved the formal integration of the governing equation over all the finite control volume, the discretization process involves the substitution of variety FDM types to approximate the integration equation of the flow problem and the solution is obtained by iterative method.

Discretization in the solver involves the approaches to solve the numerical integration of the flow problem. Usually, two different approaches have been used and once at a time.

1. *Explicit approach*

- Usually, this is the most approach that makes sense. It is relatively simple to set up and program. The limitation is that for a given Δt and Δx , must be

less than some limit imposed by stability constraints. In some cases, Δt must be very small to maintain the stability and consequently long running time required for the calculation over a given time interval, t .

2. *Implicit approach*

- For this approach, the stability can be maintained over a large value of Δt and fewer time steps required making calculation. Thus resulting less computer time. Adversely, it is complicated to set up and program. The computer time per time step is much larger than the explicit approach due to the matrix manipulation which is required for each time step. This approach is very accurate to follow the exact transients i.e. the time variations of the independent variables.

2.5.3 Post-processor

A FLUENT package provides the data visualisation tools to visualise the flow problem. This includes – vectors plots, domain geometry and grid display, line and shaded counter plots, particle tracking etc. Recent facilities aided with animation for dynamic result display and also have data export facilities for further manipulation external to the code.

2.6 Problem solving

In the computational fluid dynamic, using the FLUENT codes provide to solve the problem numerically. The fundamental involves determining the convergence, whether the solution is consistent and stable for all range of flow variables.

- *Convergence* – is a property of a numerical method to produce a solution that approaches the exact solution of which the grid spacing, control volume size is reduced to a specific value or to zero value
- *Consistent* – to produce the system of algebraic equations which can be equivalent to the original governing equation
- *Stability* – associates with the damping of errors as a numerical method proceeds. If a technique chosen is not stable, even the round-off error in the initial data can leads to wild oscillations or divergence.

Chapter 3 – Methodology

3.1 Introduction

In this chapter, the main methodology focuses on how to solve the problem using different type of biomass gasifier which are pressurised and atmospheric condition are discussed.

3.2 Gasifier modelling using CFD software

3.2.1 FLUENT 5.5[®]

FLUENT 5.5[®] have been chosen to carry out the simulation for the numerical simulations. This software has the capability on predicting the fluid flow, heat and mass transfer, chemical reaction, and related phenomena. This software help engineers with detailed product development, design optimisation, trouble shooting, scale-up and retrofitting that can help in reduces engineering cost, while improving the final design of products in many applications, and one of them is combustion system design¹⁸.

3.2.1.1 Pre-processing

In the first part of numerical simulations, the 2-dimensional geometry of the pilot biomass gasifier¹⁹ and the flow region were created using GAMBIT[®]. 2-dimensional model has been created because it is easier to model the simulation comparable to 3-dimensional in terms of computer processor's time consuming when running the simulation. Thus, in the setting model, the downdraft gasifier was examined using *2-D geometry* as the *asymmetric geometry* tends to be diverged when it was iterated.

Meshing is very important in order to get the solution with high quality results. Before meshing was done to the model, the model was drawn using unit scale in GAMBIT[®] and then it was specified or can be modified in metric scale when the meshing file was exported to the FLUENT 5.5[®]. There are different types of meshing

¹⁸ Whalen, P.(2000) *Fluent Inc. Releases Version 5.5 of Its FLUENT Software*, <http://www.fluent.com/about/news/pr/pr17.htm>

¹⁹ Dogru, M. and et al (2002) *The International Journal, Gasification of hazelnut shells in a downdraft gasifier* Vol. 27 pp 415-427.

scheme elements in this software. As for 2-D model the option is *quadrilateral* and for 3-D *hexahedron* can be used. Boundary zones were created for examples inlet, outlet, nozzle, throat, hot wall and axis This model finally exported to FLUENT 5.5[®] after the setting were specified to *2-D, axisymmetric geometry and quadrilateral meshing* although these give few cells, high quality results can be obtained.

3.2.1.2 Solver

Solver is very important in solving the flow problem. FLUENT 5.5[®] have many solvers and *segregated (implicit)* has been used to solve the direct combustion process in gasifier. This is because it can solve both compressible and incompressible flow problems. Besides that it can be used to solve the unsteady flows.

3.2.1.3 Post-processing

Post-processing is very significant in visualisation tool. Most flow properties such as pressure, temperature, species concentration and density for the combustion reaction can be displayed and analysed after simulation. Boundary conditions, meshing and physical parameters are criterions that have to be revised if the solution is not converging. The convergent solution is not essentially compulsory, but it is inevitable since the most accurate solution is needed for post-processing. Grid adaptive can be done in order to give more accuracy to the solution.

3.3 Model Setting

3.3.1 Dimension

The model's setting in GAMBIT and FLUENT are discussed.

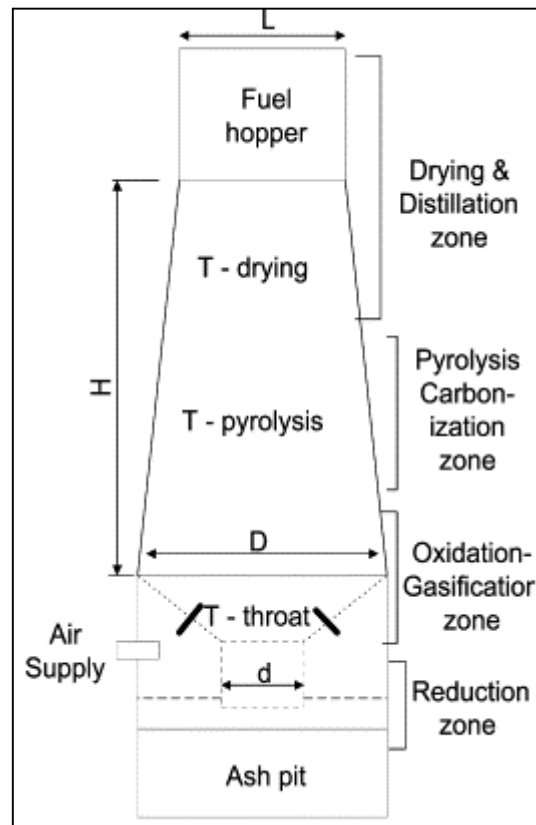


Figure 3.1: Schematic diagram of downdraft gasifier

Based on this typical diagram from pilot biomass gasifier that has been carried out by Dogru et al. (2002), the model was drawn in GAMBIT software and then imported to FLUENT code for further analysis. The model dimensions as shown below:

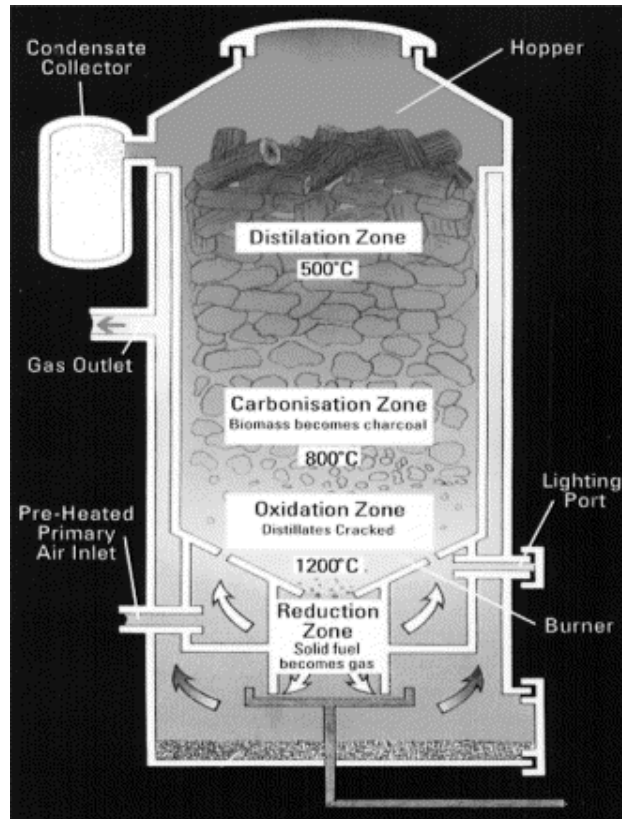
- Height, H = 810 mm
- Diameter, D = 450 mm
- Throat diameter, d = 135 mm
- Fuel hopper, L = 305 mm

The boundary condition for each segments in the gasifier are specified in FLUENT. FLUENT has a wide range of boundary conditions that permit flow to enter and exit the solution domain. FLUENT provides 10 types of boundary cell types for the specification of flow inlets and exits: velocity inlet, pressure inlet, mass flow inlet, pressure outlet, pressure far-field, outflow, inlet vent, intake fan, outlet vent, and exhaust fan. The inlet and exit boundary condition options in FLUENT that were used in this 2-dimensional model are as follows:

- *Velocity inlet* boundary conditions are used to define the velocity and scalar properties of the flow at inlet boundaries.
- *Pressure inlet* boundary conditions are used to define the total pressure and other scalar quantities at flow inlets.
- *Mass flow* inlet boundary conditions are used in compressible flows to prescribe a mass flow rate at an inlet. It is not necessary to use mass flow inlets in incompressible flows because when density is constant, velocity inlet boundary conditions will fix the mass flow.
- *Pressure outlet* boundary conditions are used to define the static pressure at flow outlets (and also other scalar variables, in case of backflow). The use of a pressure outlet boundary condition instead of an outflow condition often results in a better rate of convergence when backflow occurs during iteration.

3.3.1.1 Downdraft gasifier

For atmospheric downdraft gasifier, the first settings for temperature are as below



	<u>Expected temperature</u> °C		<u>Model set-up</u> °C
• Distillation zone	500	Fuel hopper	373
• Carbonisation zone	800	Hot-wall	800
• Oxidation zone	1200	Nozzle	737
• Reduction zone	300	Throat (outlet)	373

<u>Model</u>	<u>Settings</u>
➤ Space	2D
➤ Time	Steady
➤ Viscous	Laminar
➤ Heat Transfer	Enabled
➤ Melting-Freezing	Disabled
➤ Radiation	None

- Species Transport Reacting (6 species)
- Coupled Dispersed Phase Disabled
- Pollutants Disabled
- Soot Disabled

After that each zone are classified as below for boundary condition:

□ Zones

<u>Name</u>	<u>id</u>	<u>Type</u>
Fluid	1	fluid
Centre	2	symmetry
Outlet	3	pressure-outlet
Throat	4	wall
Nozzle	5	velocity-inlet
Outer-wall	6	wall
Fuel-hopper	7	wall
Default-interior	9	interior

□ Relaxation

<u>Variable</u>	<u>Relaxation Factor</u>
Pressure	0.1
Momentum	0.1
Energy	0.89999998
Wood volatile	1
O ₂	1
CO	1
H ₂ O	1
N ₂	1
Density	1
Body Forces	1

□ Discretization Scheme

<u>Variable</u>	<u>Scheme</u>
Pressure	Standard
Momentum	First Order Upwind
Pressure-Velocity Coupling	SIMPLE
Energy	First Order Upwind

wood_vol	First Order Upwind
O ₂	First Order Upwind
CO ₂	First Order Upwind
H ₂ O	First Order Upwind
N ₂	First Order Upwind

□ Material: wood (solid)

<u>Property</u>	<u>Units</u>	<u>Method</u>	<u>Value(s)</u>
Density	kg/m ³	constant	700
Cp (Specific Heat)	j/kg-k	constant	2310
Thermal Conductivity	w/m-k	constant	0.17299999

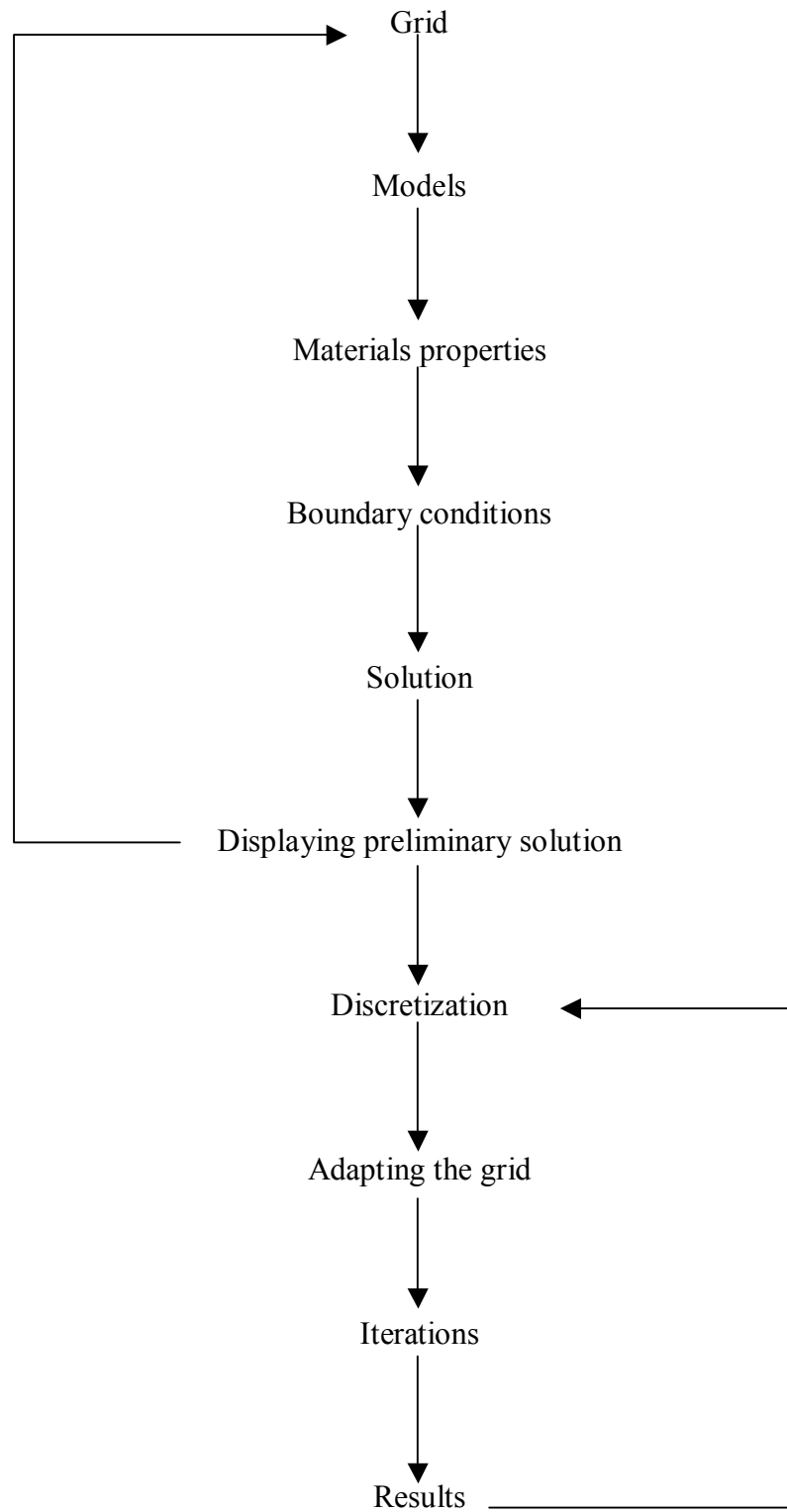
3.3.1.2 Pressurised Downdraft gasifier

<u>Expected</u>					
	<u>Temperature, °C</u>	<u>Model set-up, °C</u>		<u>Pressure, MPa</u>	
•	Distillation zone	500	Fuel hopper (inlet)	373	5.0
•	Carbonisation zone	800	Hot-wall	800	-
•	Oxidation zone	1200	Nozzle	737	-
•	Reduction zone	300	Throat (outlet)	373	-

The pressure is set to be 5.0 MPa at the fuel hopper. Here, the boundary condition is changed to *pressure inlet* instead of *wall* in atmospheric downdraft gasifier.

3.4 Modelling Procedure

The diagram below illustrates the simplified procedures for the overall process in the modelling and simulation.



(Examples: *xy Plots* & *Contour Plots* for temperature & pressure)

Chapter 4 – Result Analysis & Discussion

4.1 Introduction

In this chapter, the results are discussed and analysed between those two types of gasifier; pressurised and atmospheric gasifier.

4.2 Model Description

The downdraft gasifier operates by heating the woodchips to around 830°C (1526°F) using burner/torches that are connected at both side of cylinder. The woodchips are heated in the reactor using air as the gasifying medium to produce a syngas which contains varying amount of H₂, CO, CH₄, CO₂ and N₂. The outer wall also are being applied a heat until the wood breaks, decomposes and gives off gas which can be used as a fuel which is can be used in gas turbine. As for ignition purposes and electricity generation, the syngas is cleaned and cooled prior to injection into a spark ignition gas engine which is also fed with diesel support fuel.

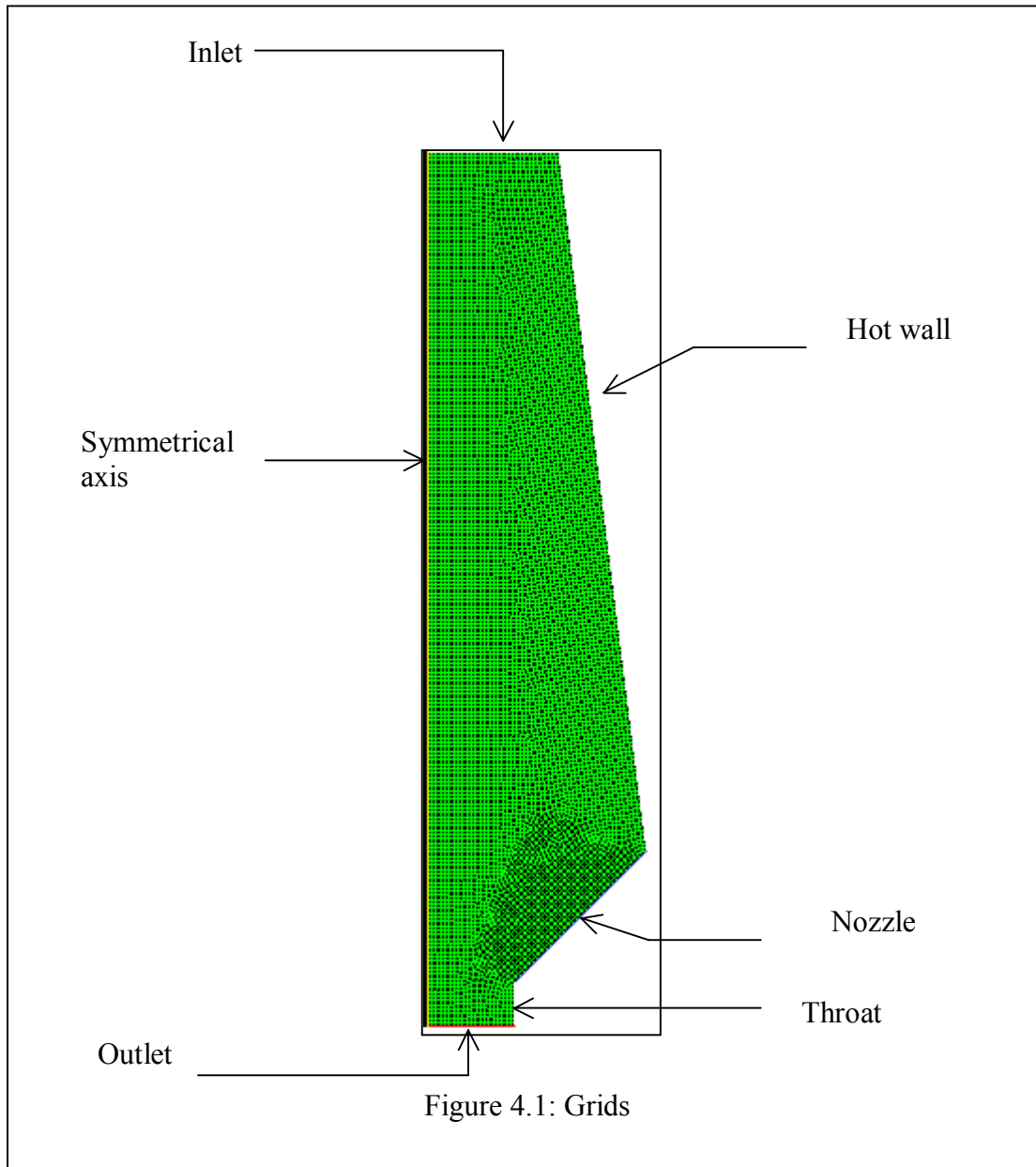
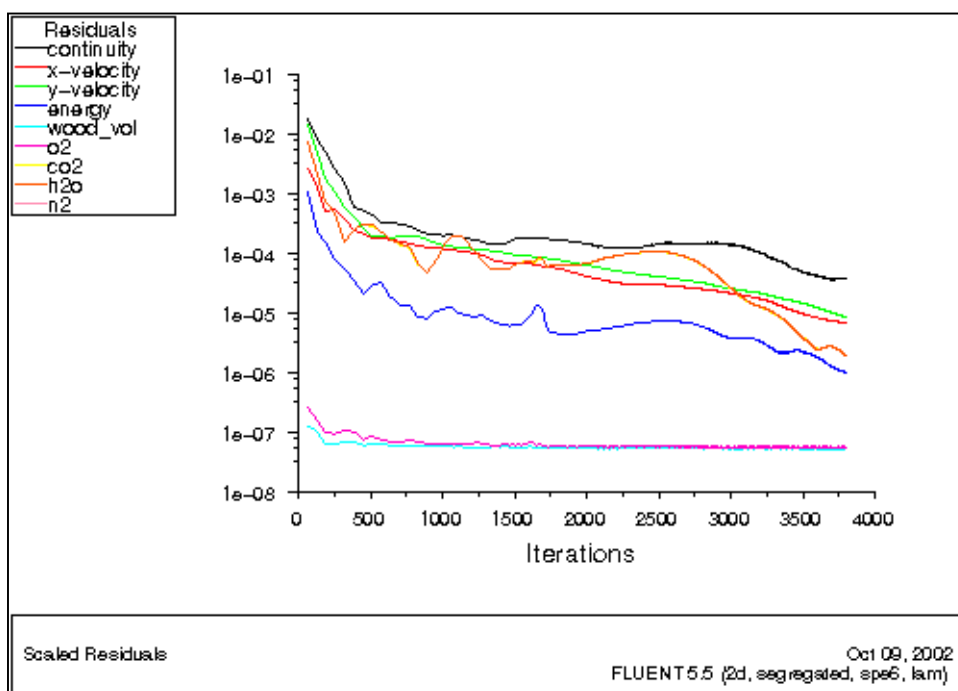


Figure 4.1 shows the grids of biomass gasifier that was modelled in GAMBIT. Only half of the gasifier was modelled due to the symmetrical geometry. Woodchips are fed from the inlet and heat is applied through the hot wall and also from the nozzle. The pressure and temperature of the gasifier are determined using the simulation and compared with the result from experimental. The results are discussed in the following topics.

4.3 Result Analysis from downdraft gasifier

4.3.1 First-order Discretization.

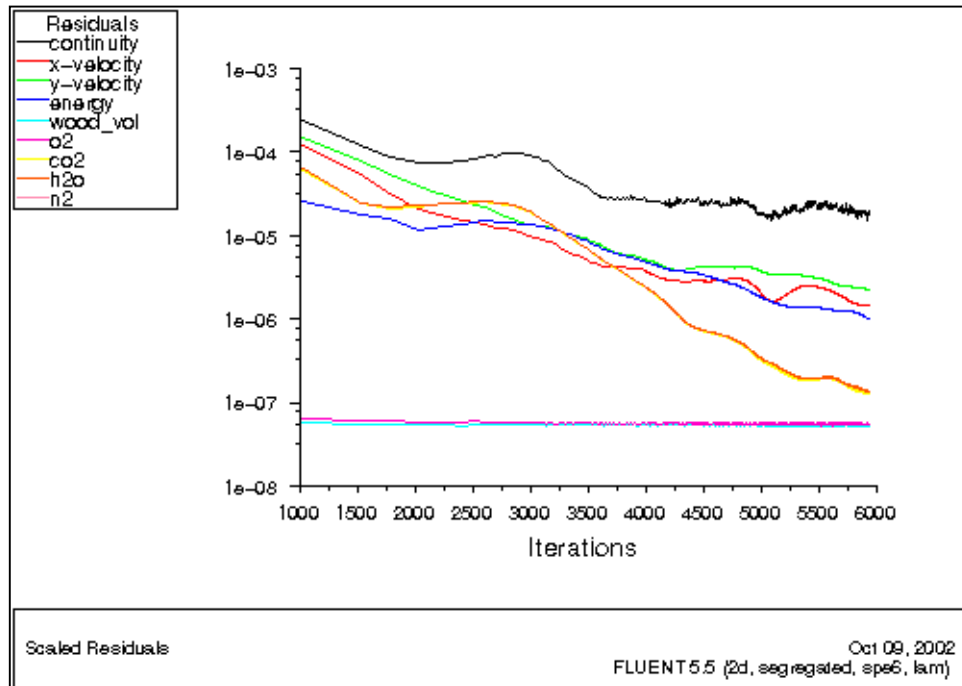
In order to get the solution convergent, the setting of the model in FLUENT has to be started from the First-order Discretization. Under-Relaxation Factors, Energy is set to be 0.9. Simulation was run until around 4000 iterations to get the convergent solution. The graph shows that the solution was not so smooth. There were sinusoidal shapes in some lines of the solution. Therefore the setting was changed to Second-order Discretization. The graph can be compared between both of the settings.



Graph 4.1: Under-Relaxation Factors, Energy is set to be 0.9.

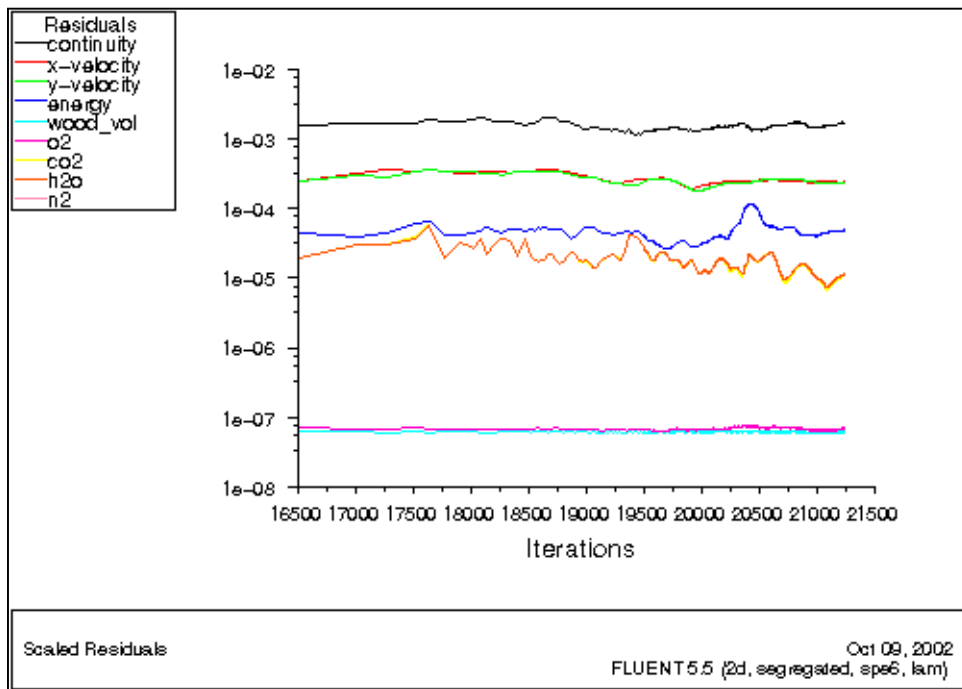
4.3.2 Second-order Discretization

Second-order Discretization is used in order to improve the accuracy of the solution. With Second-order Discretization, less aggressive (lower) values for energy under-relaxation to ensure convergence was setting up. Thus, the energy was reduced and was set up to 0.6. After 5500 iterations, the solution was convergent as show in Graph 4.2; the line is smoother compare to the First-order Discretization.



Graph 4.2: Under-Relaxation Factors, Energy is set to be 0.6.

The simulation was continued with the changed in momentum setting. The setting for momentum can be set to be small index number as well. The momentum is set to 0.6 and the solution was not converged. But for previous setting, the solution was convergent as it was set to be 0.9. From the graph, it shows that the line is continuously running until 25000 iterations.



Graph 4.3: Under-Relaxation Factors, Energy and Momentum are set to 0.6.

The gasifier solution can be improved further by refining the grid to be better resolving the flow details. In this step, the adaptation of the grid based on the temperature gradient in the current solution was used. The range of temperature gradients over which to adapt was determined before refining the grid. The small value was taken which was in the range between 0.02 to 0.01°C.

The contours will display the cell values of temperature instead of the smooth looking node values. Here, the regions to adapt are significant to display in cell by cell.

Comparison of the filled temperature contours for the first solution (using the original grid and First-order Discretization) and the last solution (using an adapted grid and Second-order Discretization) clearly indicate that the latter is much less diffusive.

While the First-order Discretization is the default schema in FLUENT, it is good to use first-order solution as a starting guess for a calculation that uses a higher-order discretization scheme and, optionally, an adapted grid. In order to get more efficient solution, to *flow-field* has to be compute first without solving the *energy* solution and then solve the *energy* without solving the *flow-field* equations.

4.4 Downdraft gasifier contour results

4.4.1 Profile for first-order discretization.

The temperature and pressure history of a particle in the downdraft gasifier was the primary focus of a detailed characterisation study as this relationship in theory could exclusively determine the extent to which the solid material reacts. Particle temperature is influenced by radiative and convective transport, internal conduction, chemical reaction and also most of it by hot wall impact.

Particle residence times are a function of the local gas flow rate and on the path the particle takes inside the reactor which depends on particle density, gravity, size, heat capacity and to some degree on particle starting location.

A simple model is not sufficient to capture the complexity of these problems. CFD simulations were employed to model many of these complex processes as the geometry and input condition can be accurately measured. This is because the model boundary conditions are based measured quantities.

From the contour, the high molecular weight biomass pyrolysis vapours were found to undergo thermal reactions at fairly moderate temperatures.

4.4.1.1 Temperature and pressure contour

1. Filled contour of temperature

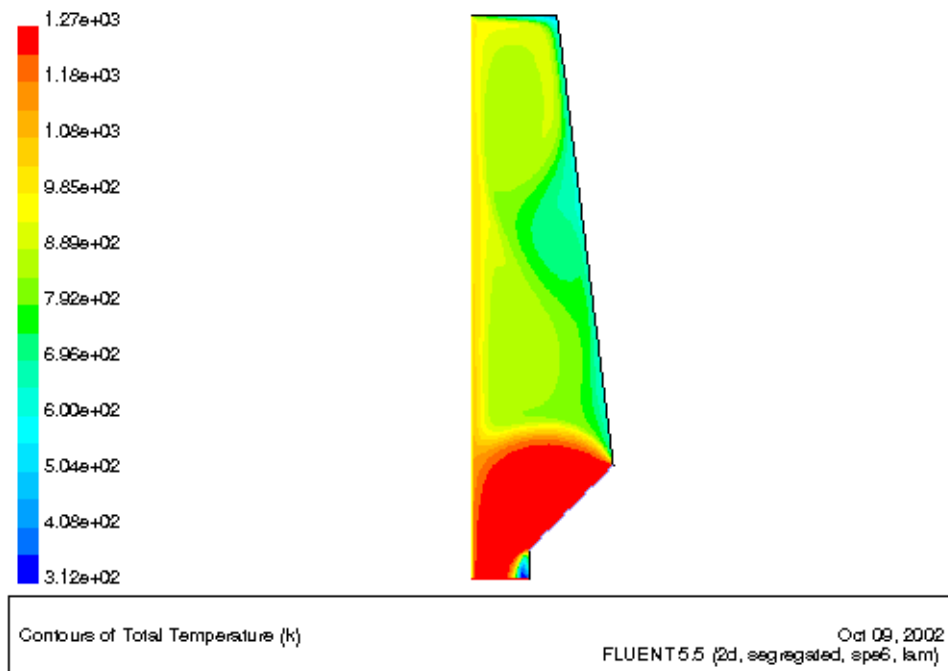


Figure 4.2: Predicted total temperature after the Initial Calculation

According to the result from the simulation, the total temperature are mostly high around the throat and nozzle. The temperature is higher at these areas because it is affected by the burner/torches that is place at the wall near the throat. Furthermore, these areas are oxidation zone and reduction zone where all the woodchips are burnt.

2. Filled contour of static pressure

From the contour of static pressure, there is not much different from predicted total pressure. The pressure distributions are roughly the same. (Refer Figure 4.3 and Figure 4.4)

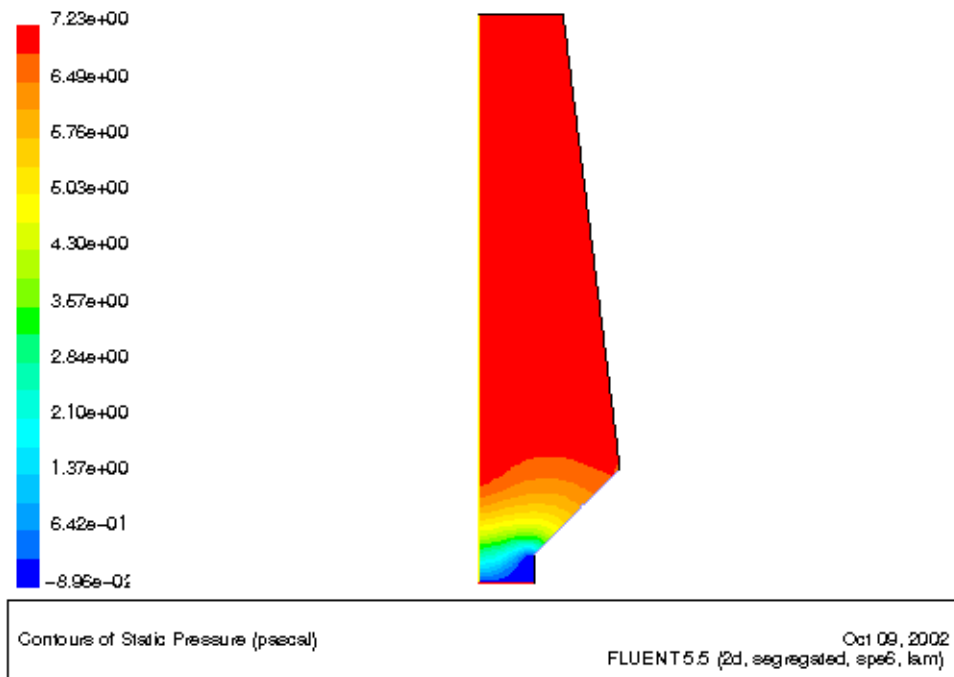


Figure 4.3: Predicted Static Pressure Distribution after the Initial Calculation

3. Filled contour of total pressure

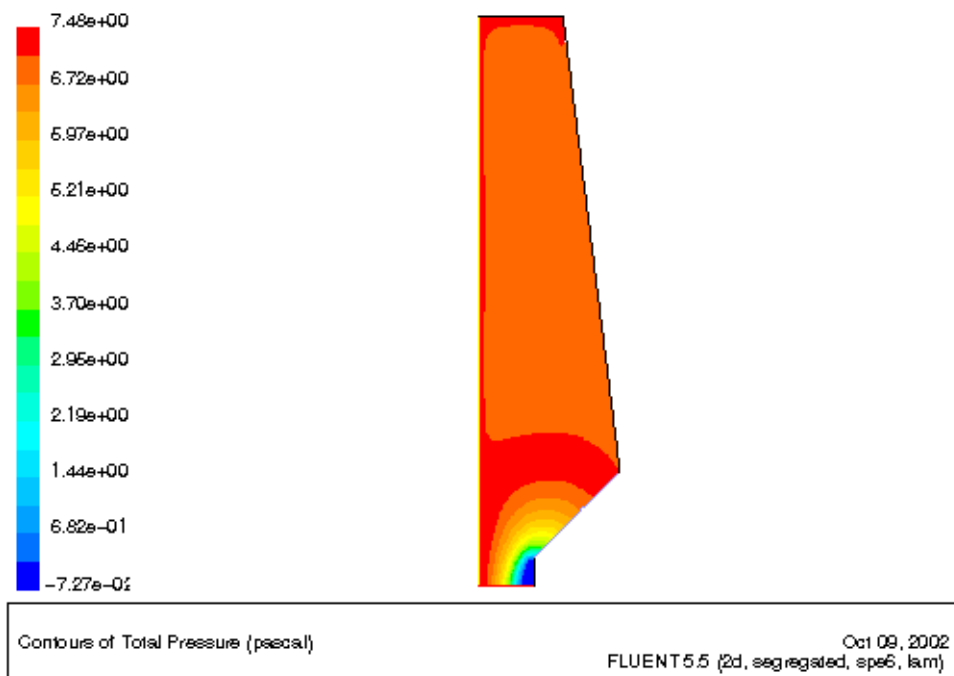
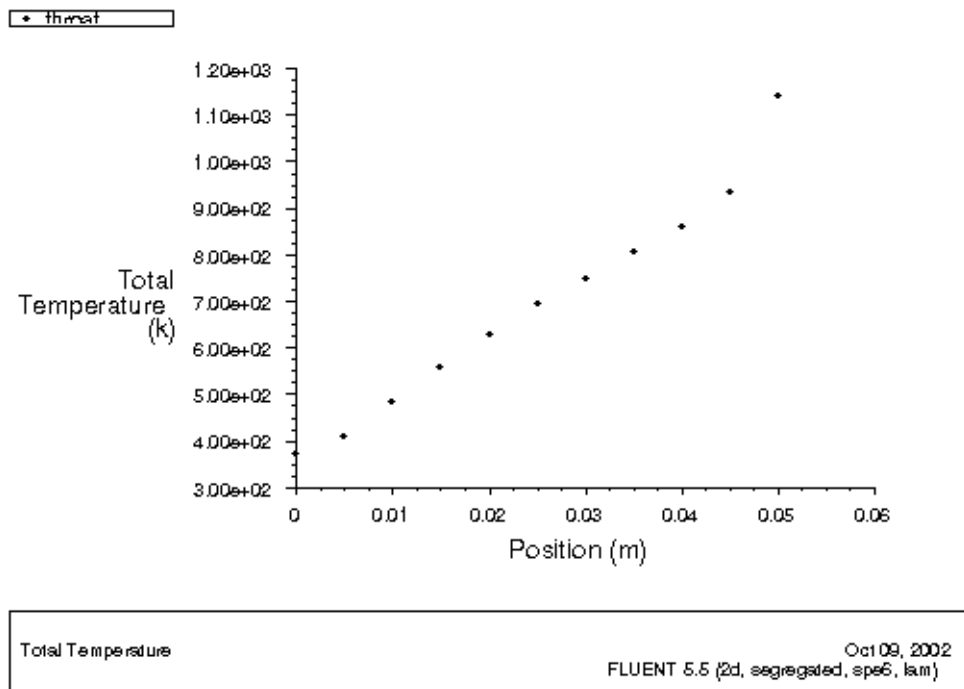


Figure 4.4: Predicted Total Pressure Distribution after the Initial Calculation

4.4.1.2 Temperature and pressure distribution



Graph 4.4: Total Temperature Distribution at the Throat

The graph above showed the total temperature inside the gasifier to the distance of the gasifier along y-direction. 0 meter is the distance at the bottom of the gasifier which is at the outlet. The distribution in Graph 4.4 is along the gasifier's throat. The temperature is increasing directly proportional to the distance.

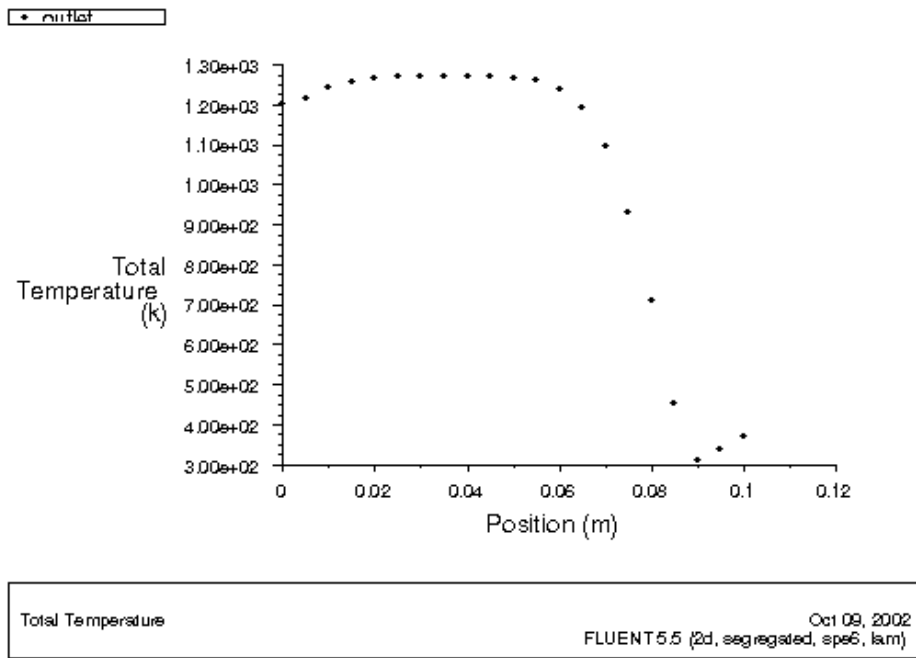


Figure 4.5: Total Temperature Distribution at the Outlet

The temperature distribution at the outlet is decreasing with the distance. Some part of the gasifier at the outlet has the constant temperature.

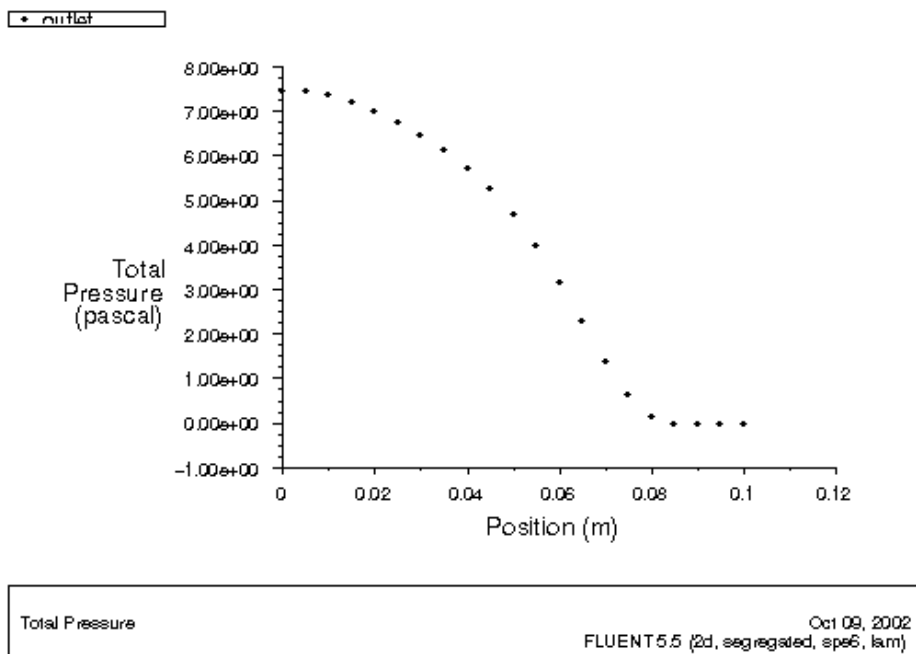
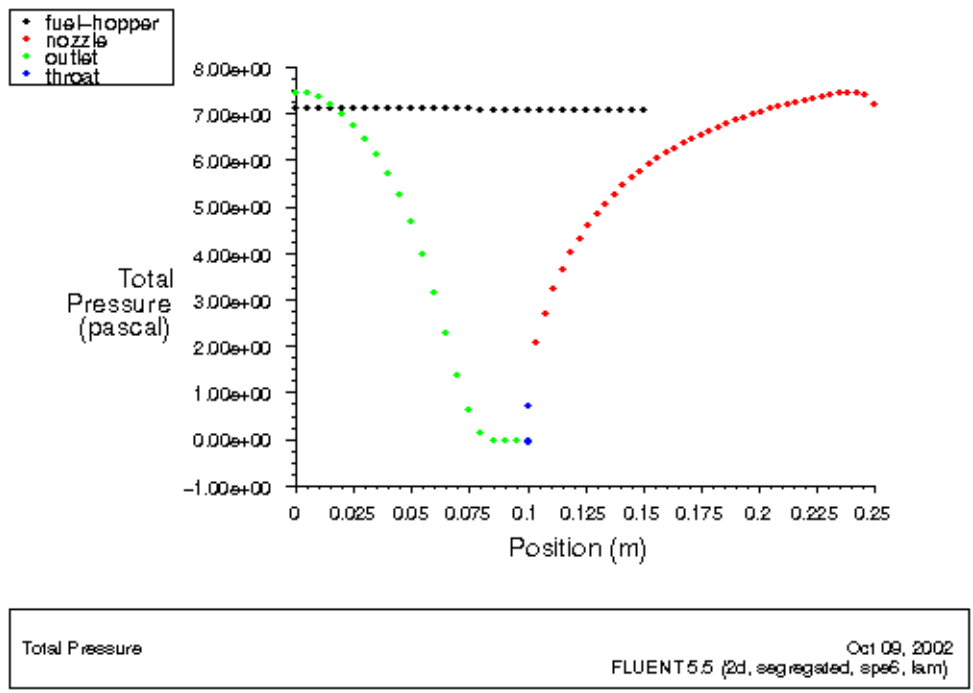


Figure 4.6: Total Pressure Distribution at the Outlet

The total pressure distribution at the outlet is decreasing gradually with the distance.

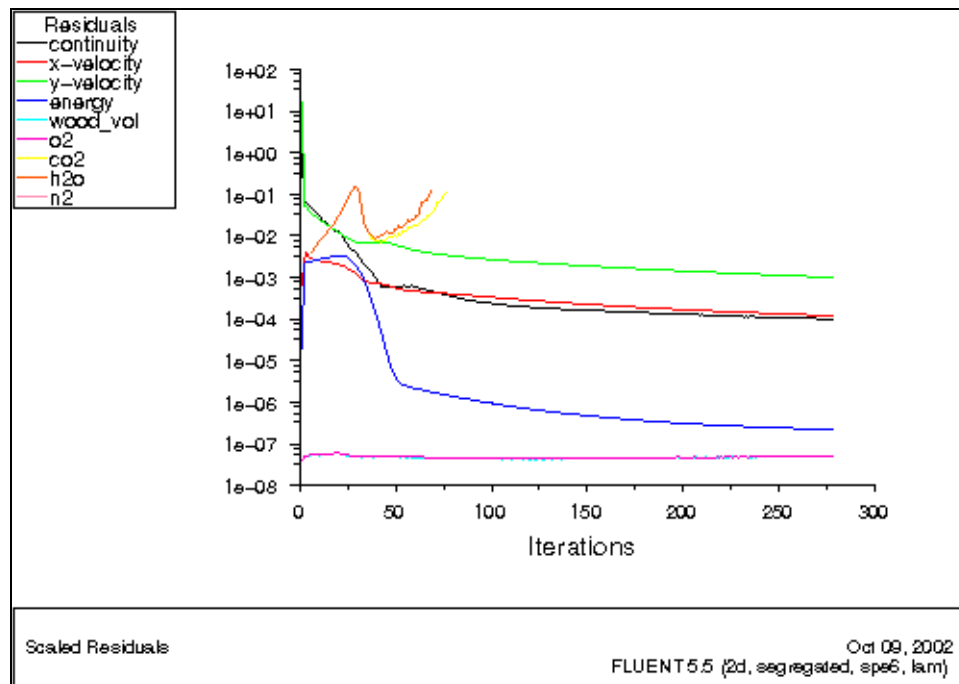


Graph 4.5: Total pressure at fuel hopper, nozzle, outer-wall, outlet and throat.

Graph showed the total pressure at all the zones inside the gasifier. Total pressure is constant at the fuel hopper. As for the outlet, the pressure is decreasing from the bottom to the top of the gasifier. On the other hand the total pressure is increasing for the area around the nozzle.

4.5 Result Analysis from pressurised downdraft gasifier

4.5.1 First-order Discretization.



As for pressurized downdraft gasifier, simulation was run only until 300 iterations in order to get the convergent solution. From the residual graph above, the solution was not stable as some simulation stopped at small iteration which is less than 100 iterations. Therefore the setting in FLUENT software was changed to Second-order Discretization. Unfortunately, the graph was almost the same. Both are not stable.

4.5.2 Second-order Discretization

After the settings were changed to second-order discretization, the residual graph was almost the same which is not stable.

4.6 Pressurised downdraft gasifier contour results

4.6.1 Profile for first-order Discretization

4.6.1.1 Temperature and pressure contour

1. Filled contour of static pressure

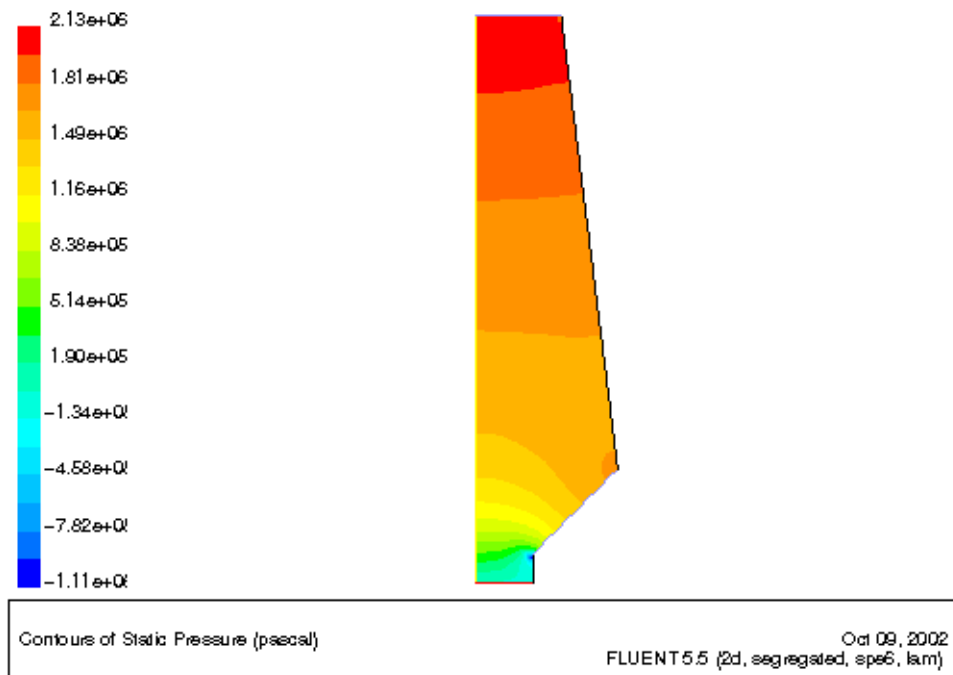


Figure 4.7: Predicted Static Pressure Distribution after the Initial Calculation

From the filled contour of static and total pressure (Refer Graph 4.7 & 4.8), the graph show that at the top of the gasifier, the pressure is high which is at the fuel hopper. Both graph are almost the same.

2. Filled contour of total pressure

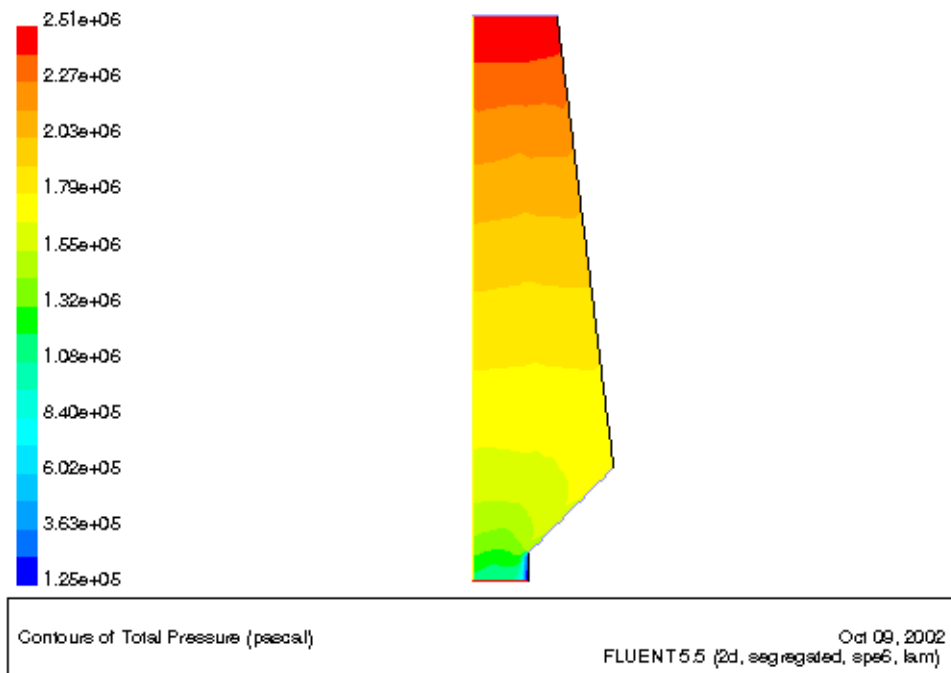


Figure 4.8: Predicted Total Pressure Distribution after the Initial Calculation

3. Filled contour of total temperature

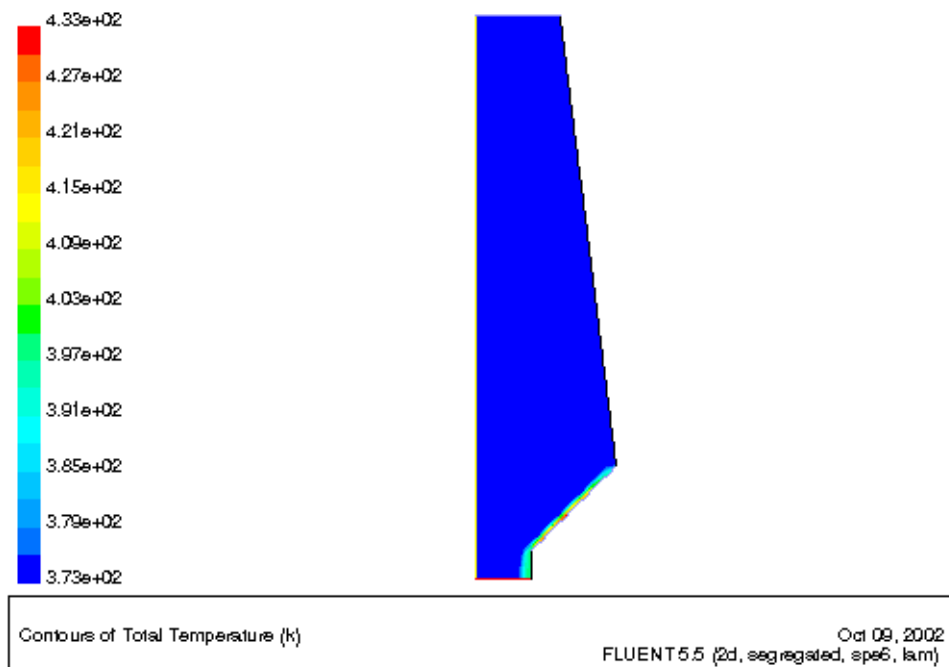
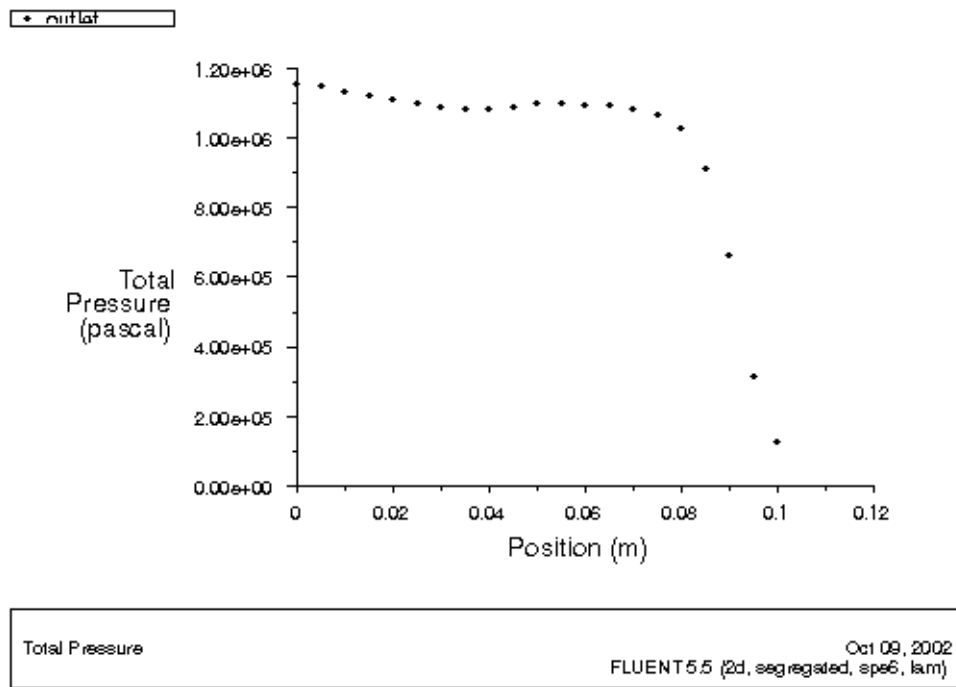


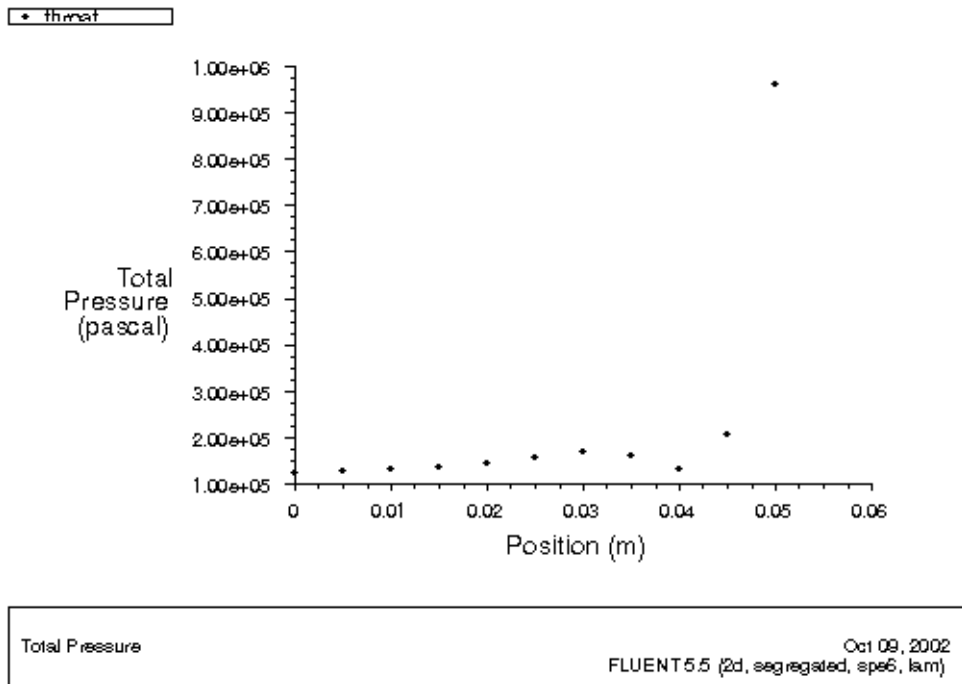
Figure 4.9: Predicted Total Temperature Distribution after the Initial Calculation
From the contour, the total temperature obtained shows no difference of temperature inside the gasifier.

4.6.1.2 Temperature and pressure distribution



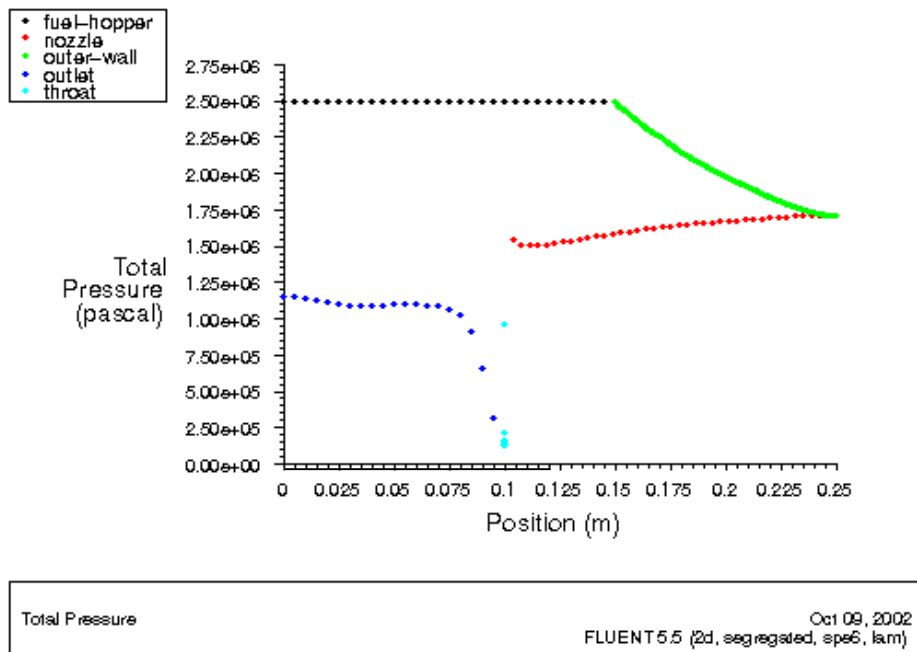
Graph 4.6: Total pressure distribution at outlet

The total pressure distributions at outlet show almost the same for atmospheric and pressurised gasifier.



Graph 4.7: Total pressure at throat

The graph above shows the total pressure distribution inside the gasifier to the distance along y-direction. It can be seen that the pressure is increasing from 1×10^5 Pascal to 1×10^6 Pascal.



Graph 4.8: Total pressure at fuel hopper, nozzle, outer-wall, outlet and throat.

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The graph above shows the pressure at all the segment in the biomass gasifier. From the fuel-hopper to the throat, the pressure drop is recorded from 2.5×10^6 Pascal to 2.5×10^5 Pascal.

Chapter 5 – Conclusion & Recommendations

The computational fluid dynamics (CFD) software is playing a strong role as a design tool computer. Today CFD can be considered as an equal partner with pure theory and pure experiment in the analysis and solution of fluid dynamics problems in dealing with fluid flow. The development of new products of gasifier for biomass is getting better if the trial and error methods are replaced with CFD software which can assist them in improving new products.

In the dissertation, some of the result obtained from this simulation is not very accurate. This is because of several factors such as model's parameters, geometry, meshing, grid and discretization that play an important role in the result accuracy.

As for model's geometry, 2-dimensional model is used because of easy iterations and time consuming. Thus, first-order discretization leads to convergent result. Second-order discretization is useful to improve the result accuracy. After some iteration, the result was not converged. Therefore second-order discretization is not suitable for 2-dimensional model²⁰.

In the first method used as a preliminary approach, the combustion process is assumed to be laminar and steady state. In real life, combustion process is involved with turbulent and unsteady state processes. Therefore, further study is needed on these processes.

There is consideration that has to put in mind about the environmental impact, from indirect and direct emissions release from the combustion process. For this dissertation, universal emission-releasing gas model based on biomass fuel is not evaluated although it is very necessary to analyse the product gas from the combustion process. This is because each case-dependent emissions associated with biomass gasification practice is quite tedious and time-consuming.

Thus, it is necessary in future to model the pollutants gas so that it can be used as reference when any gasifier are to be built on local community or society. So that they can be modelled based on simulation and can be evaluated in advance, as the result can be demonstrated from modelling using computational fluid dynamic software.

²⁰ Anderson, J.D (1995), Computational Fluid Dynamics, *The Basic With Application*, International Editions, McGraw-Hill

Finally, the software FLUENT is used and most of the work is directed towards combustion and gasification of biomass fuels. The number of persons involved in simulations is such that the computational capacity is still a limiting factor. The available workstations will as far as possible be used for pre-processing and post-processing of the problems and for tests on more coarse grids. But to be able to fulfil the real project in specified time, it is essential to get access to high computational capacity and extended memory.

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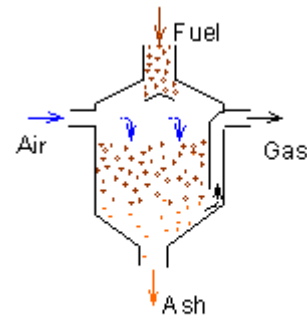
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18. Dogru, M. and et al (2002), The International Journal, *Gasification of hazelnut shells in a downdraft gasifier* Vol. 27 pp 415-427.
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Appendices

Appendix 1.1: List of gasifier

Downdraft gasifier, biomass fuel is fed in at the top, gas is sucked off near the base, and air is drawn down through the fuel.

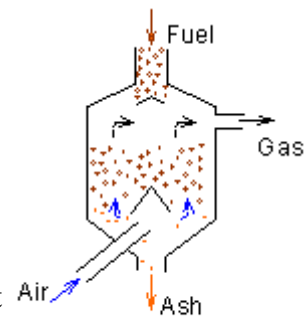
- Size, shape and moisture content of the biomass particles must be controlled within close limits.
- Quality of the gas fuel produced is generally good.
- The downdraft principle is only suitable for installations of less than about 1 MW electrical output.



Downdraft gasifier

Updraft gasifier is one where the gas flows upwards as the biomass moves down.

- The updraft principle is suitable for installations of a few tens of megawatt capacity.
- Size, shape and moisture content of the biomass particles are much less critical than with a downdraft gasifier.
- Quality of the gas produced tends to be poor.



Updraft gasifier

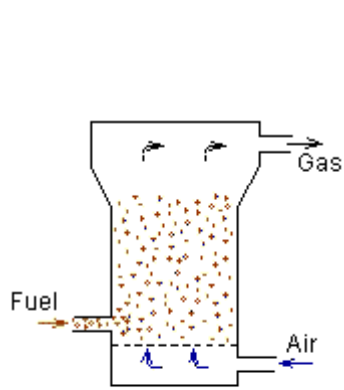
Other types of fixed bed gasifier, produced in small numbers, may involve:

- cross flow design;
- use of oxygen as the gasifying agent instead of air;
- Feeding from the bottom by means of a transport screw.

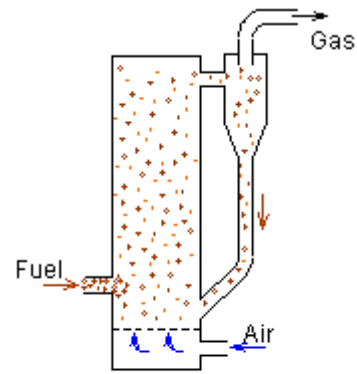
Fluidised bed gasifiers have either a bubbling bed or a circulating bed.

- There is no technical scale-up limit (though size may be limited by availability of biomass or the local energy demand).

- The gasifying agent is usually air at atmospheric pressure, but pressurised gasification can be advantageous when supplying gas turbines larger than about 100 MW.
- The danger of ash agglomeration is low, because of the relatively low temperature (about 850°C).



Bubbling fluidised bed gasifier



Circulating fluidised bed gasifier

Appendix 1.2: Summary – First-order Discretization for downdraft gasifier

FLUENT

Version: 2d, segregated, spe6, lam (2d, segregated, 6 species, laminar)

Release: 5.5.14

Title: Gasifier

Models

Model	Settings

Space	2D
Time	Steady
Viscous	Laminar
Heat Transfer	Enabled
Melting-Freezing	Disabled
Radiation	None
Species Transport	Reacting (6 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

Name	id	type

Fluid	1	fluid
Centre	2	symmetry
Outlet	3	pressure-outlet
Throat	4	wall
Nozzle	5	velocity-inlet
Outer-wall	6	wall
Fuel-hopper	7	wall
Default-interior	9	interior

Boundary Conditions

Fluid

Condition	Value

Material Name	wood-volatiles-air
Specify source terms?	no
Source Terms	((mass (constant . 0) (profile)) (x-momentum (constant . 0) (profile)) (y-momentum (constant . 0) (profile)) (energy (constant . 0) (profile)) (species-0 (constant . 0) (profile)) (species-1 (constant . 0) (profile)) (species-2 (constant . 0) (profile)) (species-3 (constant . 0) (profile)) (species-4 (constant . 0) (profile)))

Motion Type	0
X-Velocity Of Zone	0
Y-Velocity Of Zone	0
Rotation speed	0
X-Origin of Rotation-Axis	0
Y-Origin of Rotation-Axis	0
Porous zone?	no
X-Component of Direction-1 Vector	1
Y-Component of Direction-1 Vector	0
Direction-1 Viscous Resistance	0
Direction-2 Viscous Resistance	0
Direction-3 Viscous Resistance	0
Direction-1 Inertial Resistance	0
Direction-2 Inertial Resistance	0
Direction-3 Inertial Resistance	0
C0 Coefficient for Power-Law	0
C1 Coefficient for Power-Law	0
Porosity	1
Solid Material Name	aluminum

Centre

Condition	Value
-----------	-------

Outlet

Condition	Value
Gauge Pressure	0
Backflow Total Temperature	300
Backflow	((constant . 0.77993202)
(profile)) ((constant . 0.22006799) (profile)) ((constant . 0)	
(profile)) ((constant . 0) (profile)) ((constant . 0) (profile	
)))	

Throat

Condition	Value
Wall Thickness	0
Heat Generation Rate	0
Material Name	aluminium
Thermal BC Type	0
Temperature	1473
Heat Flux	0
Convective Heat Transfer Coefficient	0
Free Stream Temperature	300
Apply a velocity to this wall?	no
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation	0
Y-Component of Wall Translation	0

```

External Emissivity 1
External Radiation Temperature 300
(1 1 0 0 0)

```

```

(((constant . 0.77993202) (profile )) ((constant . 0.22006799)
(profile )) ((constant . 0) (profile )) ((constant . 0) (profile
))) ((constant . 0) (profile )))

```

```

Rotation Speed 0
X-Position of Rotation-Axis Origin 0
Y-Position of Rotation-Axis Origin 0
Specify shear stress? no
X-component of shear stress 0
Y-component of shear stress 0

```

Nozzle

Condition	Value
Velocity Specification Method	2
Reference Frame	0
Velocity Magnitude	2
X-Velocity	0
Y-Velocity	0
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0
Z-Component of Axis Direction	0
X-Coordinate of Axis Origin	0
Y-Coordinate of Axis Origin	0
Z-Coordinate of Axis Origin	0
Angular velocity	0
Temperature	1273
	(((constant . 0.77993202)
(profile)) ((constant . 0.22006799) (profile)) ((constant . 0)	
(profile)) ((constant . 0) (profile)) ((constant . 0) (profile	
)))	

Outer-wall

Condition	Value
Wall Thickness	0
Heat Generation Rate	0
Material Name	aluminum
Thermal BC Type	0
Temperature	620
Heat Flux	0
Convective Heat Transfer Coefficient	0
Free Stream Temperature	300
Apply a velocity to this wall?	no
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation	0

```

Y-Component of Wall Translation      0
External Emissivity                  1
External Radiation Temperature       300
                                      (1 1 0)

```

0 0)

```

(((constant . 0.77993202) (profile )) ((constant . 0.22006799)
(profile )) ((constant . 0) (profile )) ((constant . 0) (profile
)) ((constant . 0) (profile )))
Rotation Speed                        0
X-Position of Rotation-Axis Origin    0
Y-Position of Rotation-Axis Origin    0
Specify shear stress?                 no
X-component of shear stress           0
Y-component of shear stress           0

```

Fuel-hopper

Condition	Value
Wall Thickness	0
Heat Generation Rate	0
Material Name	
aluminium	
Thermal BC Type	0
Temperature	343
Heat Flux	0
Convective Heat Transfer Coefficient	0
Free Stream Temperature	300
Apply a velocity to this wall?	no
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation	0
Y-Component of Wall Translation	0
External Emissivity	1
External Radiation Temperature	300
	(1 1 0 0 0)

```

(((constant . 0.77993202) (profile )) ((constant . 0.22006799)
(profile )) ((constant . 0) (profile )) ((constant . 0) (profile
)) ((constant . 0) (profile )))
Rotation Speed                        0
X-Position of Rotation-Axis Origin    0
Y-Position of Rotation-Axis Origin    0
Specify shear stress?                 no
X-component of shear stress           0
Y-component of shear stress           0

```

Default-interior

```

Condition  Value
-----

```

Solver Controls

Equations

Equation	Solved
Flow	yes
Energy	yes
wood_vol	yes
o2	yes
co2	yes
h2o	yes
n2	yes

Numerics

Numeric	Enabled
Absolute Velocity Formulation	yes

Relaxation

Variable	Relaxation Factor
Pressure	0.1
Momentum	0.1
Energy	0.89999998
wood_vol	1
o2	1
co2	1
h2o	1
n2	1
Density	1
Body Forces	1

Linear Solver

Variable	Solver Type	Termination Criterion	Residual Reduction Tolerance
Pressure	V-Cycle	0.1	
X-Momentum	Flexible	0.1	0.7
Y-Momentum	Flexible	0.1	0.7
Energy	Flexible	0.1	0.7
wood_vol	Flexible	0.1	0.7
o2	Flexible	0.1	0.7
co2	Flexible	0.1	0.7
h2o	Flexible	0.1	0.7
n2	Flexible	0.1	0.7

Discretization Scheme

Variable	Scheme
Pressure	Standard
Momentum	First Order Upwind
Pressure-Velocity Coupling	SIMPLE
Energy	First Order Upwind
wood_vol	First Order Upwind

o2	First Order Upwind
co2	First Order Upwind
h2o	First Order Upwind
n2	First Order Upwind

Solution Limits

Quantity	Limit
Minimum Absolute Pressure	1
Maximum Absolute Pressure	5000000
Minimum Temperature	1
Maximum Temperature	5000

Material Properties

Material: aluminium (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	2719
Cp (Specific Heat)	j/kg-k	constant	871
Thermal Conductivity	w/m-k	constant	202.4

Material: air (fluid)

Property	Units	Method	Value(s)
Molecular Weight	kg/kgmol	constant	28.966
Standard State Enthalpy	j/kgmol	constant	0
Standard State Entropy	j/kgmol-k	constant	0
Reference Temperature	k	constant	298.15
L-J Characteristic Length	angstrom	constant	3.711
L-J Energy Parameter	k	constant	78.6
Degrees of Freedom		constant	0

Material: wood (solid)

Property	Units	Method	Value(s)
Density	kg/m3	constant	700
Cp (Specific Heat)	j/kg-k	constant	2310
Thermal Conductivity	w/m-k	constant	0.17299999

Material: wood-volatiles (fluid)

Property	Units	Method	Value(s)
Molecular Weight	kg/kgmol	constant	31.626
Standard State Enthalpy	j/kgmol	constant	-2.548e+08
Standard State Entropy	j/kgmol-k	constant	0
Reference Temperature	k	constant	298.15
L-J Characteristic Length	angstrom	constant	0
L-J Energy Parameter	k	constant	0
Degrees of Freedom		constant	0

Material: oxygen (fluid)

Property	Units	Method	Value(s)
Molecular Weight	kg/kgmol	constant	31.9988
Standard State Enthalpy	j/kgmol	constant	0
Standard State Entropy	j/kgmol-k	constant	205026.86
Reference Temperature	k	constant	298.15
L-J Characteristic Length	angstrom	constant	3.458
L-J Energy Parameter	k	constant	107.4
Degrees of Freedom		constant	0

Material: carbon-dioxide (fluid)

Property	Units	Method	Value(s)
Molecular Weight	kg/kgmol	constant	44.00995
Standard State Enthalpy	j/kgmol	constant	-
3.9353235e+08			
Standard State Entropy	j/kgmol-k	constant	213715.88
Reference Temperature	k	constant	298.15
L-J Characteristic Length	angstrom	constant	3.941
L-J Energy Parameter	k	constant	195.2
Degrees of Freedom		constant	0

Material: water-vapor (fluid)

Property	Units	Method	Value(s)
Molecular Weight	kg/kgmol	constant	18.01534
Standard State Enthalpy	j/kgmol	constant	-
2.418379e+08			
Standard State Entropy	j/kgmol-k	constant	188696.44
Reference Temperature	k	constant	298.15
L-J Characteristic Length	angstrom	constant	2.605
L-J Energy Parameter	k	constant	572.4
Degrees of Freedom		constant	0

Material: nitrogen (fluid)

Property	Units	Method	Value(s)
Molecular Weight	kg/kgmol	constant	28.0134
Standard State Enthalpy	j/kgmol	constant	0
Standard State Entropy	j/kgmol-k	constant	191494.78
Reference Temperature	k	constant	298.15
L-J Characteristic Length	angstrom	constant	3.621
L-J Energy Parameter	k	constant	97.53
Degrees of Freedom		constant	0

Material: wood-volatiles-air (mixture)

Property	Units	Method	Value(s)

Mixture Species		names ((wood_vol o2 co2 h2o n2 air) ())	
Reaction Model		finite-rate	
((reaction-1 ((wood_vol 1 0.2 1) (o2 1.058 1.3 1) (n2 1 1 1)) ((co2 1 0 1) (h2o 1.191 0 1) (n2 1 0 1)) ((air 0 1)) (stoichiometry 1wood_vol + 1.058o2 + 1n2 --> 1co2 + 1.191h2o + 1n2) (arrhenius 2.1190001e+11 2.027e+08 0) (mixing-rate 4 0.5) (use-third-body-efficiencies? . #f) (surface-reaction? . #f) (backward-reaction? . #f)))			
Density	kg/m3	incompressible-ideal-gas	#f
Cp (Specific Heat)	j/kg-k	constant	1000
Thermal Conductivity	w/m-k	constant	0.045400001
Viscosity	kg/m-s	constant	1.72e-05
Mass Diffusivity	m2/s	constant-dilute-appx	(2.88e-05)
Thermal Diffusion Coefficient	kg/m-s	kinetic-theory	#f
Thermal Expansion Coefficient	1/k	constant	0

Appendix 1.3: Summary – First-order Discretization for pressurised downdraft gasifier

FLUENT

Version: 2d, segregated, spe6, lam (2d, segregated, 6 species, laminar)

Release: 5.5.14

Title:

Models

Model	Settings
Space	2D
Time	Steady
Viscous	Laminar
Heat Transfer	Enabled
Melting-Freezing	Disabled
Radiation	None
Species Transport	Reacting (6 species)
Coupled Dispersed Phase	Disabled
Pollutants	Disabled
Soot	Disabled

Boundary Conditions

Zones

Name	id	type
Fluid	1	fluid
Fuel-hopper	7	pressure-inlet
Centre	2	symmetry
Outlet	3	pressure-outlet
Throat	4	wall
Nozzle	5	velocity-inlet
Outer-wall	6	wall
Default-interior	9	interior

Boundary Conditions

Fluid

Condition	Value
Material Name	wood-volatiles-air
Specify source terms?	no
Source Terms	((mass (constant . 0) (profile)) (x-momentum (constant . 0) (profile)) (y-momentum (constant . 0) (profile)) (energy (constant . 0) (profile)) (species-0 (constant . 0) (profile)) (species-1 (constant . 0) (profile)) (species-2 (constant . 0) (profile)) (species-3 (constant . 0) (profile)) (species-4 (constant . 0) (profile)))

Motion Type	0
X-Velocity Of Zone	0
Y-Velocity Of Zone	0
Rotation speed	0
X-Origin of Rotation-Axis	0
Y-Origin of Rotation-Axis	0
Porous zone?	No
X-Component of Direction-1 Vector	1
Y-Component of Direction-1 Vector	0
Direction-1 Viscous Resistance	0
Direction-2 Viscous Resistance	0
Direction-3 Viscous Resistance	0
Direction-1 Inertial Resistance	0
Direction-2 Inertial Resistance	0
Direction-3 Inertial Resistance	0
C0 Coefficient for Power-Law	0
C1 Coefficient for Power-Law	0
Porosity	1
Solid Material Name	aluminium

Fuel-hopper

Condition	Value
Gauge Total Pressure	2500000
Supersonic/Initial Gauge Pressure	0
Total Temperature	373
Direction Specification Method	1
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	0
Y-Component of Axis Direction	0
Z-Component of Axis Direction	1
X-Coordinate of Axis Origin	0
Y-Coordinate of Axis Origin	0
Z-Coordinate of Axis Origin	0
	((constant . 0.77993202) (profile)) ((constant . 0.22006799) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))

Centre

Condition	Value
-----------	-------

Outlet

Condition	Value
Gauge Pressure	0
Backflow Total Temperature	300
Backflow	((constant . 0.77993202) (profile)) ((constant . 0.22006799) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)) ((constant . 0) (profile)))

Throat

Condition	Value
Wall Thickness	0
Heat Generation Rate	0
Material Name	aluminium
Thermal BC Type	0
Temperature	373
Heat Flux	0
Convective Heat Transfer Coefficient	0
Free Stream Temperature	300
Apply a velocity to this wall?	no
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation	0
Y-Component of Wall Translation	0
External Emissivity	1
External Radiation Temperature	300
	(1 1 0 0 0)

```
((constant . 0.77993202) (profile )) ((constant . 0.22006799)
(profile )) ((constant . 0) (profile )) ((constant . 0) (profile
)) ((constant . 0) (profile )))
```

```
Rotation Speed 0
X-Position of Rotation-Axis Origin 0
Y-Position of Rotation-Axis Origin 0
Specify shear stress? no
X-component of shear stress 0
Y-component of shear stress 0
```

Nozzle

Condition	Value
Velocity Specification Method	2
Reference Frame	0
Velocity Magnitude	2
X-Velocity	0
Y-Velocity	0
X-Component of Flow Direction	1
Y-Component of Flow Direction	0
X-Component of Axis Direction	1
Y-Component of Axis Direction	0
Z-Component of Axis Direction	0
X-Coordinate of Axis Origin	0
Y-Coordinate of Axis Origin	0
Z-Coordinate of Axis Origin	0
Angular velocity	0
Temperature	737
	((constant . 0.77993202)
(profile)) ((constant . 0.22006799) (profile)) ((constant . 0)	
(profile)) ((constant . 0) (profile)) ((constant . 0) (profile	
)))	

Outer-wall

Condition	Value
Wall Thickness	0
Heat Generation Rate	0
Material Name	aluminium
Thermal BC Type	0
Temperature	800
Heat Flux	0
Convective Heat Transfer Coefficient	0
Free Stream Temperature	300
Apply a velocity to this wall?	no
Define wall motion relative to adjacent cell zone?	yes
Apply a rotational velocity to this wall?	no
Velocity Magnitude	0
X-Component of Wall Translation	1
Y-Component of Wall Translation	0
Define wall velocity components?	no
X-Component of Wall Translation	0
Y-Component of Wall Translation	0
External Emissivity	1
External Radiation Temperature	300
	(1 1 0 0 0)

```
((constant . 0.77993202) (profile )) ((constant . 0.22006799)
(profile )) ((constant . 0) (profile )) ((constant . 0) (profile
)) ((constant . 0) (profile )))
```

Rotation Speed	0
X-Position of Rotation-Axis Origin	0
Y-Position of Rotation-Axis Origin	0
Specify shear stress?	no
X-component of shear stress	0
Y-component of shear stress	0

Default-interior

Condition	Value

Solver Controls

Equations

Equation	Solved
Flow	yes
Energy	yes
wood_vol	yes
o2	yes
co2	yes
h2o	yes
n2	yes