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SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING

THERMAL ENGINEERING STREAM

Production, Characterization and Cleaning of Producer Gas from Gasification of Refuse Derived Fuels (RDF) for Application in IC Engines

A thesis submitted to School of Graduate Studies of Addis Ababa University as a partial fulfillment for the requirement of Masters of Science in Mechanical Engineering (Thermal Engineering).

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented in any University, and that all the source of materials used for the thesis has been duly acknowledged.

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ABSTRACT

A well-planned research activity conducted in Addis Ababa University, Addis Ababa Institute of Technology, School of Mechanical and Industrial Engineering, under Thermal and Energy Conversion Chair is utilizing a thematic research grant from AAU – Vice President for Research and Technology for this thesis and future works out side this scope, for its practical importance in the energy sector of Ethiopia, most importantly in the off-grid part of the country.

Most of the rural areas of Ethiopia are known to have no available electric power supply from the centralized main grid. This huge energy problem has retarded the economic growth of the areas due to the daily, backward and labor intensive activities of the society to meet their daily energy needs. Beyond this, Ethiopia is one of vast and most populous countries in Africa with remarkably high daily waste production rate. All these problems call for a sound measures to be implemented in terms of energy integrated waste management and this paper is aimed at solving the electric shortage problem in off grid parts by preparing high calorific waste fractions in to RDF for good output in internal combustion engine for electricity generation.

The research project is divided in to four manageable phases. Phase 1: Fuel preparation, studying theoretical gasification, modeling and solving of the theoretical gasification using computational methods, process design and sizing of the gasifier, studying gas contaminants and gas cleaning and conditioning techniques, design of the gas cleaning and condition system to meet IC engine requirements for its utilization, which are all paper and computer based tasks. Phase 2: Manufacturing a pilot gasifier – engine set up with the gas cleaning and conditioning system for test run in AAU – AAiT School of Mechanical and Industrial Engineering work shop. Phase 3: Conducting experiment/test on the pilot gasifier – engine coupled setup to carry out validation, experimental investigation and performance analysis. Phase 4: Publication of important scientific outputs from the research in high rated open access journals.

Gasification is an attractive alternative for thermo – chemical conversion of wastes for its flexibility in terms of various materials as feedstock, relatively higher conversion efficiency and wide range of applications in relatively small area per unit output energy. MSW, separated and screened from non-combustibles (soil, metals, glass …) and biodegradable

components was prepared to produce RDF fuel and characterized. The LHV value of the prepared RDF is 16.63MJ/kg, which is well accepted good RDF as its LHV is greater than 15MJ/kg as recommended by studies. Based on the good results from RDF characterization, a brief mathematical modeling of the gasification of RDF using non – stoichiometric equilibrium model was presented. The code formulated for the model was implemented on MATLAB to estimate concentration of product gas species and the corresponding heating values for wide range of gasification temperatures and equivalent ratios. The model gives optimal values of temperature and equivalent ratio to be 850^0C and 0.2 respectively for best operating conditions. The gas heating value was 8.164MJ/Nm^3, which is well accepted yield from downdraft gasifier to be used for applications such as utilization of the gas in IC engines for electricity generation.

Downdraft gasifier is found to be technically good for engine applications and the process design of the gasifier determines the capacity of the gasifier to be 147kW at feed rate of 46 kg/hr and product gas flow rate of 65.14Nm^3/hr to meet engine requirements. The cold gas efficiency of the gasifier is 70% and carbon conversion efficiency and energy balance calculations give results that support the fact that basic assumptions underlying the equilibrium model employed in the computational tool give an over estimated theoretical maximum yield. Gasifier sizing was performed based on internationally accepted used sizing method and the size calculation results were validated with recommended ranges of sizes for same product gas flow rate.

Major gas contaminants for this specific application are well identified and studied for proper cleaning and mitigation. Based on the gas quality demanded by the application, a sound gas cleaning and conditioning system is designed.

The paper based designs of the gasifier and gas conditioning system is brought to the ground by manufacturing and testing a pilot gasifier-engine setup with gas cooling and conditioning system for a test run to validate the modeling output with the experimental results and to perform performance evaluation of the gas cleaning. A good agreement was observed between experimental and simulation results for gas characterization at the gasifier outlet. Catalytic gasification and the gas cleaning system give promising results for future advanced investigations on the use of Dolomite and the secondary gas cleaning. Even though gas cleaning performance experimental tests require more investigation with laboratory facility that measure all possible product gases and tar, the results obtained so far give a satisfactory

motive to do more improvements and conduct advanced tests. Both experimental and simulation results make electricity generation using a specific producer gas engine generator set based on the proven characterization of the gas (heating value and inflammability), provided that gas suction fun or blower or gas compressor is installed before it to overcome the unexpected high pressure drop observed as the gas pass through the gas cleanup system to meet the engine pressure requirements.

This research gives promising solutions for availability of the expensive electricity in off-grid areas of Ethiopia possible form refuse derived fuels (RDF) in a micro – scale gasification plant.

So far, one scientific manuscript titled '***Equilibrium Modeling of Refuse Derived Fuels (RDF) Gasification in Imbert Type Downdraft Gasifier***' is on final stages of publication, being accepted after review from this study to an open access journal. More scientific outcomes are expected from further experimental investigations and performance analyses.

Key Words: Gasification, RDF, Modeling, Producer Gas, Gas Cleaning

DEDICATION

I devote this research work for the memory of my lovely mother, **Mrs. Ferihiwot Tilahun** (R.I.P), for her life time scarification to grow me up well being the first and the only to lay foundation for my life seeking my bright future.

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Also, some individuals deserve my special thanks and honor. Among all, the kind support and lessons from the young, devoted, knowledgeable and energetic scientist, Dr. –Ing Wondwossen Bogale was so valuable and is in my heart. It was such a privilege to work and spend more time with him for my knowledge and attachment with the science. I also give my deepest thanks for Dr. –Ing Berhanu Assefa who advised me and nominated and helped my proposal of this paper for a thematic fund grant from AAU – Research Office. Staffs of SMiE, most importantly from Thermal and Energy Conversion Stream, Mr. Sine, Mr. Aklilu, Dr. Kamil Dino, Dr. Yilma Tadesse, and my friends at office 314 C are honored and acknowledged for visiting my experimental set – up every time with their valuable comments and suggestions that used to make me think twice in most unseen cases of mine. I am very much grateful to all SMiE workshop staffs, that all supported me and trained me in some manufacturing techniques practically in manufacturing and testing phases of my research, especially, Mr. Masresha, Mr. Anteneh, Mr. Kassaye, Mr. Semma.

Now I will take time to acknowledge the help from my families, for even supporting and encouraging me in tough times on study while I steal their time to my work. This thanking goes to my father, my brother, my sisters and other close family members with big credit.

Finally, I would like to give thanks to all individuals and bodies who contributed their share in the success of this work in one way or another that I didn't mention their names here.

ACRONYMS

AAU	Addis Ababa University
AAiT	Addis Ababa Institute of Technology
ACFM	Actual Cubic Feet per Minute
BNG	Birmingham Wire Gauge
CFD	Computational Fluid Dynamics
CHP	Combined Heat and Power
CRF	Char Creativity Factor
E.R	Equivalence Ratio
EPA	Environmental Protection Authority
EU	European Union
Gc	Gravimetric Chromatography
GPM	Gallons Per Minute
HHV	Higher Heating Value
IC	Internal Combustion
ICE	Internal Combustion Engine
ID	Inner tube Diameter
kW	Kilo Watts
LHV	Lower Heating Value
LMTD	Log Mean Temperature Difference
MJ	Mega Jouls
Ms	Mass Spectrometer
MSW	Municipal Solid Waste
OD	Outer tube Diameter
PDF	Packaging Derived Fuels
PEF	Process Engineered Fuels
ppm	Parts Per Million
RDF	Refuse Derived Fuels
REF	Refused Fuels
SCBE	School of Chemical and Bio Engineering
SMiE	School of Mechanical and Industrial Engineering

SNNP	Southern Nations and Nationalities People
UNDP	United Nations Development Program
WTE	Waste – to - Energy
M_{RDF}	Molecular weight of the RDF
m	Moisture content of the RDF
m_w	Number of moles of water vapor in dry basis
n_i	Number of moles of species I in the producer gas.
n_{tot}	Total number of moles of gases
x, y, z	Normalized coefficient of atomic Hydrogen, Oxygen and Nitrogen for RDF molecule.

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1. INTRODUCTION

1.1. Background

Energy is essential for human development. Without an adequate energy supply, people cannot cook their food, light their homes, or keep essential foods and medicines chilled. The introduction of efficient and clean thermal use of renewable energy resources can provide basic energy services for lighting and communication and promote local economic growth. The provision of electricity from solid wastes/RDF is one way to meet the energy demands in electricity – deficit remote areas. Like solar, wind, tides, geothermal and hydroelectric, biomass and dry waste are popular renewable sources of the energy that are created by our everyday activities anywhere all over the world. The potential of renewable energies for urban and rural development and greenhouse gas reduction are current concerns all over the world.

Most of the rural areas of Ethiopia are known to have no available electric power supply from the centralized main grid. This huge energy problem has retarded the economic growth of the areas due to the daily, backward and labor intensive activities of the society to meet their daily energy needs. Beyond this, Ethiopia is one of vast and most populous countries in Africa with remarkably high daily waste production rate (0.17 to 0.48kg/person/day in urban areas and 0.11 to 0.35kg/person/day in rural areas), poor waste disposal and poor waste recovery activities due to lack of man power and technical skills in waste management and utilization, remain to be the most important bottleneck in addressing solid waste collection and land fill management [1]. All these problems call for sound measures to be implemented in terms of energy integrated waste management.

Thermo – chemical conversion of waste is an inalienable part of energy integrated waste management system which takes place at relatively high temperatures causing modifications in the chemical structure of the processed material, thus the three main processes available for thermo – chemical conversion of waste are: Combustion, Gasification and Pyrolysis [2]. Gasification has an interesting advantage over direct combustion and pyrolysis in some technological applications such as prior gasification of biomass and waste and subsequent utilization of producer gas in IC engines, which is a rational way to use in small scale energy producing units [3]. Gasification is a Thermo – Chemical process to convert carbon – based (fossil or non-fossil) products such as biomass, coal and solid combustible wastes in to a gas

mixture known as synthetic gas or producer gas and char [4]. For small scale power generation applications, gasification in downdraft gasifiers has been studies extensively and currently is considered to be a mature technology [3,4,5,6,7]. Therefore, it appears to be a fascinating solution that, wood or other dry biomass along with a dry consequents of the municipal/urban solid waste is converted in to a combustible gas in a gasifier employing the principles of gasification and then to electricity via an IC engine - generator set.

The small scale electricity generation using gasification enables households in off – grid part of Ethiopia to be provided with electricity for lighting and cooking. The system also assists energy intensive business and social activities like lighting, irrigation, refrigeration and cooking in the area. This technology is considered nearly carbon neutral, so using it will displace other net carbon positive forms of electricity generation. Furthermore, disposing of dry waste and woody biomass in controlled environments, as opposed to open burning, will result in improved air quality in communities in close proximity to the waste. Beyond its simplicity and environmental friendliness, it is also user – friendly plant to be owned and operated by any literate or illiterate family. It is also portable enough to be handled to where it is needed.

1.2. Thesis Objectives

1.2.1. General Objectives

The general objective of the research is to overcome the energy deficiency problem in the rural and off – grid parts of Ethiopia by making use of easily available and renewable resource. RDF will be used in small scale gasification plant to electrify households and energy intensive businesses and social activities in the rural areas where electricity is not provided from the central grid. The objective further extends to determining critical parameters and designing a sound hot gas cleaning and conditioning system for best performance of the plant. This thermal treatment of wastes (RDF) will also have a positive impact on the waste management. The operation of the plant is also aimed to give socio – economic benefits to the society (by improving their livelihood, training skills how to operate, maintain and trouble shoot the system during its working life which can be a means for living).

1.2.2. Specific Objectives

- To understand the theory of gasification and to demonstrate how RDF is gasified to provide electricity.
- To prepare and characterize a high calorific RDF fuel which can be a feed stock to the gasifier and to mathematically model gasification of RDF in the gasifier.
- To formulate a MATLAB code to implement the gasification modeling and simulate concentrations of producer gas for wide range of gasification temperatures and equivalent ratios to optimize parameters like optimum operating reactor temperature, optimum equivalent ratio, species composition of the producer gas at optimum operating condition and the respective equivalence ratio.
- To perform the process design of the gasifier (like feed rate, flow rate of the gasification medium, air to fuel ratio …) and to perform energy balance on the gasifier and carbon conversion efficiencies to check for the validity of assumptions used in the modeling.
- To size and manufacture the gasifier in AAiT workshop and conduct test runs to make validation between experimental and simulation results, with sensitivity analysis discussed for important features of the results of modeling and experimental output.
- To identify producer gas contaminants and to discuss efficient and cost-effective ways of improving product gas quality and condition, which is an input to the designing of a gas cleaning and conditioning system for the product gas to meet minimum requirements set by IC engines.
- To manufacture/install the designed gas cleaning and conditioning system on the gasifier then couple it with diesel engine and to conduct test run on the pilot set up to conduct experimental investigations and perform performance measurement analysis.

1.3. Statement of the Problem

Access to quality, reliable and affordable energy is critical for promoting economic and social development in rural areas.

The energy situation in rural Ethiopia is characterized by low quality of fuel, low reliability of supply and limited access leading to lower productivity of land, water and human effort, ultimately leading to low quality of life and environmental degradation.

Traditional use of biomass (firewood, crop residue and cattle dung) and dependence on traditional cook stoves with low efficiency emit smoke in to kitchen, leads low quality of life for rural women. Dependence on kerosene and wick lamps for lighting with uncertain supply of fuel leads to low quality and intermittent lighting.

The provision of electricity to households in the rural areas of Ethiopia is an objective which has been recognized by government as well as donor agencies and international financing institutions. The problem in the rural and off – grid Ethiopia is not only limited to the need for improving energy systems and mitigating environmental hazards [9]. It becomes worse when it comes about electricity availability. Electricity is essential in the areas because most business and social activities in the areas are electric consuming.

Vast majority of Ethiopia's agricultural products are supplied from rural areas, managed in traditional and labor intensive way with far small yield than it should. Health centers are not well equipped and functioning in the areas for almost all equipment's run by electricity which is not yet provided in the provinces. Domestics are not lighted and powered. Dependence on centralized grid electric (if any) supply to low – load rural consumptions is characterized by fluctuating voltage, unreliable supply and shortage of power in most parts of rural Ethiopia.

These all indicate the importance and realization on the need to search for decentralized and renewable energy based option to meet the rural energy needs in sustainable way. Among all renewable resources, RDF derived from biomass and other dry wastes is the largest, most diverse and readily exploitable resource in the areas. For these reasons, renewable WTE (waste – to – energy) technologies have been found promising in promoting for meeting rural off – grid electricity needs to make households lighted, the agricultural sector more yielding by cutting its dependence on human labor by powering pumping systems to facilitate irrigation, power health institutions to provide every medical services dependable on electricity and to get medicines and vaccines chilled. Achieving the target, it is also a good solution for proper waste disposal practices in Ethiopian cities and rural villages there by promoting hygienic conditions in the areas.

Further, among renewable energy technologies, the RDF gasification option for meeting the rural electrification needs of domestic, agricultural pumping and rural industrial (such as milling) activities is known to have large potential [2].

Social Benefits:

- Electricity for lighting in all houses to help school going children in their studies and women in their household chores and for those women whom used to walk kilometers to the neighboring village for milling grains.
- Powering of medical equipment in health institutions to provide enough medical access to the occupants in the area.
- Power for provision of reliable and safe water supply for households on most days near the door-step, from a deep bore well available and same power to facilitate irrigation for ease and better yield.

Economic Benefits:

- These include business from employment and income generation from increased crop production through electrically powered irrigation and farming.
- Preparation, transportation and selling of RDF chips to the decentralized power generation system.

Environmental Benefits:

- RDF combustion leads to insignificant Sulfur (S) emission to the atmosphere and CO_2 is partially in the carbon cycle which is not significantly added to the environment.
- RDF is low in ash compared to coal and other fuels, leading to insignificant ash production.
- Disposing of dry waste and woody biomass in controlled environments, as opposed to open burning, will result in improved air quality in communities in close proximity to the waste.

Socio – Economic Benefits:

- Biomass gasifier-based power generation systems will create jobs and skills in rural areas in feedstock production, transportation, processing and in operation and maintenance of the gasifier–engine/generator set systems as well as end-use systems/devices.

1.4. Research Gap

Despite the apparent benefits, there has been almost no practical experience of implementing small scale electricity generating plants using gasification in Ethiopia. Gasification researches and applications in Ethiopia are mostly limited to direct and continues utilization of the product gas for thermal energy applications like cooking. Pilot activities identified in most

important potential areas of the world use biomass gasification. Biomass composition as a fuel varies both seasonally as well as geographically. Gasifier performance is dependent on parameters like: composition of the biomass as a fuel, moisture content (biomass with moisture content of 5 - 30% can be gasified), ash content, heating value, size, bulk density, equivalence ratio, gasification temperature... therefore, using only biomass will cause fluctuations on the above parameters during the intended gasifier operation life time [3,8]. Also, the level of tar present in the producer gas obtained from the biomass gasifier causes difficulties in its use in internal combustion engines [3]. Plus heavy skewedness of Ethiopia's energy consumption towards biomass resources is attributed to deprivation of access, deep rooted poverty, technological backwardness and numerous other factors [11]. Therefore, beyond introducing gasification for small scale power generation in Ethiopia, this paper tries to address the challenges of using biomass for gasification by replacing biomass with RDF which has a considerable amount of biomass in it along with other dry consequents of municipal solid waste that has higher energy content than biomass alone, which is a new issue in Ethiopia. Hot gas cleaning and conditioning systems has not been given emphasis by researches in Ethiopia and this paper is thought to contribute some with this respect.

2. LITERATURE REVIEW

2.1. Renewable Energy Sources in Ethiopia and the Utilization Pattern

Ethiopia is a country of more than 90 million populations and covers 1.1 million Sq. Km. More than 80% of the population lives in rural areas. Access to electricity is about 16%, while average access rate of Sub – Saharan Countries is 26% and most of these customers consume less than 50KWh [9,10]. Electricity coverage in rural areas is negligible. United Nations Development Program (UNDP, 2010), ranked Ethiopia 157th in human development index, with per capita average annual income $120 and about 40% of the population is below poverty line.

Ethiopia has ample and adverse biofuel resource presenting opportunities to harness for renewable fuels, the micro energy potential and exploitation is presented below.

Table 1: Potential Supply of Biofuels in Ethiopia in Millions of Tones [11]

Region	Woody Biomass Stocks	Woody Biomass Annual Yield	Crop Residue	Animal Dung	Total	Share
Tigray	30.99	0.08	0.86	2.09	33.95	0.03
Amhara	138.89	5.84	6.24	7.43	152.55	0.15
Oromiya	373.34	19.90	10.96	10.62	394.92	0.4
SNNP	227.95	10.10	5.67	4.01	237.63	0.24
Afar	21.64	1.44	0.12	2.64	24.41	0.02
Benshangul	76.61	3.53	0.21	0.18	77.00	0.08
Gambela	69.16	3.32	0.08	0.12	69.36	0.07
Dire Dawa	0.06	0.03	0.04	0.04	0.13	0.0001
Harari	0.09	0.01	0.05	0.02	0.15	0.0002
Total	938.73	44.26	24.23	27.15	990.10	1.00
Share	0.95		0.02	0.03	1	

The above table indicated that the total biomass fuel supply of Ethiopia is about 990 million tones excluding Addis Ababa and Somali Regional State of Ethiopia. Woody biomass constitutes 95% of total potential supply. Animal dung and crop residues account mainly foe 3% and 2% respectively. Regional distribution reveals that Oromia regional state supplies

about 40% of biomass resource followed by Southern Nation and Nationalities People (SNNP) (24%) and Amhara regional state about (15%) Remaining regions own insignificant share of national biomass fuel resource. Heavy skewedness of Ethiopia's energy consumption towards biomass resources is attributed to deprivation of access, deep rooted poverty, technological backwardness and numerous other factors. 92% of Ethiopia's energy demand is met from biomass sources. Fire wood is the major biomass type consumed in Ethiopia. The country is number one producer in its share to the world's charcoal and woody fuel as compared to other African countries. 99% of households, 70% industries and 94% of service enterprises use biomass as an energy source [11].

2.2. Energy from Waste

2.2.1. Waste Potential of Ethiopia

According to Environmental Protection Authority and World Bank study conducted in 2012, per capita amount of waste generated in Ethiopia ranged from 0.17 to 0.48 kg/person/day for urban areas to about 0.11 to 0.35 kg/capita/ day for rural areas. The range depends on several factors such as income and season. The total generation of municipal solid waste in Ethiopia in 2011 is estimated to be 2.8 to 8.8 million tones. This can be split to approximately 0.6 to 1.8 million tons from urban areas and 2.2 to 7 million tons from rural areas (EPA/World Bank, 2012).

2.2.2. Waste Potential of Addis Ababa

The current daily waste production of Addis Ababa is estimated to be 2,297 m^3 or 765 tones. The waste production rate per person is about 0.45 kg/day. However, there is seasonal variation in the per capita solid waste generation. From the daily solid waste generated in Addis Ababa, 65% is collected, 5% recycled and 5% composted. The remaining 25% is simply dumped on open sites, drainage channels, rivers and valleys as well as on the streets. 70% of the waste generated comes from households, 9% from commercial areas and 6% street sweeping, 5% from industrial waste and the remaining from hotels, hospitals. [12]

The physical composition of solid waste in Addis Ababa is shown in the following table:

Table 2: The Physical Composition of Solid Waste in Addis Ababa [12]

Constituent	Percent (%)
Vegetables	2

Paper	3
Rubber	0.19
Leather	0.41
Wood	3
Plastic	1.58
Bone	2.11
Textile	1.39
Ferrous metals	0.69
Aluminum	0.0
Glass	0.79
Combustible(Leaves, Grass, etc)	27
Soil/Fines <10 mm	31
Fines<55 but >10 mm	26
Total 100%	≈100%

2.3. RDF as a Fuel

The increase in socio-economic condition during the past ten years has also significantly increased the amount of solid waste generated [13]. Studies, therefore, initiated to assess the potential of power generation from refused derived fuels (RDF) from municipal solid waste (MSW) in order to reduce the dependency on fossil fuels are currently on progress.

MSW has a very good calorific value which makes it a good source of energy. MSW power plants which are also called waste to energy plants are designed to dispose of MSW and to produce electricity as a byproduct in an incinerator. Refuse derived fuel (RDF) from municipal solid waste can be an alternative form of energy to replace fossil fuels. RDF is the component of MSW that has higher calorific like paper, plastics and textile [13].

Refuse is a general term for municipal and commercial solid waste. RDF usually refers to a separate high calorific fraction of municipal solid waste (MSW), solid and dry commercial and/or industrial process wastes. Other terms are also used for MSW derived fuels, such as: Refused Fuel (REF), Packaging Derived Fuels (PDF), and Process Engineered Fuels (PEF) [14].

The higher heating value of RDF can be as much as 23.97 MJ/kg, moisture percent, 8.54% and the ash content, 2.94% [13]. But in general the lower heating value (LHV) of a typical RDF lies in the range 15 MJ/kg to 18MJ/kg according to the selection process and amount high LHV constituents present [15].

It can be seen from EU Directive 2000/76/EC that 58.1 MW of thermal energy can be generated and the amount of power yield is 19.2 MW. The amount of energy per unit weight that is generated from RDF was 4.15kWh/kg. The limit for NO_x is 400 mg/Nm^3 as per the EU Directive 2000/76/EC and therefore it can be seen that the NO_x emission from RDF complies with the limits. The emission for SO_2 is 50mg/Nm^3 as per EU Directive 2000/76/EC and hence the emission from RDF complied with the limits.

Therefore utilizing RDF in gasifier is the best option for generation of power from waste. This can be a huge alternative to replace biomass and fossil fuels besides facilitating the waste management in positive way by overcoming environmental hazards.

2.4. Gasification Technologies for Power Generation

The manufacture of combustible gases from solid fuels is an ancient art but by no means a forgotten one. In its widest sense the term gasification covers the conversion of any carbonaceous fuel to a gaseous product with a useable heating value. This definition excludes combustion, because the product flue gas has no residual heating value. It does include the technologies of pyrolysis, partial oxidation, and hydrogenation.

In this discussion of the theory of gasification the emphasis will be limited to gasifiers that operate at temperatures of 850°C and higher. Below 850°C is, on the one hand, the realm of pyrolysis reactions that are extremely complex to model, whereas, on the other hand, the partial oxidation reactions proceed at a slow rate that they become of little practical value. In such gasifiers pyrolysis reactions are prevalent in the colder upper part of the reactor, and therefore a simple description of the process by assuming thermodynamic equilibrium is not allowable for that region of the reactor. The reactions in the hot bottom section in which coke reacts with the blast can, however, be described well by thermodynamic equilibrium [16].

Gasification has advantages over direct combustion in some technological applications like prior gasification of feed (fuel) and subsequent utilization of the producer gas in internal combustion engine, which is a rational way to use it in a small scale energy producing units. [16,17,18,19,20]

Two types of fuel are produced from gasification [16]:

- Gaseous [producer gas (CO,H_2,CH_4,CO_2), syngas (CO, H_2) and etc…]
- Solid (Charcoal)

From these fuels, come major categories of product:

- Energy (in the form of heat)
- Electricity

In the last years (2004 – 2013), the use of renewable energy sources increased about 30%. Nowadays, they are responsible for approximately 41% of the domestic energy supply. From this total, the contribution derived from biomass energy was about 60% (e.g. Sugarcane products, firewood and charcoal). In world, the average of electricity generation from renewable source is about 15%. Beyond the thermal plants, among the alternatives technologies for thermochemical conversion of solid biomass for electricity generation, the gasification process is performed with greater efficiency (65–85%). In general, the biomass gasification can be considered as a sustainable technology that requires simple management and maintenance. Furthermore, it has also been shown a feasible economic alternative for electricity generation [20].

Although conversion of biomass to gas results in loss of energy of 10 to 25%, use of gas for production of heat and power can be highly efficient. The low heating value and the process cold efficiency for a down drift type reactor were around 4 – 6 MJ/Nm^3 and 50 – 70% respectively. The lower calorific value of producer gas is around 4.54 MJ/Nm^3. Using innovative two stage air and premixed air/gas supply approach, HHV and tar improved up to 6.5 MJ/Nm^3 and down to 43.2 mg/Nm^3, respectively. Experimental results showed that gasification by air at higher temperatures (950^0C) favored gas yield [19].

In addition, the technology has a low relative capital cost (0.04–0.37 US$ $kW^{-1}h^{-1}$), low deployment cost and simple construction. However, some limitations are pointed to fuel specificity (quality of the producer gas) [19].

The gasification power plant involves three main processes: preparation, gasification and electricity generation [16].

On biomass gasification followed by power generation in the ICEs, downdraft gasifier is the most widespread gasifier model, due to low tar and particles content produced, in order to

preserve the ICE against damages. In remote areas, the access of electric power generally is performed using an electric generator coupled on diesel oil engines or spark-ignition engines. However, the fossil fuels are more expensive due to difficulty in transport access. Small-scale power generation based on biomass gasification is attracting an increasing interest as a promising technology to provide electrical power on remote areas, through local renewable sources. [20]

The small-scale generation through biomass gasification associated to an ICE has been shown a low relative capital cost per power generation unit (US$ kW^{-1}), when compared to other similar technologies (biomass boiler-steam engine or steam turbine, bio-methanation followed by ICE, external combustion engines [2].

However, the producer gas has a poor quality, when compared to other conventional fuels (gasoline, natural gas or diesel oil) commonly used on ICEs. To work with producer gas, ICEs require minimum tar and particulate concentration. Downdraft gasifier systems are more appropriated to provide producer gas with allowable quality for ICEs. In the system, the particulate concentration and tar generally are reduced using physical (e.g., dust collector, filter) and thermochemical methods [21]. A study by [22] listed some important characteristics (ideal values) related to producer gas, which has influences on the power generation performance in the ICE. The characteristics listed refers to the tar content (<50 mg N m^{-3}), dust content at the exit of the ash pit (<200 mg N m^{-3}), heating value (<5.5 MJ N m^{-3}) and cold gas efficiency (simply efficiency) (<85%).

In general, physical and chemical characteristics of the feed and the conditions of the gasification process determine the composition of the producer gas and, in consequence, their properties [19,20,23].

In general, producer gas and air are mixed in an intake collector. In diesel engine cycle, producer gas can be also applied in dual mode to decrease diesel oil consumption. On analysis of small-scale power generation through diesel engine (7.3 kW) coupled to electric generator (5 kW), [24] performed evaluation about diesel oil consumption, when it was used dual fuel mode operation, through producer gas. In this system, diesel oil was applied as pilot injection, and producer gas was injected together with air aspiration. The engine converted to dual mode decreased the diesel oil consumption up to 57%.

The performance analysis about ICE fueled with producer gas can be evaluated under different aspects, as: angular speed, compression ratio, injection timing, pilot fuel mass savings (dual mode), inlet manifold condition, thermal efficiency, exhaust gas temperature, specific fuel consumption, volumetric efficiency, cylinder pressure, heat release rate, smoke density, gaseous emissions [25]. On analysis performed by [25] to downdraft system coupled to spark-ignition engine generator, maximum thermal and electricity generation efficiency was around 13.5% and 12.8%, respectively.

Producer gas has a high potential to replace fossil fuel for decentralized energy generation, but it contains some undesired compounds (e.g. tar, particulates, fly ash … etc.) that is need to be reduced to guarantee an applicable operation of the prime mover, most importantly, IC engines. The presence of tar in producer gas is one of the key technology barriers for the use of gasification systems for engine application. Tar is bituminous oil present in the producer gas in vapor phase that is difficult to remove with a simple condensation or cleaning since it may cause clogging of filter and valves and also may cause corrosion of metallic components [26].

Several methods have been tasted for the reduction of tar as a part of gasification system. Theses includes:-

- ✓ The gasifier design
- ✓ Cleaning and appropriate operating conditions
- ✓ The use of bed additive or catalysts and the gasification technology itself

Desirable concentration of tar depends on the intended use of producer gas in downstream prime movers for CHP applications. IC engine is sensitive to heavy tar, which is usually deposited in the engine manifold and on the cylinder wall. Tar concentration depends on several factors such as:-

- ✓ **Temperature –** fundamental parameter for formation and maturation of tar. Higher operation temperatures reduce overall tar production but can lead to lower heating values.
- ✓ **Pressure**
- ✓ **Moisture and ash content**
- ✓ **Size of the feed stock**
- ✓ **Gasifying medium**

- ✓ **Equivalence ratio –** increasing equivalence ratio leads to lower tar production due to higher amount of oxygen for oxidation of volatile matter
- ✓ **Additive**

Chromatography Mass Spectrometry (Gc - Ms) Analysis and Gravimetric Approach are the common methods to experimentally analyze tar concentration in gasifier systems. In (Gc - Ms) Analysis**,** the samples collected by means of gas sampling of the tar sampling equipment was analyzed by a gas chromatograph coupled with a mass spectrometer and capillary column. [26]

Open top down drift gasifier showed satisfactory performance with respect to the reduced generation of tar and clean producer gas increased residence time in high temperature zones compared to the closed top designs [26].

2.5. Description of a Typical Gasifier – Engine Coupled Set – Up

The gasifier – engine coupled set up is composed of the following main components [16].

1. Gasifier and the feeding system
2. Gas cleaning and conditioning
3. Engine – generator set.

2.5.1. The Gasifier and the Feeding System

The gasifier/reactor performs the reduction step and thus production of producer gas and the hopper performs three function steps of gasification, namely, drying, pyrolysis and combustion [26]. The reactor is made of vertical sections and, in general, can be used as either single- or double-stage air-supply reactor with separate air-inlets to each section. To avoid channeling and bridging within the volume of biomass inside the reactor, a vibrating mechanism driven by an electrical motor with a special timing device is installed and this mechanism generates vibration motions inside biomass at regular time intervals. Such vibrations maintain continuous downwards movement of the feed in the reactor. Another similar vibrating mechanism is installed in the lower part of the gasifier to provide grate shaking which results in the ash discharge. If the gasifier works with a single stage of the air supply then the controlled amount of air is provided to its middle section. When used as a double-stage gasifier, the air supply to the reactor's first stage provides conditions for biomass partial combustion with a heat release maintaining the drying and pyrolysis phases. The downdraft gasifier is a fixed bed reactor, in which the feedstock is fed from the top

whilst air is supplied to the reactor in its middle section and syngas comes out the exit at the bottom of the reactor. [6]

2.5.2. Gas Cleaning and Conditioning

The gas cleaning and conditioning systems are composed of mainly:

- ✓ Cyclone
- ✓ Hot Gas Line
- ✓ Venturi Scrubber
- ✓ Wet Blower
- ✓ Separation Box
- ✓ Heat Exchanger
- ✓ Chiller
- ✓ Mist Eliminator
- ✓ Fine Filters
- ✓ Pleated – safety filter

Down Draft Gasifier allows maximum mixing of gases at high temperature region, helping in tar cracking and further reduction of hot char in to producer gas. This increase in quality of producer gas at the gasifier output contributes for good engine performance. Existence of char at the gasifier exit indicated loss of carbon in ash as a result of inefficient reduction.

2.6. Modeling of Gasification in Downdraft Gasifier [27]

Modeling implies the representation of a chemical or a physical system by a set of equations which in a limited way can represent the system under study [34].

The gasifier is generally modeled at two distinct zones:

1. Pyro - Oxidation Zone
2. Reduction Zone

2.6.1. Pyro - Oxidation Zone

- The Pyro - Oxidation Zone has been solved by considering chemical equilibrium of species as reduction occur very fast due to high temperature at the end of the zone to determine the concentration of species (H_2, CO, CO_2, CH_4, H_2O, N_2 and char) and the temperature of the gas which follows from Pyro - Oxidation to the reduction zone.

2.6.2. Reduction Zone

- Many researchers employ kinetics modeling in the reduction zone of gasifier for the char reduction rate, for it is a surface phenomenon on the char particles. The reduction zone has been solved based on chemical kinetics of reduction reaction by char, considering a large number of elemental control volumes along the length of the zone to predict final gas temperature.
- Temperature decays along the distance as the reduction reactions are endothermic in nature.
- Rate of temperature drop depends on the rate of reduction reactions guided by their kinetics. Here Char Creativity Factor (CRF) play an important role in predicting the temperature distribution as it takes care of the active reduction sites in the reduction zone.

2.7. Why Gas Conditioning and Cleaning?

For a gas to be used in burner application, an updraft gasifier can be used, and no cleanup is needed. However if the fuel gas will be fed to an engine, then a downdraft or another tar cracking gasifier must be used, and the gas must be cleaned and conditioned before it is fed to the engine. The gas emerging from downdraft gasifier is usually hot and laden with dust, containing up to 1% tars and particulates. If these materials are not removed properly, they can cause maintenance, repair and reliability problems much more costly and troublesome than operation of the gasifier itself. In fact it is likely that more gasifier engine systems have failed because of improper cleanup systems than any other cause [29].

In order to design effective gas clean up systems, one must determine the magnitude, size and nature of contaminants and then couple that information with knowledge of methods available for their removal.

2.8. Producer Gas Contaminants

The product gas exiting the gasifier normally contains unwanted components like particles, alkali compounds, tars, and nitrogen containing compounds. Depending on the design of the gasifier and type of fuel used, there can be more or less of the mentioned components. These components are normally incompatible with end – use systems and therefore gas cleaning is requited for those systems. The most frequent impurities are hydrocarbons (tars), dust (particles), ammonia, sulfur, chloride, alkalis etc... that need to be removed or converted [29].

Cooling is also required for the following cases [41]:

I. To meet engine combustion requirements
II. When filters are applied with maximum allowable temperature

The various contaminants that need to be removed from the producer gas used in internal combustion engines for power generation are summarized in the table below.

Table 3: Producer Gas Contaminants [41]

Contaminant	Example	Potential Problem
Particles/Solid particulate matter	Ash, char, fluidized bed material	Erosion
Alkali compounds/metals	Sodium and potassium compounds	Hot erosion and catalyst poisoning
Nitrogen compounds	NH_3 and HCN	Emissions
Tars	Refractive aromatics	Clogging of filters and engine cylinders
Sulfur and Chlorine	H_2S and HCl	Corrosion, emissions, catalyst poisoning

2.8.1. Solid Particulate Matter

Solid particles in a raw gas leaving the gasifier comprise the following unwanted materials [42]:

- Inorganic fuel residues (ash)
- Non reacted fuel in the form of charred material (the so called coalite)
- Inert material of gasifiers bed
- Soot present in the dust

Problems: Gasifiers with bubbling and circulating fluidized bed produce gases with high concentration of solid particles due to the turbulent conditions inside the reactor. Solid particulate matter together with tar forms scale deposit on pipe walls and causes abrasion and fouling effect will introduce additional thermal resistance that will affect heat exchangers performance along the gas line [42].

Remedies: Particle separation can be carried out at high temperatures (cyclones, moving bed filters, ceramic filter candles) or at low temperatures (scrubbers, wet electrostatic

precipitators). Cyclones are suitable for 1st stage separation but normally the particle content in the clean are still too high. Therefore, for high temperature particle separation, moving bed filters or filters containing filter candles are necessary to meet the clean gas requirements [42,43].

Table 4: Comparison of Different Particle Separators [43]

Particle separation method	Temperature range (^{0}C)	Particle reduction (%)
Cyclone	20 – 900	45 – 70
Sand bed Filter	20 – 900	80 – 95
Bag Filter / Candle Filter	150 – 750	90 – 99
Scrubber	20 – 200	40 – 65
Wet Electrostatic Precipitator	40 – 50	95 – 99

2.8.2. Alkali Compounds

Certain components of dust that include alkali metals will cause several operational problems due to the potassium (K) and sodium (Na) that may be present in the stalkculum plants that may be introduced in to RDF as a biomass fraction [42].

Problems: Salts of potassium and sodium evaporate below 700^{0}C, they easily melt and form deposits of ash on cooler surfaces of equipment (below 650^{0}C). The deposits mostly affect heat exchangers and combustion engines. This is because unless the compounds are removed from the gas, they pass through the whole system and condensate and deposit beyond filtering devices. High temperature corrosion of metal materials is another problem which may be caused by alkali salts, especially if vanadium catalyzes the corrosion (in co-gasification of biomass and waste) [42].

Remedies: Disposition of alkali salts is usually traced by cooling the gas and eliminating fine particles where salts condensate at temperature below 600^{0}C. Technologies like electrostatic precipitator, bag filters or wet scrubbers are highly efficient tools [42,37].

2.8.3. Nitrogen Compounds

Most nitrogen in the produced gas is in the form of N_2, and its concentration depends on type of the gasifying medium. Ammonia (NH_3) is the main nitrogen component in the raw gas which is formed by conversion of protein and other nitrogen containing fuel components and cyanide (HCN) is the less significant compound [42].

Problem: Polluted emissions as a result of the ammonia. Nitrogen compounds cause various operational problems in the scrubbers due to high solubility in water since their elimination from water is very difficult (water is saturated with HCN and NH_3, and is not capable of collecting them any more) [42].

Remedies: Standard catalytic methods (addition of dolomite catalyst with the feed) may be performed for NO_x reduction. If gas temperatures are low enough, it is better to use catalytic distraction of NH_3 prior to combustion or wet scrubbing [42].

2.8.4. Sulfur

Sulfur exists in the raw gas in the form of H_2S (93-96%) and CS_2, COS, and SO_X concentrations are minimum. H_2S concentrations are commonly below limits of traceability.

Problem: Yet, elimination of sulfur from the gas is highly desirable for majority of gas applications because it may cause various operation complications. Sulfur together with Chlorine, Fluorine and Alkali salts is corrosive for steel constructions. It is also poisonous to tar removal catalysts.

Remedies: Wet scrubbing, using additives (Very costly), reactions of suitable absorbents or adsorption on metal catalysts are technologically available solutions. While sulfur removal by wet scrubbing is a well proven technology and is used in large scale applications, high temperature desulfurization is still under development [43].

2.8.5. Chlorine

Concentrations of chlorine in Biofuel are low. Despite this fact, chlorine may cause formation of HCl and persisted organic compounds. HCl is most common form of chlorine in gas [42].

Problems: Corrosion, emissions [42].

Remedy: Wet scrubbing eliminates certain chlorine compounds most importantly HCl [42].

2.8.6. Tar

Tar is a by-product of pyrolysis whose main source is a volatile combustible. Tar designates a group of organic substances with various structures and chemical properties with boiling point higher than boiling point of benzene (80.1^0C). Tar exists in gaseous stream in the form of vapors and/or persistent aerosols. Tar condenses at lower temperatures [42].

Problem: Tar condensed at cool surfaces, together with solid particles fouls pipes and equipments.

If gasification temperatures are below 400^0C, tar components may be dehydrated and started to create char and coke [42].

Remedies: To decrease concentrations of tar in gas, there are generally two methods [44].

I. Primary Method (Procedures performed inside the gasifier)
II. Secondary Methods (Methods applied outside the gasifier) – further distinguished as dry and wet procedures.

2.8.6.1.Primary Methods for Tar Removal

Primary methods are tar reduction procedures performed inside the reactor.

Advantages: this practice is advantageous because beyond reducing tar concentration from producer gas, increases energy conversion efficiency and eliminates the subsequent tar disposal had it been removed outside the gasifier [42].

Two procedures are applied here [43]:

- **Thermal Destruction**
- **Catalytic Destruction**

2.8.6.1.1. Thermal Destruction

There is no minimum temperature defined for efficient destruction which depends on type of tar produced in reactor. For a pyrolysis process taking place at temperatures above 1200^0C, no catalysts needed [42].

Gasifiers with counter current arrangement and sliding bed create primary tar and sufficient temperature for thermo-destruction is 900^0C, partial combustion of the produced gas usually increases the temperature. However, this process is accompanied by decrease in lower heating value of 25 – 30%. Use of plasma also increases temperature but this is more suitable for waste disposal where electrical energy necessary for plasma creation is a by-product. Both processes are expensive. Therefore, thermal destruction is not a very promising method of elimination of tar from gas [42].

2.8.6.1.2. Catalytic Destruction

Various materials such as divenite, silica sand and other minerals and metals are added in to reactor as catalysts to enhance tar cracking. Dolomites, zeolites, calcites and silicates are commonly used for tar distraction as well as metal catalysts based on Ni, Mo, Co, Pt, Ru and other metals. Majority of metal catalysts are highly sensitive to sulfur deactivation and their life is rater short. Tar elimination using dolomite is achieved 95 – 99% efficiency in laboratory conditions with temperatures ranging from 750^0C to 900^0C. Major disadvantage is the need to reheat the gas to 900^0C. (Temperature of the gas leaving the reactor in most cases is below 800^0C). Dolomite, the abundant and cheap catalyst with its good properties seems to be a very promising additive. Relatively high temperatures and turbulent streaming produces intensive reactions in fluidized beds, makes the catalyst deactivate. On the other hand, there is sufficient contact between catalyst and tar in fixed bed reactors, and tar destruction is often incomplete [42]. A study by [45] used activated carbon and dolomite and observed that activated carbon was better than dolomite for tar removal.

2.8.6.2.Secondary Methods for Tar Removal

Secondary methods for decrease in tar concentration are applied outside the reactor. The following techniques may be applied.

2.8.6.2.1. Barrier Filters

Fixed layer of loose material, for example, wood chips, saw dust, cork and sand remove especially dust (tar elimination is less significant). Also, there has to be continuous renewal of filtration material so that high pressure drop due to filtration cake is avoided. Used filtration material has to be either regenerated, combusted or disposed [42].

2.8.6.2.2. Wet Scrubbing

Droplets of separated matter and scrubbing liquid precipitate in the scrubber, and then decrease tar concentration. Formation of tar droplets has to be preceded by cooling of the gas temperatures below 100^0C. (Usually filtration below 250^0C separates solid particles) Exhaust temperature of gas is required to range from 35^0C to 60^0C. Therefore, scrubber must comprise a cooler, fine mist separator and occasionally a solid particle separator at the same time. To eliminate the problem of concentration of solid particles it should be focused on the properties of scrubbing liquid, which not only collects the relevant particles but also cleans the gas. Disadvantage of gas scrubbing systems is their decreased efficiency which may be

influenced by applying organic liquids, high capacity sensible heat of the gas passes in to the scrubbing liquid but cannot be utilized due to low output temperature of the liquid. Unless different liquid is used, polluted water is produced and has to be pre-heated before entering the sewage system [44].

3. METHODOLOGY

Within this frame work of small scale power generation, the most attractive alternative to RDF conversion is to gasify it in a downdraft gasifier and couple it to an internal combustion engine for utilization, which powers an electricity generator. The gasification system would consist of a gasifier (down draft) with gas filter and cleaning, an internal combustion engine as well as electric generator.

This paper uses two approaches, simulation and experimental methods. Gasifier and feedstock will be modeled and simulated in MATLAB to determine optimum operating parameters for optimum design of the system along with characterization of the product gas. The results will be kept and validated using actual results determined from a test run on a manufactured pilot gasifier – engine set up. Gas cleaning and conditioning system designed and manufactured based on the requirements demanded by this application is further investigated using experimental approach for its performance.

Finally results will be analyzed; sensitivity analysis for few critical cases like effects of temperature on gas composition and catalytic gasification will be performed to draw valid conclusions from the work.

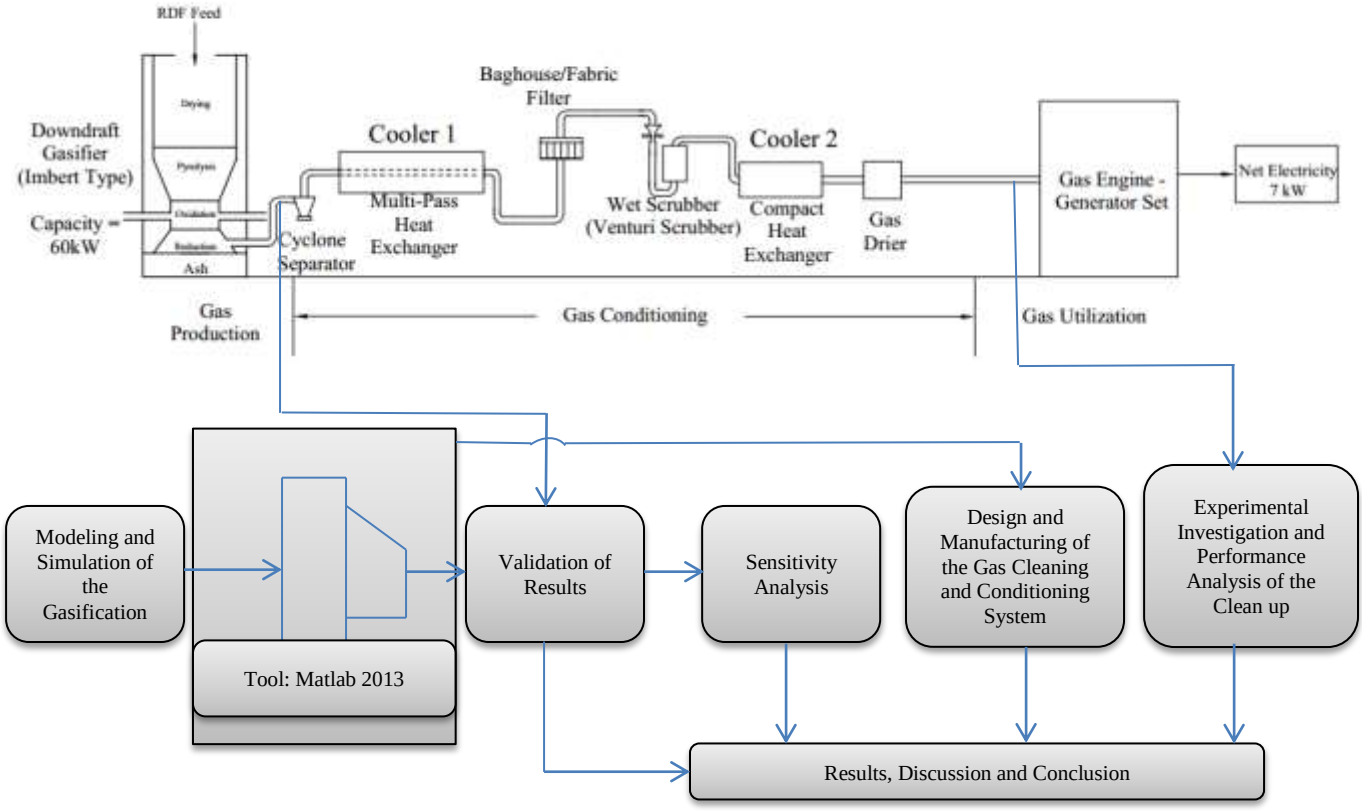

Figure 1: A Brief Description of Methodology of the Research

The Construction of the set - up is in accordance to the following principles:

- Using Locally available and durable materials
- Cost-effectiveness
- Simplicity and friendliness
- Safe – non-hazardous while operating
- Most efficient as possible
- Portability

3.1. Scope and Delimitations

The scope of this particular research includes modeling, simulating, manufacturing and testing of a small scale electricity generating plant from RDF gasification. The sciences of mechanical engineering (most importantly, thermal engineering) and chemical engineering to some extent will be dealt with to design and test a micro-scale gasification-electrification plant fed by RDF as input. Further efficiency improvement techniques will be future work that depends on experimental results so it will not be included in this research. The environmental analysis will not be included in this research and yet it will be dealt in the future work along with the economic evaluation of the plant. H_2, H_2O and Tar measurements for their content in the product gas was not possible for the unavailability of the measuring apparatuses like genuine Producer Gas (Syn Gas) Analyzer in AAiT and other labs outside AAiT, and this counts for the delimitations on the experimental work and test result accuracy plus working with locally available outdated and less accurate apparatuses (gas analyzer with $\pm$1ppm accuracy) has put limitations on the work. Unavailability producer gas engine – generator set has limited the scope of this work to the point where a cleaned and conditioned gas produced for its utilization. Wet venturi scrubber is also equipment that was not possible to get from abroad and yet gas cleaning was made to have all the designed components except this one. I am hopeful that these material and facility limitations will be overcome from the continuing thematic fund from AAU research office for the next consecutive two years for future advancements on this work.

4. THEORY OF GASIFICATION AND GASIFIERS

Gasification is the conversion of chemical feedstock that can be burned to give convenient gaseous fuel or used for production of value-added chemicals. Gasification and combustion are the two closely related thermo chemical processes, but there is an important difference between them. Gasification packs energy into chemical bonds in the product gas; combustion breaks those bonds to release the energy [4].

Gasification: Feed Stock + Limited Oxygen/Air + steam (optional) → Usable Gas, [29]

4.1. Gasification - The Conversion Alternative: Why Gasification?

For conversion of biomass and waste to energy, technologies like digestion, gasification, incineration and steam generation are some of the available processes [17]. But gasification is the best alternative due to the following reasons [28].

- Gasification offers high flexibility in terms of various materials as feedstock.
- Gasification has thermo – chemical conversion efficiency in the range of 70% to 90% which is the highest among various alternatives.
- Gasification output capacity, especially in the high output ranges is controlled only by availability of adequate feed materials rather than other technical considerations.
- The area requirement for gasification equipment is the lowest per unit output energy in the form of heat and/or electricity.
- The gasification equipment has high turndown ratios comparable to biogas and higher than steam turbine system.
- Gasification outputs are suitable as a fuel to all types of internal combustion engines with capacity ranging 15% to 30%.

4.2. Theory of Gasification

In this discussion of theory of gasification the emphasis will be limited to gasifiers (the reactors, will be discussed in next topic) that operate at temperatures of 850^0C and higher. Below 850^0C is, on the other hand, the domination of pyrolysis reactions that are extremely complex to model, where the partial oxidation reactions proceed at so slow rate that they became of little practical value [50].

Based on the interaction of air and oxygen and the feed, gasifiers are classified as downdraft, updraft and crossdraft to the way the gasifying medium (air or oxygen) and feed is introduced in it [52]. They are shown schematically in figure below.

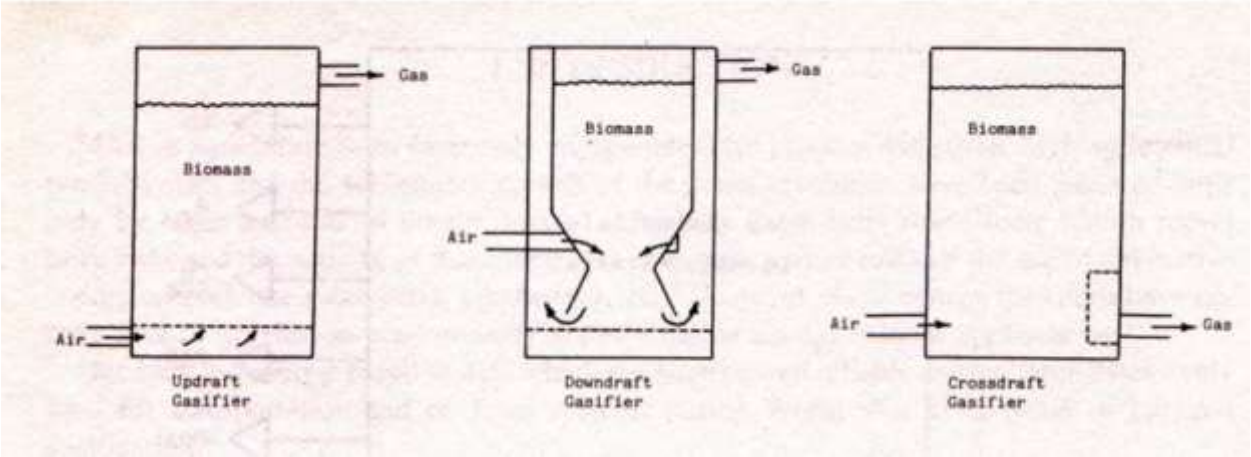

Figure 2: Various Types of Gasifiers

4.2.1. Process Zones

Four distinct processes take place in a gasifier as fuel makes its way to gasification. These are [52]:

- Drying of the fuel
- Pyrolysis – a process in which tar and other volatiles are driven off
- Combustion
- Reduction

Though there is a considerable overlap of the process, each can be assumed to occupy separate zones with fundamentally different chemical and thermal reactions taking place.

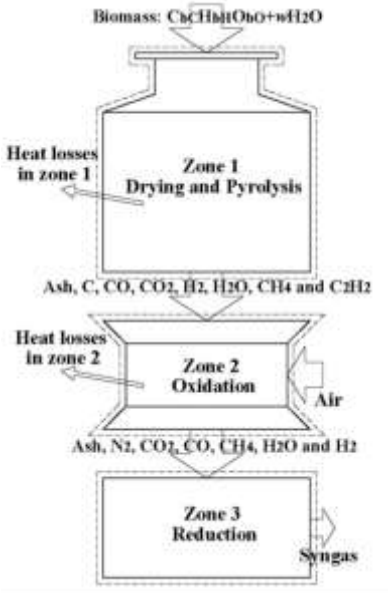

Figure 3: Process Zones of a Typical Downdraft Gasifier [53]

4.2.2. Reaction Chemistry

- Combustion reactions, [50]

$C + \frac{1}{2} O_2 \rightarrow CO$ -111MJ/Kmol

$CO + \frac{1}{2} O_2 \rightarrow CO_2$ -283MJ/Kmol

$H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ -242MJ/Kmol

- The Boudouard reaction, [50]

$C + CO_2 \leftrightarrow CO$ +172MJ/Kmol

- The Water Gas reaction, [50]

$C + H_2O \leftrightarrow CO + H_2O$ +131MJ/Kmol

- Methane Formation reaction, [50]

$C + 2\,H_2 \leftrightarrow CH_4$ -75MJ/Kmol

In general it is concerned with situations where also the carbon conversion is essentially complete. Under these circumstances, the Boudouard and Water Gas reactions can be reduced to the following reversible gas reactions called CO Shift reaction (Water – Gas Shift reaction).

$CO + H_2O \leftrightarrow CO_2 + H_2$ -41MJ/Kmol

4.3. Gasifier

Gasifier is a vertical flow packed reactor through which oxygen or air for combustion is passed through it which may pass downward, upward or across the bed depending on the type of the gasifier [4].

4.4. Classification of Gasifiers

Gasifiers are classified as per the type of the bed [28]. That are:

1. Fixed Bed
2. Fluidized Bed

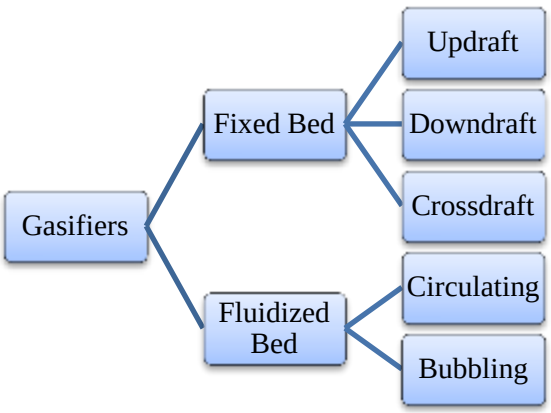

Figure 4: Classification of Gasifiers

4.4.1. Fixed Bed Gasifiers

When the air or oxygen is passed upwards, and gases leave at the top of gasifier, this is known as updraft gasifier. When the air is passed downward and gases leave at the bottom, this is known as downdraft gasifier. When air passed across the bed and gases leave across the bed, this is known as cross draft gasifier. Schematics of the three fixed bed gasifiers are shown below [4].

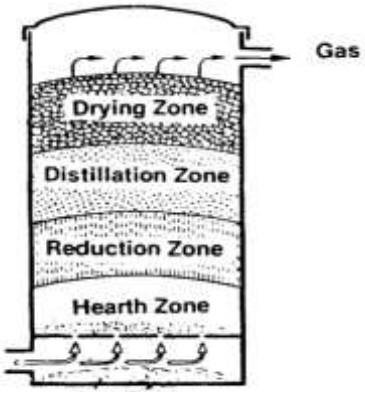

Figure 5: Schematics of Up Draft Gasifier [29]

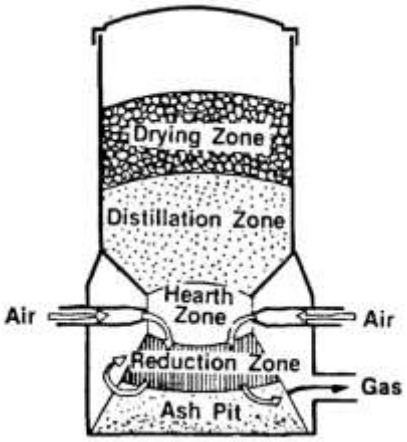

Figure 6: Schematics of Down Draft Gasifier [29]

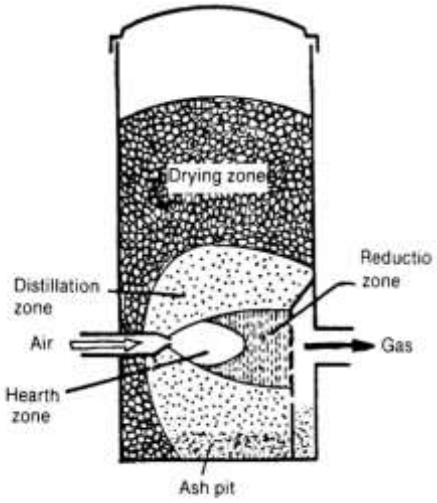

Figure 7: Cross Draft Gasifier [29]

Table 5: Comparison among Various Types of Fixed Bed Gasifiers [28]

No	Gasifier Type	Advantages	Disadvantages
1.	Up draft Gasifier	▪ Small pressure drop ▪ Good Thermal Efficiency ▪ Little tendency towards slag formation	▪ Great sensitivity to tar and moisture content of the fuel ▪ Relatively long time to start – up of an IC engine ▪ Poor reaction capacity with heavy gas load.
2.	Down draft gasifier	▪ Flexible adaptation of gas production to load. ▪ Low sensitivity to charcoal dust and tar content of the fuel.	▪ Design tends to be tall. ▪ Not feasible for very small particle size of fuel.
3.	Cross draft gasifier	▪ Short design height. ▪ Very fast response time to load. ▪ Flexible gas production.	▪ Very high sensitivity to slag formation. ▪ High pressure drop.

4.4.2. Fluidized Bed Gasifiers

Fluidized bed gasification system is used for the fuel which has high ash content and the ash has low melting point. In fluidized bed gasifiers the air is blown upwards through the biomass bed. The bed under such conditions behaves like boiling fluid and has excellent temperature uniformity and provides efficient contact between solid and gaseous and solid phases. Generally the heat is transferred internally by hot bed of sand. Normally the operation temperature of the bed is maintained within the range 750 – 950 ^{0}C so that the ash zone will not be heated to its initial deformation temperature and this prevents clinkering and slagging

[28]. The major advantage of fluidized bed gasifiers is over down draft is its flexibility with regard to feed rate and rate of consumption but it produces more dust and tars as compared to down draft gasifier. This puts a heavy load on the cleaning and cooling system [30]. Schematics of fluidized bed gasifier types are shown below.

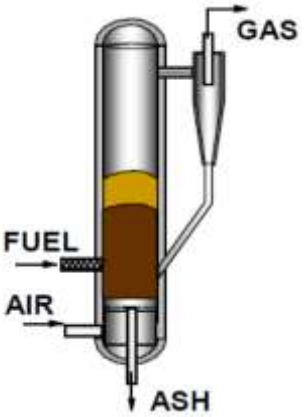

Figure 8: Circulating Bed Gasifier [41]

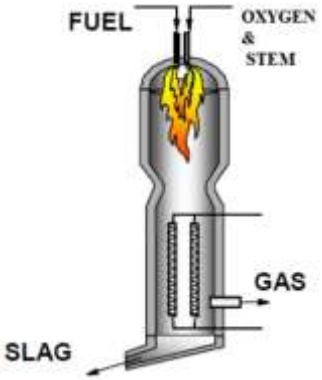

Figure 9: Entrained Flow Gasifier [41]

Fixed bed gasifiers are suitable to use for appropriate applications. Up draft gasifier has higher conversion efficiency, but it produces more tar than down draft gasifier. The figure below shows preferred gasification technologies at different scales.

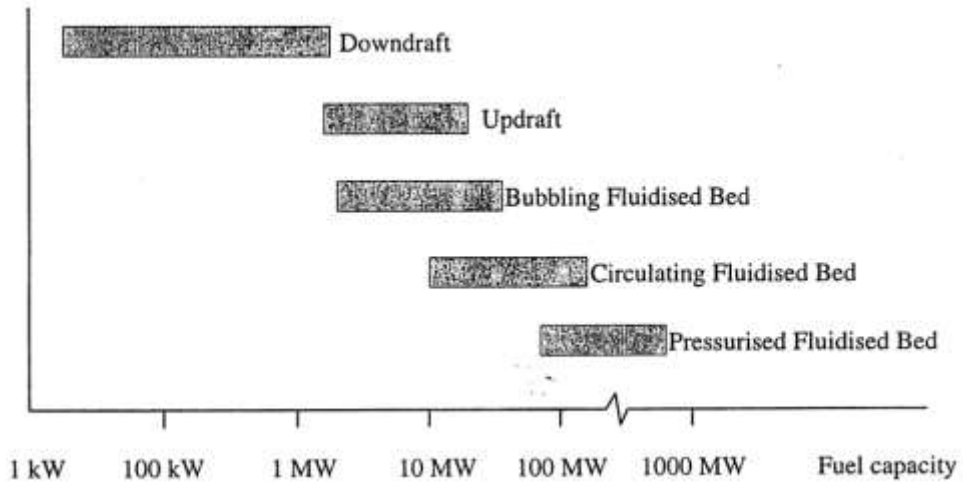

Figure 10: Preferred Gasifier Types at Different Scales [31]

4.5. Gasifier for Engine Applications for Electricity Generation

Among the available alternatives, fluidized bed gasifier is not nominee for engine application for its high tar content and for its heavy cleaning and cooling load duty [30].

Selection criteria:

The selection criteria are set to achieve best performance in IC engines. These are:

- Thermal Efficiency
- Sensitivity to tar content of the fuel
- Gas cleaning load demand
- Flexibility of gas production to load
- Application on ICEs
- Relative time to start up an IC engine

Table 6: Gasifier Selection Check List [Judgments Based on Researches 28,29,30,31]

Gasifier Type	Thermal Efficiency	Sensitivity to tar content of the fuel	Flexibility of gas production to load	Application on ICs	Relative time to start up an IC engine	Gas Cleaning load demanded
Up draft	V. Good	High	------	Good	Poor	Very High
Down draft	Good	Low	V. Good	V. Good	V. Good	High
Cross draft	Good	------	V. Good	Poor	V. Good	-------

The above table shows clearly that down draft gasifier has best fits for the intended engine application and the same thing is true as discovered from review of literatures as discussed in the literature review part.

4.6. Downdraft Gasifier and Its Configuration

In downdraft gasifier the feed stock and the gasifying medium both move in the same direction (downwards). According to the design, the pyrolysis products are passed through the blowing bed of the fuel and tar is cracked in to gaseous products, so the amount of tar in this particular type of gasifier is relatively low. Drawbacks of the downdraft gasifier are the high amounts of ash, dirt particles in the gas and excessive pressure drop. Downdraft gasifiers demand relatively strict requirements of the fuel like moisture content less than 25% (wet basis). Syngas exits the reactor at high temperatures (>700^{0}C). Schematic of a typical downdraft gasifier is shown in figure 4.

Generally, two types of fixed bed down draft gasifier configurations are distinguished [29].

1. Imbert (Throated or Closed Top Gasifier)
2. Stratified (Throat less or Open Top Gasifier)

4.6.1. Imbert Downdraft Gasifier

This gasifier is characterized by hearth and nozzle. Below air nozzle is the reduction zone consisting of classical Imbert hearth. The hearth constriction causes all gases to pass through the hot zone. The design of the hearth also allows retained ash to accumulate, improving the insulation which results in lower tar production. Schematic of an Imbert gasifier is shown below.

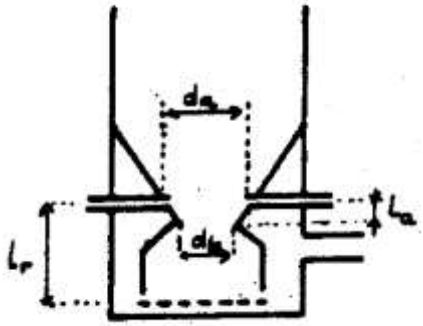

Figure 11: Schematic of an Imbert Gasifier [29]

4.6.2. Stratified Down Draft Gasifier

This gasifier consists of cylindrical vessel with a hearth at the bottom. During operation the air and biomass move downwards through the four zones in the reactor. Open top ensures uniform access of air and permits fuels to be fed easily and uniformly with local temperatures kept in control but has higher dust generation. The figure below shows schematics of stratified down draft gasifier.

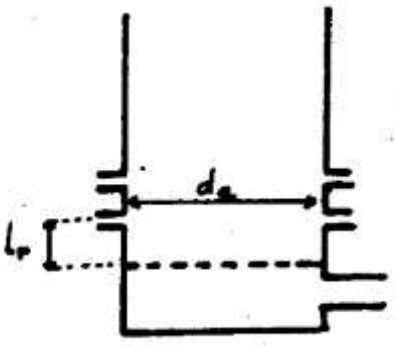

Figure 12: Schematic of Stratified (No Throat) Gasifier [*29]*

The throat on Imbert gasifier increases the conversion efficiency of the gasifier. Smaller

throat diameter gives high conversion efficiency and vice versa. The throat angle also affects conversion efficiency and small angles give high conversion efficiencies and vice versa due to divergent nature of large angles. However, small angles require long reduction zones. The improvement on gasifier conversion efficiency is well managed by optimizing the throat size and angle [37]. Dust and tar are less with this configuration, therefore Imbert gasifier is best suited so ICs application.

5. RDF FUEL PREPARATION AND CHARACTERIZATION

5.1. Refuse Derived Fuels (RDF)

Refuse is a general term for municipal and commercial solid waste. RDF usually refers to a separate high calorific fraction of municipal solid waste (MSW), solid and dry commercial and/or industrial process wastes. Other terms are also used for MSW derived fuels, such as: Refused Fuel (REF), Packaging Derived Fuels (PDF). Paper and Plastic Fraction (PPF) and Process Engineered Fuels (PEF). These all usually refer to a source separated, processed, dry combustible MSW fraction which may or may not be too contaminated to be recycled. It has a high calorific value, lower moisture content and lower ash content (on combustion) than mixed waste fractions [14]. The higher heating value of RDF can be as much as 23.97 MJ/kg, moisture percent, 8.54% and the ash content, 2.94% [13]. The amount of energy per unit weight that is generated from RDF was 4.15 kWh/kg [15]. Even though there are quality standards set for RDF production and utilization, there is no usage of RDF fuel and regulation of the respective quality standards in Ethiopia. According to Quality standards set for RDF by European Union (EU) dictates that, the limit for NOx is 400 mg/Nm^3 as per the EU Directive 2000/76/EC and therefore it can be seen that the NOx emission from RDF complies with the limits. The emission for SO_2 is 50 mg/Nm^3 as per EU Directive 2000/76/EC and hence the emission from RDF complied with the limits. The following figure shows various routes for using MSW for energy generation.

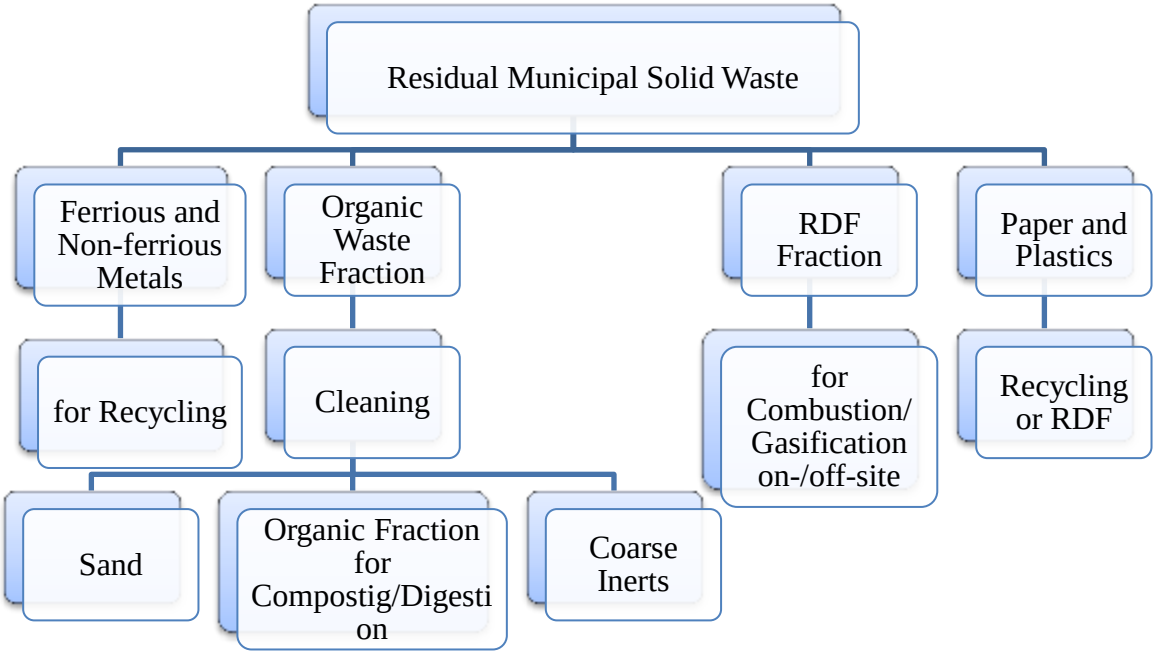

Figure 13: MSW Conversion Routes [EU Directive 2000/76/EC]

5.2. RDF Production Process

RDF can be processed from MSW through a number of different processes consisting in general of [14]:

1. Separation at source
2. Sorting or mechanical separation
3. Size reduction (Shedding, Chipping and milling etc …)
4. Separation and Screening
5. Blending
6. Drying and Pelletizing
7. Packaging
8. Storage

In this case, the waste is separated from the nearby small landfill in Addis Ababa. To separate metallic recyclable fractions, a manual sorting is carried out instead of mechanical (magnetic) separation for it is too expensive and inaccessible. Shearing and milling operations are performed in mechanical workshop to reduce size. Right after that, the inert fractions like glass and sand, and the wet putrescible fractions like food and garden waste containing high moisture and ash are manually screened before pulverized is allowed to dry and palletized to 2 – 6 cm particle size as recommended by [15]. Here the resulting fuel is blended with dolomite catalyst as a treatment for tar reduction inside the gasifier (detail discussion is in design of gas cleaning system section). The RDF prepared this way is packed for characterization.

The separated and screened out fractions from this process of preparation of RDF has to be disposed properly. But it is recommended that the wet organic materials can undergo further treatment such as composting or anaerobic digestion, and can be used as soil conditioner for landfill restoration work or be landfilled. The coarse fraction is either rejected to the pulverizer. The medium fraction consisting of paper, card, wood, plastics and textiles can either be burnt as coarse fuel (c-RDF) or dried and palletized in to dense RDF (d-RDF) [14].

Figures 14: Landfill for Waste Separation

Figure 15: Separated, Dried, Screened and Palletized Waste Sample

Figure 16: RDF Composition

Figure 17: Sample RDFs

Figure 18: Crashing RDF for Characterization

Figure 21: Crashed Sample RDF 1

Figure 20: Crashed Sample RDF 2

Figure 19: Crashed Sample RDF 3

5.3. RDF Characterization

Characterization is a method used to determine the materials being discarded from fuel stream and in what proportions. It gives information like elemental composition of the fuel, fixed carbon, volatile matter present, moisture and ash content [33].

Prepared RDF samples shown in figure 15 are analyzed in a laboratory at Chemistry Department at College of Natural and Computational Sciences, Addis Ababa University for ultimate analysis and at Geological Survey of Ethiopia laboratory for the proximate analysis. The test results for three RDF samples are attached on Appendix A.1 and compiled in the following tables.

Table 7: Ultimate Analysis Result for RDF Samples

Sample No	Sample code	C [%]	H [%]	N [%]	S [%]
1	RDFS1a	44.02082	6.360334	1.197624	0
2	RDFS1b	41.64986	5.907319	0.87342	0
3	RDFS2a	41.14566	5.92037	0.441625	0
4	RDFS2b	42.96608	6.130091	0.379078	0
5	RDFS3a	41.1352	5.984506	0.274145	0
6	RDFS3b	39.42715	5.4862	0.256009	0
Average		**41.7241**	**5.9648**	**0.5703**	**0**

Table 8: Proximate Analysis Result for RDF Samples

Sample No	Sample code	Lab no.	Moisture [%]	Volatile matter [%]	Fixed carbon [%]	Ash [%]	Calorific value [cal/gm]
1	A.D.F.S -1	1267/17	6.10	72.42	11.84	9.64	4035.91
2	A.D.F.S -2	1268/17	6.72	74.32	11.74	7.22	3996.72
3	A.D.F.S -3	1269/17	6.59	73.17	10.79	9.45	3927.68
4	A.D.F.S -3	1269/1 Dup	6.84	72.56	11.06	9.54	3938.43
Average			**6.5625**	**73.12**	**11.36**	**8.96**	**3974.69 = 16.63MJ/Kg**

The average values are taken and the characterization of RDF is shown in the following table.

Table 9: Characterization of the RDF

Fuel	**C**	**H**	**N**	**O***	**S**	**FC**	**VM**	**Ash**	**Moist.**	**LHV** [MJ/Kg]
RDF	**41.7241**	**5.9648**	**0.5703**	**36.2183**	**0**	**11.36**	**73.12**	**8.96**	**6.5625**	**16.63MJ/Kg**

*O = 100 – (C + H + N + S + Ash + Moist.)

In general the lower heating value (LHV) of a typical RDF lies in the range 15 MJ/kg to 18MJ/kg according to the selection process and amount high LHV constituents present [15]. The LHV value of the prepared RDF is 16.63MJ/kg which confirms it is a good range to be accepted as a good RDF. Percent contribution of each constituent in the RDF sample is:

Table 10: Percent Contribution of Each Constituent in the RDF Sample

Constituent in sample RDF	Percent share in the sample RDF
Plastics	7.31%
Garden wastes	7.75%
Biomass	38.68%
Textiles	13.28%
Card paper	11.70%
Paper waste	21.28%
Total	100%

The chemical formula that describes the RDF is: $\mathbf{CH_{1.7155}O_{0.6510}N_{0.01172}}$

6. MODELING OF RDF GASIFICATION IN IMBERT TYPE DOWNDRAFT GASIFIER

6.1. Gasification Models

One of the most wide spread approach to recover energy from waste is gasification of RDF which is performed by processing raw waste to obtain a refuse – derived fuel (RDF) which can be utilized in gasifier. During gasification, four key processes occur inside the reactor, namely drying, pyrolysis, oxidation and reduction [4]. Each of these processes has certain physical and chemical features. Modeling implies the representation of a chemical or a physical system by a set of equations which in a limited way can represent the system under study [34]. When considering downdraft gasifier, the modeling of chemical reactions taking place in each different zones (shown in figure below) should be carried out separately.

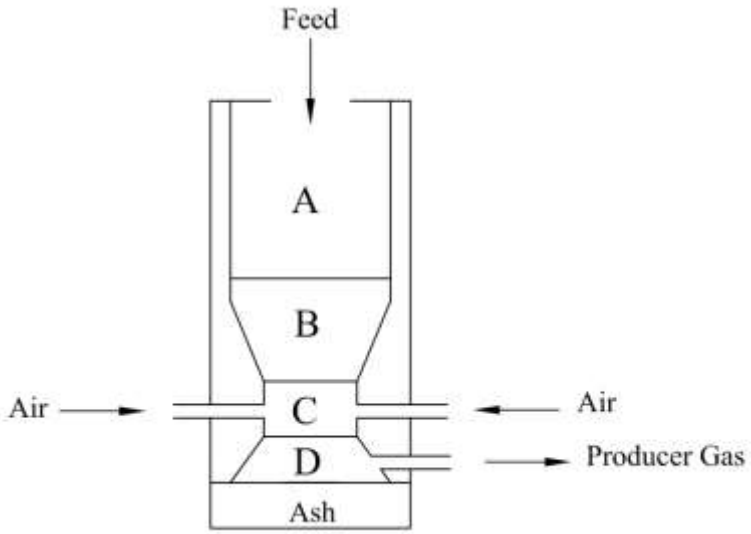

Figure 22: Schematics of Key Reaction Zones of Downdraft Gasifier

Gasifier simulation models can be classified in to thermodynamic equilibrium model, kinetic model, CFD model and antificial neural network [4]. The thermodynamic equilibrium models can be approached by either stoichiometric or non-stoichiometric models. Stoichiometric equilibrium models incorporate the thermodynamic and chemical equilibrium of chemical reactions and the species included. The model can be designed either for a global gasification reaction or can be divided in to sub-models for drying, pyrolysis, oxidation and reduction reactions. The non-stoichiometric equilibrium model is solely based on minimizing Gibbs free energy of the system and there is no specification for particular reaction mechanisms. However, Moisture content and elemental composition of the fuel is needed which can be obtained from ultimate analysis data of the feed [4,35]. Therefore this method is particularly

suitable for fuels like biomass and RDF whose exact chemical formula is not directly known [35]. A kinetic model allows predicting the gas yield, product gas composition after finite residence time in finite volume and temperature inside the gasifier. Moreover, it involves parameters such as reaction rate, residence time, reactor hydrodynamics (superficial velocity, diffusion rate) and length of the gasifier [4]. Kinetic model provides a wide provides a wide dimension to investigate the behavior of a gasifier via simulation and it is more accurate model but computationally intensive [35]. Modeling of gasification using different approaches considers the following reactions as basic gasification reactions [4]:

Boudouard Reaction:

$$C + CO_2 \rightarrow 2CO$$

Water-Gas Reaction:

$$C + H_2O \rightarrow H_2 + CO$$

Methane Forming Reaction:

$$C + 2H_2 \rightarrow CH_4$$

Steam Reforming Reaction:

$$CH_4 + H_2O \rightarrow H_2 + CO_2$$

This section is devoted to build a realistic model for gasification of RDF in a fixed bed downdraft gasifier to estimate species concentration in the producer gas and the respective heating values for wide range of gasification temperatures and equivalent ratios to determine optimal operating gasifier temperature and equivalent ratio (E.R).

The non-stoichiometric equilibrium model for gasification of RDF was formulated and solved using MATLAB for determination of optimal operating conditions.

6.2. Model Formulation

Empirical relations were developed for predicting the individual fraction of major combustible species of the producer gas. Although these equations can be used for any type of gasifier, it is more accurate for a downdraft gasifier due to its low tar content. The composition of producer gas is dependent on parameters like: composition of the fuel, moisture content, ash content, heating value, size, bulk density, equivalence ratio, gasification temperature…etc[19,23]. In this study a thermodynamic model was formulated based on the following assumptions:

- The species considered to appear in the producer gas are: CO, CO_2, H_2, CH_4, N_2, water.
- All carbon content in RDF is converted in gaseous form and the residence time is high enough to achieve thermodynamic equilibrium.
- Ash in feedstock is assumed inert in all gasification reactions although it hold true only for reaction temperatures below 700 ^{0}C.
- All gaseous products are assumed to behave as ideal gases and the temperature drop inside gasifier is assumed to be negligible.
- The process is completely adiabatic so that no heat loss occurs from the gasifier.
- Sulfur and Chlorine content in RDF is negligible since they have a very small share (<0.6%) in total feedstock.

The chemical composition of RDF is taken to be in the form $CH_xO_yN_z$ and the global gasification reaction can be written as:

$CH_xO_yN_z + m_wH2O + X_{air}\ (O_2 + 3.76N_2) \rightarrow n_1CO + n_2H_2 + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6N_2$

- m_w can be calculated by:

$$m_w = \frac{M_{RDF} \times m}{[18(1-m)]}$$

(a) Mass Balance

Carbon Balance:

$$n_1 + n_5 + n_3 = 1 \quad (1)$$

Hydrogen Balance:

$$x + 2m_w = 2n_2 + 2n_4 + 4n_5 \quad (2)$$

Oxygen Balance:

$$y + m_w + 2X_{air} = n_1 + 2n_3 + n_4 \quad (3)$$

Nitrogen Balance:

$$n_6 = 0.5z + 3.76X_{air} \quad (4)$$

(b) Basic Chemical Equilibrium Reactions and Equilibrium Constants

The major reactions that occur inside downdraft gasifier are [4]:

$$\left.\begin{array}{l} C + CO_2 \rightarrow 2CO \\ C + H_2O \rightarrow H_2 + CO \end{array}\right\} \quad (5)$$

The two reactions shown above can be combined into one single reaction known as water-gas shift reaction [4].

$$CO + H_2O \rightarrow H_2 + CO_2 \quad (6)$$

The other reaction that is important in the gasification process is methane formation reaction.

$$C + 2H_2 \rightarrow CH_4 \quad (7)$$

Now equation 6 and 7 are the two major reactions in the gasification process. The equilibrium constants for the above two major reactions as a function of their molar composition can be written as:

$$K_1 = \frac{n_{CO_2} * n_{H_2}}{n_{CO} * n_{H_2O}} = \frac{n_3}{n_1}\frac{n_2}{n_4} \quad (8)$$

$$K_2 = \frac{n_{CH_4} * n_{tot}}{(n_{H_2})^2} = \frac{n_5}{n_2}\frac{n_{tot}}{n_2} \quad (9)$$

Where, $n_{tot} = n_1 + n_2 + n_3 + n_4 + n_5 + n_6$

Gibbs free energy is used in determining the values of K_1 and K_2. For the given ideal gases, the Gibbs free energy is a strong function of temperature [4].

$$\ln K(T) = \frac{-G(T)}{RT} \quad (10)$$

$$\Delta G\,(T) = \sum_i n_i\, \Delta g^o_{f,i}(T) \quad (11)$$

The change in Gibbs free energy for each individual gas is empirically given by [4].

$$\Delta g^o_{f,i}(T) = H^o_{f,i} + aT\ln T - bT^2 - 0.5cT^3 - \left(d/3\right)T^4 + \left(e/2T\right) + f \quad (12)$$

Table 11: Enthalpy Formation and Constant Coefficients for Equation 12 [4]

Species	$\bar{H}^0_{f,298}$	a x10^2	b x10^5	c x10^8	d x10^{12}	e x10^{-2}	f	g
CH4	-74.8	-4.62	1.13	1.32	-6.65	-4.89	14.1	-0.223
CO	-110.5	0.562	-1.19	0.638	-1.85	-4.89	0.868	-0.0613
CO2	-393.5	-1.95	3.12	-2.45	6.95	-4.89	5.27	-0.121
H20	-241.8	-0.895	-0.367	0.521	-1.48	0	2.87	-0.0172

Now, there are six equations for seven unknowns therefore one additional equation has to be added from the energy balance inside the gasifier.

(c) Energy Balance inside the Gasifier

The total energy content in any chemical species is the sum of its chemical enthalpy and sensible enthalpy, which can be written as:

$$H^{O}_{f,RDF} + m_w \left(H^{O}_{f,H_2O\,(l)} + H_{vap}\right) + X_{air}\left(H^{O}_{f,O_2} + 3.76\, H^{O}_{f,N_2}\right) =$$
$$n_1\left[H^{O}_{f,CO} + \int_{298K}^{T_g}\left(C_{p,CO}dT\right)\right] + n_2\left[H^{O}_{f,H_2} + \int_{298K}^{T_g}\left(C_{p,H_2}dT\right)\right] +$$
$$n_3\left[H^{O}_{f,CO_2} + \int_{298K}^{T_g}\left(C_{p,CO_2}dT\right)\right] + n_4\left[H^{O}_{f,H_2O} + \int_{298K}^{T_g}\left(C_{p,H_2O}dT\right)\right] + n_5\left[H^{O}_{f,CH_4} +$$
$$\int_{298K}^{T_g}\left(C_{p,CH_4}dT\right)\right] + (0.5z + 3.76\, X_{air})\int_{298K}^{T_g}\left(C_{p,N_2}dT\right) \quad (13)$$

Since heat of formation of all diatomic molecules ($H^{O}_{f,N_2}, H^{O}_{f,O_2}, H^{O}_{f,H_2}$) is zero at reference temperature and pressure of 298K and 1 atm, equation 13 is reduced to:

$$H^{O}_{f,RDF} + m_w \left(H^{O}_{f,H_2O\,(l)} + H_{vap}\right) = n_1\left[H^{O}_{f,CO} + \int_{298K}^{T_g}\left(C_{p,CO}dT\right)\right] + n_2\left[H^{O}_{f,H_2} +$$
$$\int_{298K}^{T_g}\left(C_{p,H_2}dT\right)\right] + n_3\left[H^{O}_{f,CO_2} + \int_{298K}^{T_g}\left(C_{p,CO_2}dT\right)\right] + n_4\left[H^{O}_{f,H_2O} + \int_{298K}^{T_g}\left(C_{p,H_2O}dT\right)\right] +$$
$$n_5\left[H^{O}_{f,CH_4} + \int_{298K}^{T_g}\left(C_{p,CH_4}dT\right)\right] + (0.5z + 3.76\, X_{air})\int_{298K}^{T_g}\left(C_{p,N_2}dT\right) \quad (14)$$

C_p can be determined from an empirical correlation that is valid for wide range of temperatures [4].

$$C_p(T) = C_1 + C_2T + C_3T^2 + C_4T^4 \quad (15)$$

Table 12: Coefficients of Specific Heat Capacity for Various Gases [4]

Species	C_1	C_2	C_3	C_4
N_2	31.2	$-1.36\ (10)^{-2}$	$2.68\ (10)^{-5}$	$-1.17\ (10)^{-8}$
CO_2	19.8	$7.34\ (10)^{-2}$	$-5.60\ (10)^{-5}$	$1.72\ (10)^{-8}$
H_2	29.1	$-1.92\ (10)^{-2}$	$4.00\ (10)^{-6}$	$-8.70\ (10)^{-10}$
CO	30.9	$-1.29\ (10)^{-2}$	$2.79\ (10)^{-5}$	$-1.23\ (10)^{-8}$
CH_4	19.3	$5.21\ (10)^{-2}$	$1.20\ (10)^{-5}$	$-1.13\ (10)^{-8}$
H_20 (g)	32.2	$1.92(10)^{-2}$	$1.06\ (10)^{-5}$	$-3.60\ (10)^{-9}$

6.3. Model Implementation

The equilibrium constants of gasification reactions (equations 8 and 9) and the elemental composition of the fuel (RDF) from ultimate analysis data are input to the model to obtain producer gas composition. It involves solving equations 1, 2, 3, 4, 8, 9 and 14 in MATLAB using Newton –Jacob Iteration, shown on Appendix A.2. Once the producer gas composition is determined from the feedstock, a linear equation is developed to calculate the concentration of each gas species in the producer gas.

6.4.Model Input

The ultimate and proximate analysis data of RDF sample is an input to the model. Therefore characterization of the RDF was carried out for three RDF samples screened, separated from landfills. The characterization of RDF is shown in table 7 on previous section.

The ultimate and proximate analysis data of the RDF sample and operating parameters which are fed to the model are summarized in table 11.

Table 13: Model Input Parameters and Values

Ultimate Analysis (w/w %)	
Carbon	41.7241
Hydrogen	5.9648
Oxygen	36.2183
Nitrogen	0.5703
Sulfur	0
Proximate Analysis (w/w %)	
Ash Content	8.96
LHV [MJ/kg]	16.63
Operating Conditions	
Temperatures (K)	300 - 1200
E.Rs	0.2 – 0.35

The chemical formula that describes the RDF is: $\mathbf{CH_{1.7155}O_{0.6510}N_{0.01172}}$

6.5. Results and Discussion

6.5.1. Characterization of the Producer Gas and Optimizations

Molar fractions of compositions of the producer gas for gasification temperatures ranging from 573.15K to 1523.15K and for equivalence ratios ranging from 0.2 to 0.35 are simulated and results are shown in Appendix A.3 and are displayed charts below. The variation of LHV of the producer gas at different temperatures and for equivalence ratios ranging from 0.2 to 0.35 are estimated using the following formula and is shown by the plot.

LHV of the producer gas (LHV_g) is calculated from the gas analysis data of the producer gas. Lower heating value of different constituent of the producer gas at STP (20 ^{0}C and 1 atm) is used in the calculation. The following expression is used for calculation of lower heating value of the producer gas.

$$LHV_g = \sum X_i H_i$$

Where, X_i = Volume fraction of producer gas constituent and H_i = Heating value of constituent gases. Heating values of constituent gases referred from Table C.2 of [4].

Equivalent ratio (E.R) is the ratio of actual air fuel ratio to stoichiometric air fuel ratio which provides the basis for evaluating the amount of air supplied for gasification with respect to the amount of air required for complete combustion or stoichiometric oxidation of the feedstock. E.R is the most influential parameter in any gasification process and often has significant impact on product gas composition. The theoretical gasification occurs between E.R values of 0.19 – 0.43 and the optimum point is near to 0.25 [35]. The results show that molar concentrations of H_2 and CO decrease at higher E.R values. This results in decreased heating value of the product gas at higher E.Rs. The concentrations of H_2 and CO increases to considerably good values for temperatures above 800^{0}C and concentrations slightly decrease as E.R is increased.

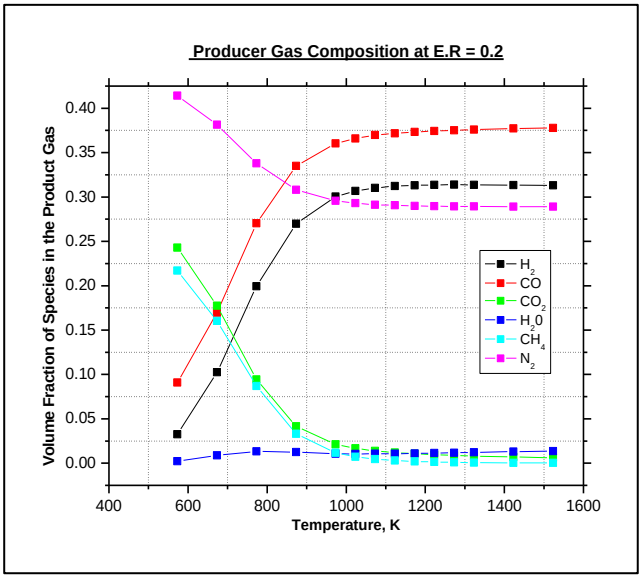

Figure 26: Product Gas Composition at E.R=0.2

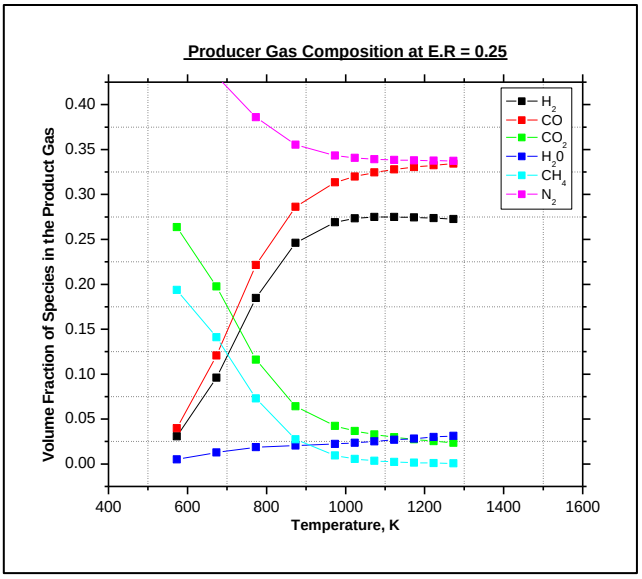

Figure 25: Product Gas Composition at E.R=0.25

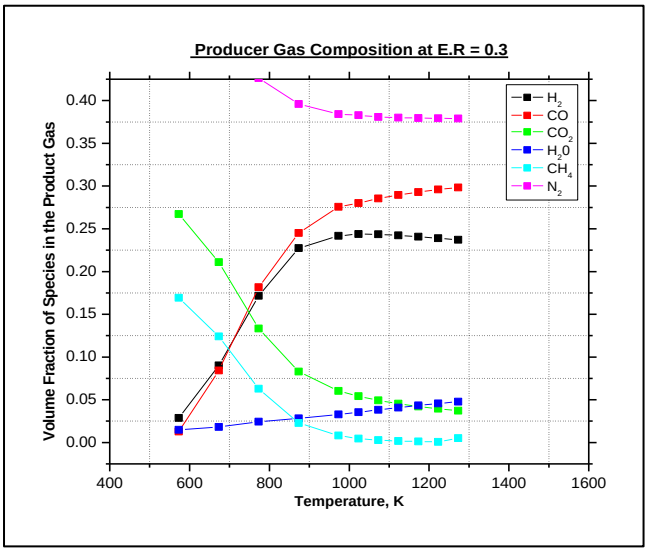

Figure 23: Product Gas Composition at E.R=0.3

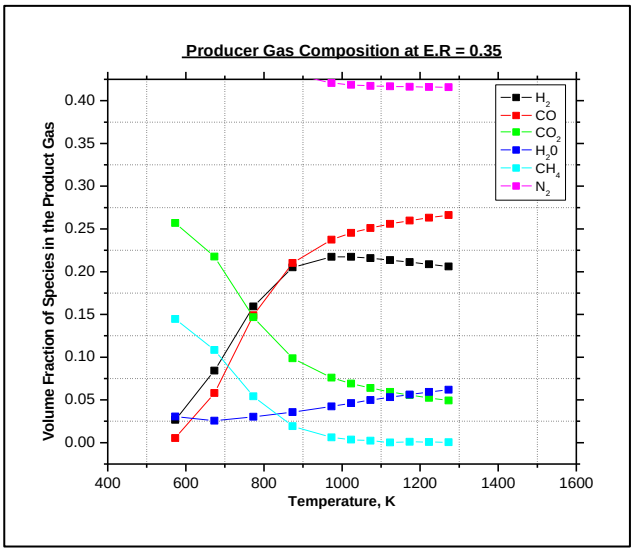

Figure 24: Product Gas Composition at E.R=0.35

Molar concentrations of carbon monoxide and hydrogen reach peak at temperatures above 800^0C with no or slight variation after the peak value. This makes LHV of the producer gas to be constant after 800^0C for all equivalence ratios. The LHV of species concentration gives the maximum value of 8.164MJ/Nm^3. The Optimal parameters for this maximum LHV value are a gasification temperature of 850^0C and an equivalence ratio of 0.2. This temperature is a point at which more carbon monoxide and hydrogen discovered in the product gas at

equivalence ratio of 0.2, with a remarkable contribution to the maximization of the gas heating value.

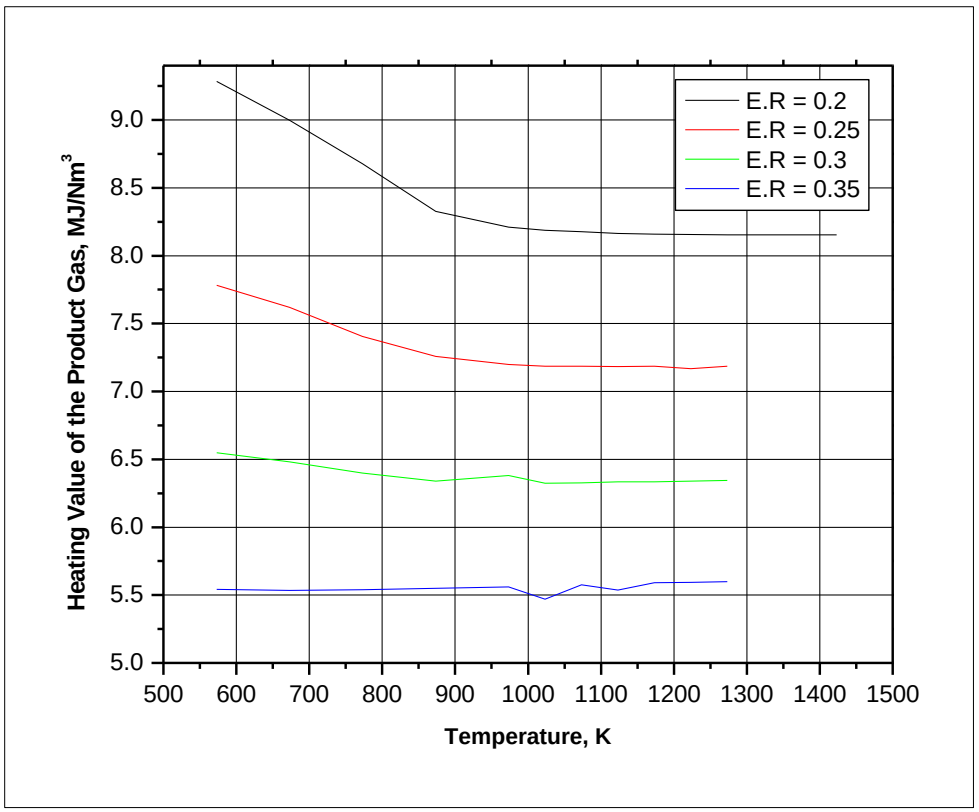

Figure 27: Heating Values of the Product Gas at Different E.Rs

6.5.2. Sensitivity Analysis

Generally concentration of H_2 very slightly declines or stays nearly constant at temperatures above 800^0C and the concentration of CO slightly increases or stays nearly constant for the same temperature range. This is due to water gas shift reaction which is reversible reaction and more active at temperatures above 800^0C, characterized by increased mole fractions of carbon dioxide and hydrogen. The reaction is a forward reaction at temperatures up to 700^0C and further increase in temperature would initiate reverse reaction favoring production of carbon monoxide. The model calculation results indicate that in each cases carbon monoxide is the most dominant component in the product gas, followed by hydrogen and carbon dioxide. This is due to the water gas reduction and reaction partial combustion of carbonaceous char materials at the bed. Hydrogen is also formed in the bed due to gasification reactions involving water with further release of carbon monoxide and carbon dioxide. Methane formation is encouraged at temperatures less than 700^0C as postulated from its reaction thermodynamics and at temperatures above 900^0C, production of methane is almost negligible.

6.6. Conclusion

In gasification, the most important objective is to produce a cleaner (low tar) gas with high heating value. To achieve the production of gas with relatively high heating value, it is important to convert carbon dioxide and water to as much carbon monoxide, hydrogen and methane as possible, as these constituents contribute relatively high heating values for the gas. Therefore it can be seen that it is desirable to give emphasis and encourage the two main reduction reactions (the Boudouard and Water Gas reaction). The maximum LHV of the product gas (8.1MJ/Nm^3) is high enough for downdraft gasification as recommended by [4,19] and is good yield from downdraft for applications such as utilization of the gas in IC engines for electricity generation. Operating conditions of the gasifier for this best operating condition are at 850^0C and equivalence ratio of 0.2. Tar has relatively high tendency to be observed in lower equivalence ratios and further gas cleaning and conditioning system has to be considered. Non-stoichiometric model appears to give reliable results for producer gas characterization from simple input that can be determined from elemental composition and proximate analysis data based on comparison of result features with other studies.

7. PROCESS DESIGN AND SIZING OF IMBERT TYPE DOWNDRAFT GASIFIER

Process design of a gasifier uses a sequence of steps and design judgments to determine the following important parameters as design outputs.

7.1. Design Outputs

- ✓ Fuel feed rate
- ✓ Flow rate of the gasifying medium (air)
- ✓ Product gas flow rate
- ✓ Gasifier efficiency (cold gas efficiency)
- ✓ Diameter of the constriction (the throat diameter) and throat angle
- ✓ Diameter of the tube, the reaction vessel itself
- ✓ Length of the oxidation zone,
- ✓ Length of the reduction zone,
- ✓ Diameter, Place and configuration of air inlets (nozzles),
- ✓ Velocity of air.

7.2. Design Criteria

The main criteria for a well-functioning gasifier for engine application are [4,36]:

- ➢ High heating value of the gas, meaning high content of H_2 and CO (3.5 – 5 MJ/Nm^3) is quiet good yield (for biomass) for engine application.
- ➢ There is no consensus about what should the gas quality limit be for tar and particulates. Various manufacturers indicate that 50 – 100 mg/Nm^3 for engines and low tar content, commonly a value of below 0.5 g/Nm^3 are preferable.
- ➢ In order to increase breathing or volumetric efficiency of engine, it is necessary to cool down the gas closer to ambient temperature. Generally, it is observed that for every 10^0C rise in gas temperature, the engine efficiency drops by 1%.
- ➢ Carbon conversion efficiency (>95%), which implies a high efficiency of the process.
- ➢ Unhampered down flow of the feed
- ➢ Low pressure drop

7.3. Design Specifications

The input includes the specification of the fuel, gasifying medium, product gas heating value and molar fractions of constituents. A typical fuel specification includes proximate and ultimate analyses, operating conditions and properties. Retention time, mass of fuel gasified, volumetric gas production rate or energy throughput in the producer gas, hearth load required power output and gasifier efficiency are determined in the designing process to be input to the sizing process.

7.4. Design Calculations

Gasifier process design concepts and formulae are adapted from [P. Basu, 2010]

7.4.1. Fuel Feed Rate

To find the RDF fuel feed rate, M_f, the required power output (P) is divided By the LHV of the RDF (LHV_f) multiplied by gasifier efficiency [4].

$$M_f = \frac{P}{LHV_f \times \eta_{gasif.}} \tag{16}$$

The power of the gasifier, P is given by [4]:

$$P = LHV_g \times V_g \tag{17}$$

Where: LHV_f, LHV_g, V_g is the lower heating value of the RDF feed, lower heating value of the product gas and the flow rate of the product gas respectively.

7.4.2. Determination of the Product Gas Flow Rate

The gasifier required power output is an important parameter here. The volume flow rate of the product gas, V_g [Nm^3/s], from LHV of the gas (LHV_g) is given by:

$$V_g = \frac{P}{LHV_g} \tag{18}$$

But the volumetric gas production rate for a gasifier coupled with IC engine must be calculated in such a way that it considers the volume swept by the engine [4]. That is the volume of vacuum created in cylinder. Prior to that, the engine specifications need to be stated.

7.4.2.1.Engine Specifications

Detail of the selected engine specifications can be found from Appendix A.6.

Table 14: Engine Specifications

Type	4 – Stroke IC Engine (Gasoline Engine)
Piston Diameter (D)	110mm
Piston Stroke (S)	100mm
Number of Cylinders (N)	4
Engine RPM	1500
Volumetric Efficiency (η_{Vol})	80%
Air – Fuel Ratio	1.1:1.0 (Initial Guess, to be checked later)

7.4.2.2.Engine Swept Volume (V_s)

That is the volume of vacuum created in all the cylinders (V_s) is given by [37]:

$$V_S = {}^{1}/_{2}\, RPM \times N \times \pi / 4 \times D^2 \times S \quad (19)$$

$$= {}^{1}/_{2}\,(1500) \times 4 \times {}^{\pi}/_{4} \times (0.11)^2 \times 0.1$$

$$= 0.0475\ \frac{m^3}{s} = 2.85\ \frac{m^3}{min} = 171\ \frac{m^3}{hr}$$

For stoichiometric air – fuel ratio of 1.1:1.0, the air requirement for m^3 of gas is 1.1 m^3 fuel and air intake volume will be 1.1+1.0 = 2.1 V_g. The engine cylinder gas intake rate will be [37]:

$$2.1V_g = \eta_{vol} \times V_s \quad (20)$$

$$= \frac{0.8 \times 171\ {}^{m^3}/_{hr}}{2.1}$$

$$V_g = 65.14\ \frac{Nm^3}{hr}$$

Then, $LHV_g = 8.164\ \frac{MJ}{m^3}$ as determined from the model, the power, P of the gasifier will be calculated as:

$$P = LHV_g \times V_g \quad (21)$$

$$= 8.164\ \frac{MJ}{m^3} \times 65.14\ \frac{m^3}{hr}$$

$$= 148kW$$

Assuming 0.7% efficient gasifier as recommended by [4] (to be checked later), and taking value of LHV_f from the characterization of RDF,

$$M_f = \frac{148\text{kW}}{16630\text{kJ/kg}\times 0.7}$$

$$= 0.0127\frac{kg}{s} = 46\ \frac{kg}{hr}$$

If there is no measured value of for the lower heating value of the RDF, LHV_f of the RDF can be determined from the following correlation:

$$LHV_f = HHV_f - 20300H - 2260M \quad (22)$$

Where, H is hydrogen mass fraction in fuel, M is moisture mass fraction and HHV_f is HHV of the fuel (RDF) in KJ/kg on moisture – ash free basis. It can be related to the only dry basis value (HHV_d) by the following relation.

$$LHV_f = HHV_f\ (\frac{1-M}{1-ASH-M}) \quad (23)$$

Where, ASH is the ash fraction in fuel on row – fuel basis.

The HHV_f can be calculated from ultimate and proximate analysis of RDF fuel using the following equation.

$$HHV_f = 0.3491C + 1.1783H + 0.1005S - 0.0151N - 0.1034O - 0.0211ASH \quad (24)$$

Substituting equations 22,23 and 24 in to 16 and inserting the elemental and ash composition of the feed, the gasifier power and efficiency, the fuel feed rate will be:

$M_f =$

$$\frac{P}{\left\{\left[\left(0.3491\text{C} + 1.1783\text{H} + 0.1005\text{S} - 0.0151\text{N} - 0.1034\text{O} - 0.0211\text{ASH}\right)\left(\left(\frac{1-\text{M}}{1-\text{ASH}-\text{M}}\right)\right)\right] - 20300\ \text{H} - 2260\ \text{M}\right\} \times \eta_{\text{gasif}}}$$

(25)

7.4.3. Flow Rate of the Gasifying Medium (Air)

As illustrated on previous sections, the amount of gasifying medium, which is air in this case has major effect on gas yield and composition of producer gas. The theoretical or stoichiometric air requirement for complete combustion of a unit mass of fuel, m_{th} is an important parameter. For an air blown gasifier, the amount of air required, $m_{a,}$ for complete gasification of a unit mass of RDF is calculated by multiplying the theoretical air requirement by the equivalence ration (ER) [4].

$$m_a = m_{th} \times ER \tag{26}$$

For a fuel feed rate of $M_{f,}$ the air requirement of the gasifier, m_{fa}, is given by [4]:

$$m_{fa} = m_{th} \times ER \times M_f \tag{27}$$

The theoretical (Stoichiometric) amount of air required (kg air/kg fuel) is calculated from the following formula [4]:

$$m_{th} = \left[0.1152C + 0.3434\left(H - \frac{O}{8}\right) + 0.0434S\right] \tag{28}$$

Where: C, H, O and S are weight percent of Carbon, Hydrogen, Oxygen and Sulfur in the RDF.

$$m_{th} = \left[0.1152 \times 41.7241 + 0.3434\left(5.9648 - \frac{36.2183}{8}\right) + 0.0434 \times 0\right]$$

$$= 5.3\ {}^{kgair}/_{kg\ fuel}$$

The actual amount of air required for gasification 1kg of feed, m_a is:

$$m_a = 5.3\ {}^{kgair}/_{kg\ fuel} \times 0.2$$

$$= 1.06\ {}^{kgair}/_{kg\ fuel}$$

For fuel feed rate of 46 kg/hr, the actual amount of air required is m_{fa}:

$$m_{fa} = m_a \times M_f \tag{29}$$

$$= 1.06\ {}^{kgair}/_{kg\ fuel} \times 46\ {}^{kg\ fuel}/_{hr}$$

$= 49\ {}^{kgair}/_{hr}$

The air – fuel ratio is then:

$$Air - Fuel\ Ratio = \frac{49 \frac{kg\ air}{hr}}{46\ \frac{kg\ fuel}{hr}}$$

$$Air - Fuel\ Ratio = 1.07 : 1.00$$

The $Air - Fuel\ Ratio$ assumed for product gas flow rate is $1.10 : 1.00$, is close to the above figure, therefore it is accepted.

7.4.4. Cold gas Efficiency of the Gasifier, $\eta_{gasif.}$

Cold gas efficiency is the energy input over potential energy output, given by [4]:

$$\eta_{gasif.} = \frac{LHV_g \times V_g}{LHV_f \times M_f} \quad (30)$$

$$= \frac{8.164\ \frac{MJ}{m^3} \times\ 65.14\ \frac{Nm^3}{hr}}{16.63\text{MJ/kg} \times\ 46\ \frac{kg}{hr}}$$

$= 69.51\%$, which makes initial assumption of 70% cold gas efficiency valid with close approximation.

7.4.5. Specification Gasification Rate (Hearth Load, G_H)

The design of an Imbert type down drift gasifier is based on specific gasification rate, also called the hearth load, G_H. It is defined as the amount of producer gas to be obtained per unit cross - sectional area of the throat, which is the smallest area cross section in the reactor. It is normally expressed in terms of $Nm^3/Hr.\ cm^2$, where N indicates the gas volume is calculated at normal pressure and temperature conditions. Swedish Academy of Engineering Sciences reported that gasifiers can be operated with G_H in the range 0.1 – 0.9 $Nm^3/Hr.\ cm^2$. Based on the maximum value of the hearth load, the throat area can be calculated [37].

$$G_H = \frac{Volumetric\ Gas\ Productio\ Rate\ (V_g)}{Hearth\ Crossectional\ Area\ (A_t)} \quad (31)$$

7.4.6. Superficial Gas Velocity (Space Velocity, v_g)

The hearth load in volume flow rate of gas per unit of cross section area is known as superficial gas velocity or space velocity as it has unit of velocity at reference temp and pressure. The superficial gas velocity is given by the following relation [4].

$$v_g = \frac{Volumetric\ Gas\ Productio\ Rate\ (V_g)}{Hearth\ Crossectional\ Area\ (A_t)} \quad (32)$$

7.4.7. Throat Area, A_t

Gasifier sizing methods and charts are adapted from [Swedish Academy of Engineering Sciences (FAO)]

To determine the throat area, A_t, [4]

$$V_g = G_{H,max} \times A_t \quad (33)$$

$$A_t = \frac{\mathrm{Vg}}{G_{H,max}}$$

$$= \frac{65.14\ \frac{m^3}{Hr}}{0.9\ \frac{m^3}{Hr.\ Cm^2}}$$

$$= 72.38 cm^2$$

The throat diameter, d_t

$$d_t = \sqrt{\frac{4 \times A_t}{\pi}} \quad (34)$$

$$= 10\mathrm{cm}$$

The superficial velocity of the gas, v_g,

$$v_g = \frac{65.14\ \frac{m^3}{Hr}}{72.38\ cm^2}$$

$$= 2.5\ {}^{m}/_{s}$$

7.4.8. Throat Inclination, θ

Most manufacturers use throat inclination in the range, 45^0 - 60^0. The throat angle affects the gasifier conversion efficiency and small angles give maximum conversion efficiency and vice versa due to diverging effect of large angles. However, small angles require large reduction zones [37]. Due to this an inclination angle of 45^0 is preferred.

$\theta = 45°$

Other dimensions such as height, h of nozzle plane above throat, nozzle area (nozzle diameter), and height of reduction and pyrolysis zones can be determined from the graph given by Swedish Academy of Engineering Sciences (FAO) reproduced in figures below. Some of the geometrical design parameters are shown in the figure below.

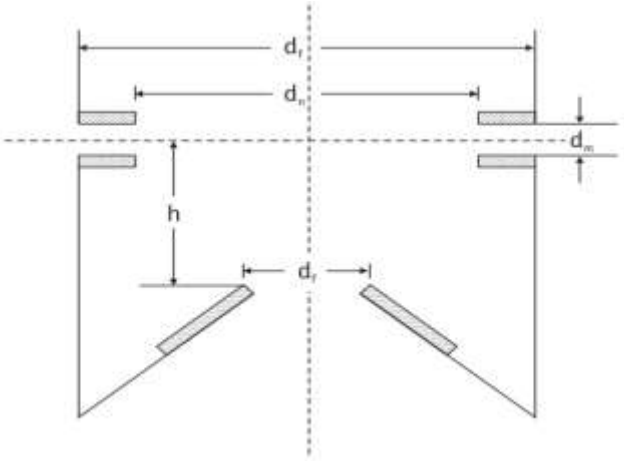

Figure 28: Geometrical Design Parameters for Imbert Gasifier

Where,

d_t = Throat Diameter

h = Height of Nozzle Plane above the Throat

d_m = Nozzle Diameter

d_n = Top Nozzle Ring Diameter

d_f = Reactor Diameter (Inner)

7.4.9. Height of Nozzle Plane above the Throat, h

The following graph reproduced from FAO gives relation of h with throat diameter. [Appendix A.4, Figure A.4.1]

h = 9.79cm

7.4.10. Height of Oxidation Zone, h_{oxd}

Oxidation takes place at the middle space equi – distance from pyrolysis and reduction zones. Real burning of pyrolysis gases is taking place only in area close to the actual air inlets. Therefore, air inlets (nozzles) must be constructed at this position for real and efficient

burning. Height from the reduction zone to the nozzle plane is known, doubling it will give the total height of the oxidation zone.

h_{oxd} = 19.58 cm

The volume of the oxidation zone is, V_{oxd}:

$$V_{oxd} = \frac{\pi d_t^2 h_{oxd}}{4} \quad (35)$$

$$= 1.42 \times 10^{-3} m^3$$

7.4.11. Area Air Inlet (Nozzle), A_t

The area of nozzle and air velocity is determined from the graph in [Appendix A.4, Figure A.4.2].

A_{noz} = 4.27cm^2

Air Velocity, V_{air} = 24.8 $m.s^{-1}$

To find the number of nozzles required, A:

$$\dot{Q_{air}} = A \times V_{air} \times A_{noz} \quad (36)$$

Where: $\dot{Q_{air}}$is volume flow rate of air, which can be calculated as:

$$\dot{Q_{air}} = \frac{m_a}{\rho_{air}} \quad (37)$$

Density of air, $\rho_{air} = 1.17 \frac{kg}{m^3}$ at 298K [38]

$$\dot{Q_{air}} = \frac{49 \frac{kg}{hr}}{1.17 \frac{kg}{m^3}}$$

$$= 35 \frac{m^3}{hr} = 1.1 \times 10^{-2} \frac{m^3}{s}$$

The calculation for A yields:

$$1.1 \times 10^{-2} \frac{m^3}{s} = A \times 24.8 \frac{m}{s} \times 4.27 \times 10^{-4} m^2$$

$$A = 1.03 \rightarrow 1 \text{ Nozzle}$$

For good air distribution, the number of nozzles must be greater than one and has to be odd in order to avoid nozzle – to – nozzle pressure from the straight opposite arrangement of nozzles as a result of having even number [37].
Selecting number of air inlet nozzles, A = 5 (to be checked later)

The nozzle inner diameter, d_m:

$5\frac{\pi\, dm^2}{4} = 4.27cm^2$

$= 1.043$ cm

7.4.12. Top Nozzle Ring Diameter, d_n

Top Nozzle Ring Diameter, d_n is determined from top nozzle rig diameter as a function of throat diameter from [Appendix A.4. Figure A.4.3].

$d_n = 22.08$ cm

7.4.13. Height of the Reduction Zone, h_r

The height of reduction zone of the gasifier is related to the throat diameter as illustrated in the graph in [Appendix A.4. Figure A.4.4].

$h_r = 18.72$ cm

The geometry of the reduction zone is a frustum of a cone and the volume of the reduction zone (V_{red}) is calculated as:

$$V_{red} = \frac{\pi h_r}{3}(R_f^2 + R_f \times r_t + r_t^2) \quad (38)$$

Where: R_f is radius of the reactor and r_t is throat radius.

From the geometry, R_f is calculated using trigonometry as follows:

$$d_f = 2(h_r \tan 45°) + d_t \quad (39)$$

$= 47cm$

$R_f = \frac{d_f}{2}$

$= 23.5cm$

$$V_{red} = \frac{\pi \times 0.1872}{3}(0.235^2 + 0.235 \times 0.047 + 0.047^2)$$

$$V_{red} = 0.0135m^3$$

7.4.14. Height of the Pyrolysis Zone, h_p

To determine the height of the pyrolysis zone, a residence time approach is used. The total volume of the reactor will be determined from this method and the reactor volume minus the volumes of reduction and oxidation zones give volume of the pyrolysis zone from which the height of the pyrolysis zone will be calculated. The total reactor volume, V_r is related to the retention time, R_t and volumetric gas production rate, V_g by the following relation.

$$V_r = R_t \times V_g \tag{40}$$

Using retention time from literature, [34] R_t = 10 – 15s for gasification. Taking the average,

$R_t = 12.5s$

$V_r = 12.5s \times 65.14 \frac{Nm^3}{hr}$ = 0.226 m^3

$V_r = 0.226m^3$

The volume of the pyrolysis and drying zones, V_p zone will be:

$$V_p = V_r - (V_{oxi} - V_r) \tag{41}$$

$= 0.226 - (0.00142 + 0.0135)$

$= 0.211m^3$

The geometry of the pyrolysis zone is in such a way that, it has cylindrical and frustum parts. Making quarter of the volume a frustum part and the rest of the volume a cylindrical part, the height of the pyrolysis zone, h_p is calculated as follows:

$$V_p = V_{cylinderical\ part} + V_{furstum\ part} \tag{42}$$

Optimizing for the cylindrical part:

$$0.9V_p = \frac{\pi d_f^2 h_{p1}}{4} \tag{43}$$

$h_{p1} = 1m$

Optimizing for the frustum part:

$$0.1V_{rp} = \frac{\pi h_{p2}}{3}(R_f^2 + R_f \times r_t + r_t^2) \tag{44}$$

$h_{p2} = 0.3m$

The height of the pyrolysis and drying zone, h_p is the sum total of h_{p1} and h_{p2}:

$h_p = 1.3m$

7.4.15. Total Height of the Reactor, H

The total height of the reactor will be the sum total of the heights of the three zones. Additional small height (R = 10cm) is added for ash on the bed space based on the sizing data on Appendix A.4, Table A.4.5 for this specific gas production rate.

$$H = h_{oxi} + h_r + h_p + R \quad (45)$$

$$= 0.1958\text{m} + 0.1872\text{m} + 1.3\text{m} + 0.1\text{m}$$

$$H = 1.8m$$

7.4.16. Design Validation

The design validation is carried out by comparing the basic design parameters with what is recommended on Imbert gasifier design/sizing handbooks. The basic parameters are: throat diameter ($d_t = d_h$), height of nozzle plane above throat (h), air nozzle inner diameter (d_m), total air inlet area ($A_{noz} = A_m$) and air velocity. Total tube/reactor diameter and total reactor height cannot be fixed because one can reduce total height by increasing reactor diameter and vice versa as far as the reactor volume is fixed.

The validation carried out by performing linear interpolation between design specifications range to meet the current requirement. In this case, maximum range of gas output is 65.14 Nm^3/h and this value is between 63 Nm^3/h and 90 Nm^3/h as shown in [Appendix A.4, Table A.4.5]. Linear interpolation between the values for other sizing parameters will give the design recommendations.

The following table shows the recommended values of sizing parameters for this specific case [29].

Table 15: Recommended Values of Sizing Parameters [29]

Max. Gas Output [Nm^3/h]	d_t [mm]	h [mm]	$\frac{A_{noz}}{A_h}$ (100)	d_m [mm]	A	R [mm]	Air Velocity [$m.s^{-1}$]
63	100	100	5.5	10.5	5	100	24.2
65.14	101.793	100.793	5.46	10.65	5	100	24.34
90	120	110	5	12	5	100	26

The following table shows the comparison between the calculated and recommended physical sizes of the gasifier for the specified gas output.

Table 16: Comparison between the Calculated and Recommended Physical Sizes of the Gasifier for the Specified Gas Output

Resign Parameter	Recommended Standard	Design Output	Percent Error
Max. Gas Output [Nm^3/h]	65.14	65.14	-----
d_t [mm]	101.739	100	0.017
h [mm]	100.739	97.9	0.028
$\frac{A_{noz}}{A_h}$ (100)	5.46	5.89	0.0787
d_m [mm]	10.65	10.43	0.0206
A	5	5	0
R [mm]	100	100	0
Air Velocity [$m.s^{-1}$]	24.34	24.8	0.0189
		Average Error	3.2%

Accepting error up to 5%, all of the design output parameters are found to be precise. Some errors introduced here might also be from the linear interpolation performed based on the assumption that data points are close and the curve is nearly straight line in between. The drawing of the gasifier included in [Appendix A.4, Figure A.4.5] shows the detail physical design of the gasifier.

7.5. Energy Balance on the Gasifier

Performing energy balance between the gasifier input and output (first law of thermodynamics), provides an indirect means to determine the amount of energy lost to the surrounding. The energy balance will also quantify the performance of the gasifier items of percent heat loss.

The energy balance is governed by a general conservation of energy equation:

$$\sum Energy\ in = \sum Energy\ out + Energy\ loss \quad (46)$$

Energy balance calculation methods and formulae are adopted from [34,39]

The energy introduced to the gasifier (energy in) is the form of the following:

I. Sensible heats of the fuel (RDF).
II. Specific heat of the air

Energy leaving the gasifier (Energy out) is in the form of the following:

III. Sensible heat of the producer gas
IV. Sensible heat of water/moisture
V. Latent heat of steam
VI. Sensible heat of fly ash
VII. Heat loss from reactor walls
VIII. Chemical energy in the producer gas
IX. Energy in condensate (Ash, Carbon and Tar)

The energy balance over the gasifier is governed by:

$$\text{Sensible heat of RDF} + \text{Sensible heat of air} = \text{Sensible heat of the producer gas} + \text{Sensible heat of water} + \text{Sensible heat of fly ash} + \text{Latent heat of steam} + \text{Heat loss from reactor walls} + \text{Chemical energy in the producer gas} + \text{Energy in condensate (Ash, Carbon and Tar)} \quad (47)$$

Calculations:

I. Sensible heats of the fuel (RDF).

$$\text{Sensible heats of the fuel (RDF)} = m_f \times HHV_{RDF} \quad (48)$$

From previous sections, $m_f = 46\frac{kg}{hr}$, $LHV_{RDF} = 16.63\frac{MJ}{kg}$.

$$HHV_{RDF} = LHV_{RDF} + 2.442\ \frac{MJ}{kg}\left(P_{H_2O} + Y_{moisture}\right) \quad (49)$$

Where:

$$P_{H_2O} = 8.94Y_H - 0.254Y_{Cl} \quad (50)$$

Y_H – Mole fraction of hydrogen in the RDF

Y_{Cl} – Mole fraction of chlorine in the RDF

$Y_{moisture}$ – Mole fraction of moisture in the RDF

$$P_{H_2O} = 8.94(0.05965) - 0$$

$$P_{H_2O} = 0.53325$$

$$HHV_{RDF} = 16.63\frac{MJ}{kg} + 2.442\ \frac{MJ}{kg}\ (0.53325 + 0.065625)$$

$$HHV_{RDF} = 18.09\frac{MJ}{kg}$$

$$\text{Sensible heats of the fuel (RDF)} = 46\ \frac{kg}{hr} \times 18.09\frac{MJ}{kg}$$

$$\text{Sensible heats of the fuel (RDF)} = 832.14\frac{MJ}{hr}$$

II. Sensible heat of the air.

Assuming air enters the gasifier at 20^0C, and introduced to combustion zone at 300^0C

$$\text{Sensible heats of the air} = C_{P_{air}} \times m_a \times (300℃ - 20℃) \quad (51)$$

From previous sections, $m_a = 49\ {}^{kg}/_{hr}$

The specific heat of air at film temperature of 413K, $C_{P_{air}} = 1016\frac{J}{kg\ K}$ [38]

$$\text{Sensible heats of the air} = 1016\frac{J}{kg\ K} \times 49\frac{kg}{hr} \times (300℃ - 20℃)$$

$$\text{Sensible heats of the air} = 13.93\ \frac{MJ}{hr}$$

Then,

$$Energy\ in\ to\ the\ gasifier$$
$$= \text{Sensible heats of the fuel (RDF)} + \text{Sensible heats of the air}$$

$$Energy\ in\ to\ the\ gasifier = 832.14\frac{MJ}{hr} + 13.93\ \frac{MJ}{hr}$$

$$\boldsymbol{Energy\ in\ to\ the\ gasifier = 846.07\frac{MJ}{hr}}$$

III. Sensible heat of the producer gas

Assuming the feed enters at 20℃,

$$\text{Sensible heat of the producer gas} = \sum\left[C_{P_{i,out}} \times m_{i,out}\right] \times \left(T_{g,out} - 20℃\right) \quad (52)$$

Where:

$C_{P_{i,out}}$ – Specific heat capacity of component i in the producer gas

$m_{i,out}$ – Mass flow rate of component i in the producer gas

$T_{g,out}$ – Temperature at the gasifier outlet, reasonably assumed to be 700 ℃

$$\sum[C_{P_{i,out}} \times m_{i,out}] = \left[\left(m_{H_2} \times C_{P_{H_2}}\right) + \left(m_{CO} \times C_{P_{CO}}\right) + \left(m_{CO_2} \times C_{P_{CO_2}}\right) + \left(m_{CH_4} \times C_{P_{CH_4}}\right) + \left(m_{N_2} \times C_{P_{N_2}}\right)\right] \quad (53)$$

The mass flow rate of species i in the product gas can be determined from the relation [4,39]:

$$m_{i,out} = Y_{i,out} \times V_g \times \rho_{i,out} \quad (54)$$

Where: $Y_{i,out}$, V_g, $\rho_{i,out}$ are volume fractions of component i in the product gas, total product gas flow rate, density of component I in the product gas.

Referring [4], the densities and specific heats of the components of the producer gas are:

Table 17: Densities and Specific Heats of the Components of the Producer Gas [4]

Densities and Specific Heats of the Components of the Producer Gas			
Densities		Specific Heats	
ρ_{H_2}	$0.0899\ \frac{kg}{m^3}$	$C_{P_{H_2}}$	$3467\ \frac{J}{kg\ K}$
ρ_{CO}	$1.2498\ \frac{kg}{m^3}$	$C_{P_{CO}}$	$1050\ \frac{J}{kg\ K}$
ρ_{CO_2}	$1.9637\ \frac{kg}{m^3}$	$C_{P_{CO_2}}$	$850\ \frac{J}{kg\ K}$
ρ_{CH_4}	$0.7157\ \frac{kg}{m^3}$	$C_{P_{CH_4}}$	$34.3\ \frac{J}{kg\ K}$
ρ_{N_2}	$1.249\ \frac{kg}{m^3}$	$C_{P_{N_2}}$	$1050\ \frac{J}{kg\ K}$
$\rho_{H_2O,l}$	$985.22\ \frac{kg}{m^3}$	$C_{P_{H_2O,l}}$	$4184\ \frac{J}{kg\ K}$
$\rho_{H_2O,g}$	$49.02\ \frac{kg}{m^3}$	$C_{P_{H_2O,g}}$	$6181\ \frac{J}{kg\ K}$

The mass flow rates of each components of the product gas are calculated as follows.

$$m_{H_2} = Y_{H_2} \times V_g \times \rho_{H_2} = 0.3132 \times 65.14\frac{m^3}{hr} \times 0.0899\ \frac{kg}{m^3} = 1.834\frac{kg}{hr}$$

$$m_{CO} = Y_{CO} \times V_g \times \rho_{CO} = 0.3732 \times 65.14\frac{m^3}{hr} \times 0.0899\ \frac{kg}{m^3} = 30.38\frac{kg}{hr}$$

$$m_{CO_2} = Y_{CO_2} \times V_g \times \rho_{CO_2} = 0.0106 \times 65.14\frac{m^3}{hr} \times 1.9637\ \frac{kg}{m^3} = 1.356\frac{kg}{hr}$$

$$m_{CH_4} = Y_{CH_4} \times V_g \times \rho_{CH_4} = 0.0019 \times 65.14\frac{m^3}{hr} \times 0.7157\ \frac{kg}{m^3} = 0.0886\frac{kg}{hr}$$

$$m_{N_2} = Y_{N_2} \times V_g \times \rho_{N_2} = 0.29 \times 65.14\frac{m^3}{hr} \times 1.249\ \frac{kg}{m^3} = 23.59\frac{kg}{hr}$$

Sensible heat of the producer gas $= \left[\left(m_{H_2} \times C_{P_{H_2}}\right) + \left(m_{CO} \times C_{P_{CO}}\right) + \left(m_{CO_2} \times C_{P_{CO_2}}\right) + \left(m_{CH_4} \times C_{P_{CH_4}}\right) + \left(m_{N_2} \times C_{P_{N_2}}\right)\right] \times \left(T_{g,out} - 20℃\right)$

Sensible heat of the producer gas $= \left[\left(1.834\frac{kg}{hr} \times 3467\frac{J}{kg\ K}\right) + \left(30.38\frac{kg}{hr} \times 1050\frac{J}{kg\ K}\right) + \left(1.356\frac{kg}{hr} \times 850\frac{J}{kg\ K}\right) + \left(0.0886\frac{kg}{hr} \times 34.3\frac{J}{kg\ K}\right) + \left(23.59\frac{kg}{hr} \times 1050\frac{J}{kg\ K}\right)\right] \times (700℃ - 20℃)$

$$\text{Sensible heat of the producer gas} = 43.644\frac{MJ}{hr}$$

IV. Sensible heat of water/moisture

Water boils at 92^0C at Addis Ababa, Ethiopia.

Sensible heat of steam $= m_{H_2O} \times C_{P_{H_2O,l}} \times (92\ ℃ - 20\ ℃)$ (55)

$$m_{H_2O} = Y_{H_2O\ in\ RDF} \times M_f = 0.065625 \times 46\frac{kg}{hr} = 3\frac{kg}{hr}$$

$$\text{Sensible heat of steam} = 3\frac{kg}{hr} \times 4184\frac{J}{kg\ K} \times (92\ ℃ - 20\ ℃)$$

$$\text{Sensible heat of steam} = 1\frac{MJ}{hr}$$

V. Latent heat of steam

Latent heat of steam $= m_{H_2O,g} \times C_{P_{H_2O,g}} \times \left(T_{g,out} - 92\ ℃\right)$ (56)

$$m_{H_2O,g} = Y_{H_2O} \times V_g \times \rho_{H_2O,g} = 0.0110 \times 65.14\frac{m^3}{hr} \times 49.02\ \frac{kg}{m^3} = 35.125\frac{kg}{hr}$$

$$\text{Latent heat of steam} = 35.125\frac{kg}{hr} \times 1999\frac{J}{kg\ K} \times (700\ ℃ - 92\ ℃)$$

$$\text{Latent heat of steam} = 42.7\frac{MJ}{hr}$$

VI. Sensible heat of fly ash

Since equilibrium model is used, it assumes all carbon in the RDF is totally burned therefore no ash and tar is determined in the product gas.

Therefore,

$$\text{Sensible heat of fly ash} = 0\,\frac{MJ}{hr}$$

VII. Heat loss from reactor walls

Heat loss through reactor walls can be determined from [40]:

$$H_{wall} = \frac{K \times A \times \Delta T}{X} \quad (57)$$

Where:

K – Thermal conductivity of the insulation

A – Total surface area

X – Thickness of the insulation

ΔT – Temperature difference between the inside and outside walls = (T_g - T_w)

The insulation is made by commercially available glass fiber blanket (glass wool insulation, K = 0.038W/mK) with thickness of 0.025m (to be checked later). The outer geometry of the gasifier is of cylindrical shape.

Top area, A_t = Bottom area, $A_b = 2 \times 0.25 \times \pi \times D_O^2 = 0.347m^2$

Lateral surface area, $A_l = \pi \times D_O \times l = 2.746m^2$

$$A = A_t + A_b + A_l$$

$$A = 2A_t + A_l$$

$$A = 3.093m^2$$

The wall heat loss is calculated as:

$$H_{wall} = \frac{0.038\frac{W}{mK} \times 3.093m^2 \times (700℃ - 30℃)}{0.025m}$$

$$H_{wall} = 11.34\frac{MJ}{hr}$$

Performing energy balance (1st law of thermodynamics) on the control surface on outer surface of the insulation yields, rate of energy in is equal to rate of energy out. Therefore, this conduction heat loss will be swept by convection to the surrounding.

VIII. Chemical energy in the producer gas

The chemical energy in the producer gas calculated based on HHV of the gas as follows:

$$\text{Chemical energy in the producer gas} = V_g \times HHV_g$$

$$= V_g \left[\left(Y_{H_2} \times HHV_{H_2}\right) + \left(Y_{CO} \times HHV_{CO}\right) + \left(Y_{CH_4} \times HHV_{CH_4}\right)\right] \quad (58)$$

$$= 65.14 \frac{m^3}{Hr} \left[\left(0.3132 \times 12.74 \frac{MJ}{m^3}\right) + \left(0.3732 \times 12.63 \frac{MJ}{m^3}\right) + \left(0.0019 \times 39.82 \frac{MJ}{m^3}\right)\right]$$

$$\text{Chemical energy in the producer gas} = 573.88 \frac{MJ}{hr}$$

IX. Energy in condensate (Ash, Carbon and Tar)

Since equilibrium model is used, it assumes all carbon in the RDF is totally burned therefore no ash and tar is determined in the product gas.

Therefore,

$$\text{Energy in condensate (Ash, Carbon and Tar)} = 0 \frac{MJ}{hr}$$

Total energy out from gasifier is then:

$$Energy\ out\ from\ gasifier =$$

$$\text{Sensible heat of the producer gas} + \text{Sensible heat of moisture} +$$

$$\text{Sensible heat of fly ash} + \text{Latent heat of steam} + \text{Heat loss from reactor walls} +$$

$$\text{Chemical energy in the producer gas} + \text{Energy in condensate (Ash, Carbon and Tar)} \quad (59)$$

$$Energy\ out\ from\ gasifier = 43.644 \frac{MJ}{hr} + 1 \frac{MJ}{hr} + 42.7 \frac{MJ}{hr} + 0 \frac{MJ}{hr} + 11.34 \frac{MJ}{hr} + 573.88 \frac{MJ}{hr} + 0 \frac{MJ}{hr}$$

$$\boldsymbol{Energy\ out\ from\ gasifier = 672.564 \frac{MJ}{hr}}$$

Then to determine the accounted heat loss:

$$Energy\ loss = \sum Energy\ in - \sum Energy\ out \quad (60)$$

$$Energy\ loss = 846.07 \frac{MJ}{hr} - 672.564 \frac{MJ}{hr}$$

$$\boldsymbol{Energy\ loss = 173.5 \frac{MJ}{hr}}$$

The percent energy/heat loss is calculated as:

$$\%\, Energy\ loss = \frac{\sum Energy\ in - \sum Energy\ out}{Energy\ in\ to\ gasifier} \times 100 \quad (61)$$

$$\%\, Energy\ loss = \frac{173.5\frac{MJ}{hr}}{846.07\frac{MJ}{hr}} \times 100$$

$$\%\ \boldsymbol{Energy\ loss = 20.4\%}$$

Energy utilization performance is described by energy ratio, which is given as:

$$Energy\ Ratio = \frac{\sum Energy\ out}{\sum Energy\ in} \quad (62)$$

$$Energy\ Ratio = \frac{672.564\frac{MJ}{hr}}{846.07\frac{MJ}{hr}}$$

$$\boldsymbol{Energy\ Ratio = 0.8}$$

7.6. Carbon Conversion Efficiency

The dry RDF flow rate (m_{dry}) can be calculated by subtracting the amount of moisture in the total feed stock (m_f):

$$m_{dry} = m_f - m_w \quad (63)$$
$$= 46\frac{kg}{hr} - (\frac{6.5625}{100}) \times 46\frac{kg}{hr}$$
$$= 42.9\frac{kg}{hr}$$

The amount of carbon present in the RDF can be found by multiplying the dry RDF flow rate with its carbon content of 41.7241(as reported in the RDF characterization).

$$Carbon\ flow\ rate\ per\ in\ dry\ feed\ (C_{in}) = 42.9\frac{kg}{hr} \times 0.417241$$
$$= 17.9\frac{kg}{hr}$$

The amount carbon in the producer gas can be determined by multiplying the sum of molar fractions of CO, CO_2, CH_4, molar density of ideal gas ($\rho_{mol} = 44.6\frac{mol}{m^3}$), molecular weight of carbon ($M_c = 12\frac{gm}{mol}$), and producer gas flow rate [39].

$$Carbon\ flow\ rate\ per\ hour\ in\ the\ produt\ gas\ (C_{out}) = (Y_{CO} + Y_{CO_2} + Y_{CH_4}) \times \rho_{mol} \times M_c \times V_g \quad (64)$$

$$= (0.3716 + 0.0119 + 0.0029) \times 44.6 \frac{mol}{m^3} \times \frac{12}{1000} \frac{kg}{mol} \times 65.14 \frac{m^3}{Hr}$$

$$= 13.47 \frac{kg}{hr}$$

The carbon conversion efficiency is then:

$$Carbon\ conversion\ efficiency = \frac{C_{out}}{C_{in}} \times 100 \quad (65)$$

$$= \frac{13.47 \frac{kg}{hr}}{17.9 \frac{kg}{hr}} \times 100$$

$$\boldsymbol{Carbon\ conversion\ efficiency = 76\%}$$

From the above energy balance and carbon closure calculation results it can be deduced that, the adiabatic assumption of the equilibrium model has tolerable errors and as the real carbon closure value is 76%, far less beyond the model assumption. It can be concluded that the model gives over estimated values which are ideally maximum outputs that are not achieved in practice. This conclusion is well validated with [4].

8. DESIGN OF GAS CLEANING AND CONDITIONING SYSTEM

The basic cleanup system design strategy should be based on the required cleanliness goals determined by the application as stated on the specifications for the gasifier, the order of removal, temperature and intended site for removal of collected materials. In addition size, weight, cost, durability, the need for exotic materials, water consumption, effluents disposal, time taken between cleaning cycles and ease of equipment servicing must be considered.

The first step towards producing clean gas is to choose a gasifier design that minimizes production of tars and particulates to be removed, such as downdraft or other low tar gasifier and to make sure that the gasifier is operated in a manner that will minimize particulate production by proper sizing as done on previous chapters.

The next step which simplifies the handling of captured contaminants is to remove particulates, tars, and water in the proper order and at the right temperature. If the gas is immediately cooled and quenched in one operation, the char, tar and water all are removed at one location to form sticky tarry mess.

The objective of this section is to design a gas conditioning system to clean the gas to the cleanness level demanded by IC engines, listed in table below [46]

Table 18: Gas Quality Requirements for Power Generation Applications in IC Engines [46]

Major Contaminants	Level of Purification demanded by IC Engine
Particle concentration	< 50 mg/Nm^3
Particle size	< 10 μm
Tar	< 100 mg/Nm^3

The minimum energy content requirement for the gas for this application is 4 MJ/Nm^3 [29].

The recommended procedure is as follows [29]:

1. Particulates are first removed at temperature below dew point of tars ($\approx 300^0C$)
2. Next tars are removed at intermediate temperatures ($\approx 100^0C$)
3. Later water is removed at 30^{0}C to 60^{0}C, and then each separate contaminant will be handled more easily.

8.1. Selection of Effective Gas Cleanup Techniques

The final step of effective gas cleanup is to wisely choose a site for disposing the collected materials. Devices can be classified as '**In-line**' and '**Off-line**'. Devices such as fabric filter and packed fiber filter are inline and devices such as cyclones, wet scrubbers and electrostatic precipitators where deposits captured outside of the flow path are off-line devices [29].

Table 19: Gas Contaminants Cleaning Methods Selection

	Contaminants	**Available cleaning/filtering methods**	**Methods employed on this study**
1	Particulates	• Cyclone separator • Barrier filter • Electrostatic precipitator • Wet scrubber	• Cyclone separator (**Justification**: easy design and uses gravity for settling of particles out of gas line. High efficiency cyclone separators can be fabricated by a sheet metal at low cost.)
2	Alkali Compounds	• Cooling below 600^0C + electrostatic precipitator • Cooling below 600^0C + fabric filter • Cooling below 600^0C + bag filter	• Cooling below 600^0C + fabric filter (**Justification**: has good efficiency, ease of manufacturing and for cost reason)
3	Nitrogen Compounds	• Standard Catalytic Methods	
4	Sulfur	• Wet scrubbing • Wet scrubbing + additives	• Wet scrubbing (**Justification**: limitation on availability of additives)

5	Chlorine	• Wet scrubbing	• Wet scrubbing
6	Tar	• Thermal destruction • Catalytic destruction • Barrier filters • Wet scrubbers	• Catalytic destruction + Wet scrubbers (**Justification**: this technique will not affect heating value of the gas and used the c heap dolomite catalyst and has high efficiency)

Finally, the gas will be dried to suit for engine application.

8.2. Components of the Gas Cleaning and Conditioning System

The relation between gas temperature and cleaning operation (as discussed in chapter 5) is shown below in the full schematics of the gas cleaning and cooling system.

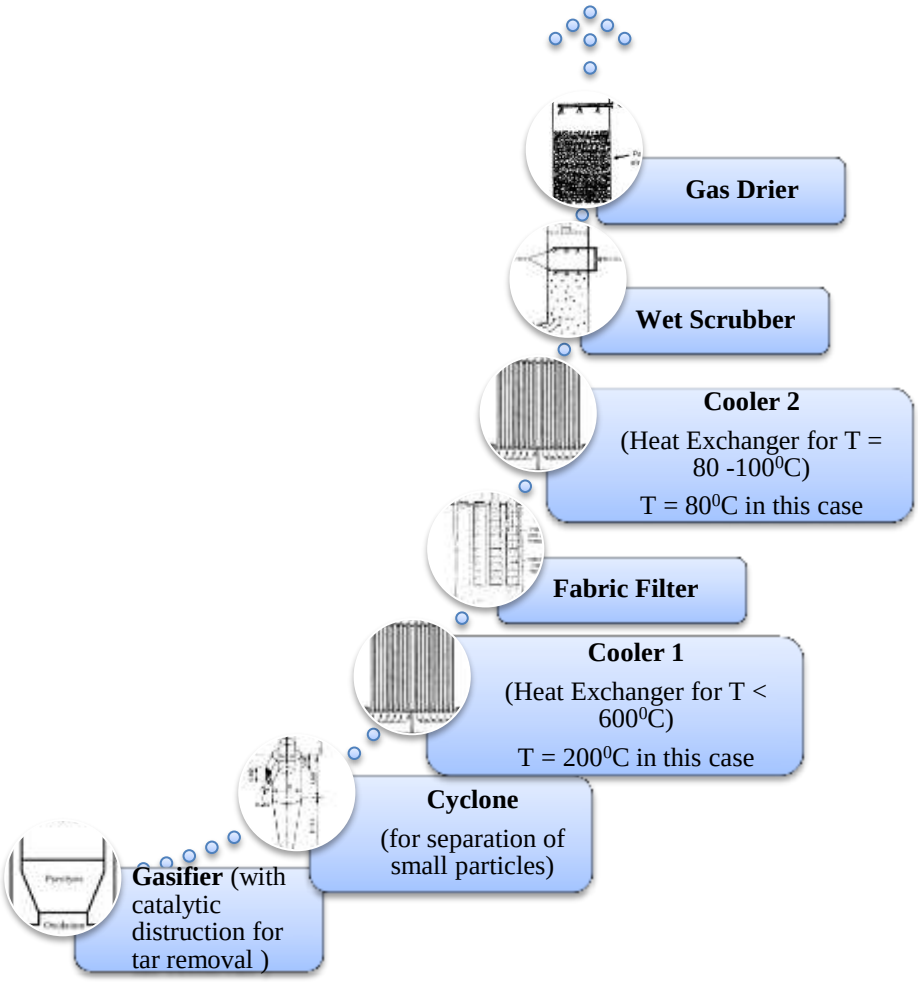

Figure 29: Schematics of gas cleaning and conditioning system

Components of the gas cleaning system are:

1. Grate
2. Cyclone Separator
3. Cooler 1 (Heat Exchanger)
4. Fabric Filter
5. Cooler 2 (Heat Exchanger)
6. Wet Scrubber
7. Gas Drier

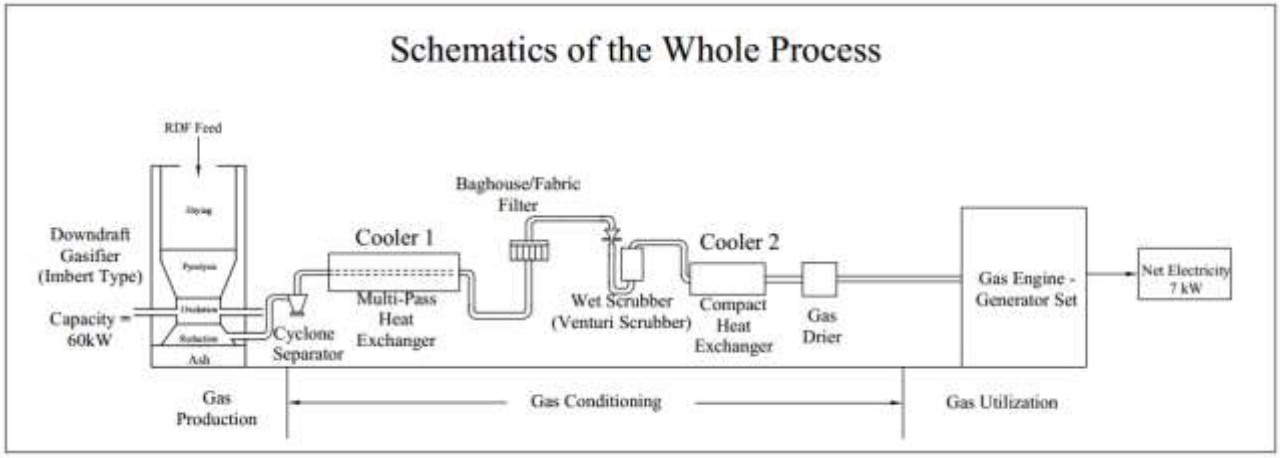

Figure 30: Schematics of The whole Process

The working principles and designs and/or selections (the above components) will follow.

8.3. Grate

Grate is a part of gasifier assembly that is used for ash removal. The configuration of this component is completed with the sizing of the gasifier.

8.4. Cyclone Separator

Cyclones are gravity settling chambers most for dry collection. Cyclones are a simple and inexpensive dust and droplet separators; widely used on gasifiers. Hot gas cyclone separators are well suited to remove solid particle larger than 10μm as a pre-filter for gas cooler and fine particles removal.

8.4.1. Working Principle of Cyclone

Cyclone separator imparts a rotary motion to the gas thereby enhancing the settling rate to many times that could by induced by gravity alone. A cyclone separator is essentially a gravitational separator that has been enhanced by centrifugal force component [29].

8.4.2. Cyclone Design

Cyclone performance is rated in terms of particle cut diameter or cut size. The cut size, d_{p50}, is the particle size which is captured 50%. d_p is the particle diameter and the numerical subscript denotes the collection efficiency at that particle. Example: A cyclone rated at d_{p50} = 10μm is expected to capture 50% particles having 10μm aerodynamic diameter [29].

The gas contaminants consist of solids and liquids. The solids include char, ash and soot. The liquids include mist or fog composed of droplets smaller than 1μm. The solids can be quite abrasive and tar mist that can cause inlet valves, rings, throttle shafts and other moving parts of the engine to stick. Aerosols are solids and liquids suspended in a gas. Thus, both contaminants should be removed for reliable engine operation.

8.4.2.1.Design Considerations

Factors that affect cyclone performance, presented below, are considered in the design process: [29]

- Optimum velocity intake. Low velocity and oversized cyclones should be avoided.
- Air leakage into the char/ash hopper at the bottom of a cyclone separator deteriorates the performance substantially.
- Entrainment of solid particles caused by improper cone design or faulty design of the discharge receiver.

8.4.2.2.Design Specifications

I. The diameter of the pipe leading from the gasifier outlet to the cyclone inlet should be selected to allow an adequate solids conveying velocity in the pipe. Ranges of conveying velocities for different contaminants are given in the table below.

Table 20: Gas Velocity Requirements for Conveying Solids [41]

Contaminant	Velocity (m/s)
Smoke, fumes, very light dust	10
Dry medium density dust (sawdust grain)	15
Heavy dust (metal turnings)	25

II. Select the cyclone inlet pipe width (B_c) equal to the gasifier outlet pipe diameter or set the cyclone inlet velocity equal to the pipe velocity and design the cyclone according to proportions given in [Appendix A.5, Figure A.5.1].

8.4.2.3.Design Calculations

For this 148kW gasifier – engine system, the gas flow rate at the engine manifold is 65.14Nm^3/hr. and inlet conditions to the engine are assumed to be 27^{0}C (300K) and 1 atm. According to [handbook, ref], it is desirable to reduce solid particles to 10mg/Nm^3 form the row gas that exits the gasifier at 700^{0}C. In addition cyclone inlet temperature is assumed to be 700^{0}C (973K). Therefore the volume flow rate at the gasifier inlet is calculated as follows [29]. Assuming isobaric process and product gas behaves as ideal gas at higher temperatures:

$$\frac{\dot{Q}_1}{T_1} = \frac{\dot{Q}_2}{T_2}$$

(66)

Where:

$\dot{Q}_1$ = Volume flow rate at cyclone inlet, Nm^3/hr.

T_1 = Temperature at the cyclone inlet = 973K

$\dot{Q}_2$ = Volume flow rate at the engine manifold, 65.14 Nm^3/hr.

T_2 = Temperature at the engine manifold = 300K

$$\dot{Q}_1 = \frac{65.14\,\frac{\mathrm{Nm}^3}{\mathrm{hr}}. \times 973\mathrm{K}}{300\mathrm{K}}$$

$$= \underline{211.27\mathrm{Nm}^3/\mathrm{hr}}. = \underline{0.0587\mathrm{m}^3/\mathrm{s}}$$

From table 10, it can be seen that the recommended minimum velocity for conveying medium density dust is 15m/s. Thus 1 ½ inch (3.81cm diameter) pipe will provide a velocity of:

$$\mathrm{V} = \frac{4\dot{Q}_1}{\pi D^2} = \underline{51.5\mathrm{m/s}}$$

This value is above the minimum. Selecting the cyclone inlet with equal to the gas pipe diameter, the cyclone was designed from the proportions given in [Appendix A.5, Figure A.5.1].

B_c = 1 ½ inch = 38.1mm

$D_c = B_c \times 4$ = 152.4mm

$D_e = \frac{D_c}{2}$ = 76.2mm

$H_c = \frac{D_c}{2}$ = 76.2mm

$L_c = D_c \times 2$ = 304.8mm

$S_c = \frac{D_c}{8}$ = 19.02mm

$Z_c = D_c \times 2$ = 304.8mm

$J_c = \frac{D_c}{4}$ = 38.1mm

8.4.2.4.Design Validation

For the cyclone inlet area of $B_c \times H_{c,}$ = 0.0381m × 0.0762m, the cyclone inlet velocity will be:

$$V = \frac{\dot{Q}_1}{Bc \times Hc} = \underline{20.22 \text{ m/s}}$$

20.22m/s > 15m/s, this is a safe design!

8.4.3. Calculation of Particle Cut Diameter (Particle Cut Size)

Cyclone cut size is the particle size that will be collected with 50% efficiency. The particle size that can be separated with 50% efficiency is predicted for general cyclones by the following equation.

$$d_{pc} = \sqrt{\frac{9\mu_G b}{2\pi N_e V_i (\rho_P - \rho_G)}} \quad (67)$$

Where:-

d_{pc} = Particle cut size, μ m

b = Cyclone inlet with = 0.0381m.

μ_G = Gas dynamic viscosity, kg/ms^{-1}

N_e = Effective number of turns in a cyclone; 5 is assumed considering highly efficient cyclone.

V_i = Inlet gas velocity, ms^{-1}

ρ_P = Actual gas density, kg/m^3

ρ_G = Gas density at the inlet, kg/m^3

The variation of gas viscosity and density with temperature is shown in [Appendix A.5, Figure A.5.2].

At cyclone inlet temperature of 700^0C, the density and dynamic viscosity of the gas are:

$$\rho_P = \underline{0.3\ kg/m^3}$$

$$\mu_G = \underline{75(10)^{-7}\ kg/m\ s}$$

Taking ash density, ρ_P = 2000 kg/m^3 and char density of 200 kg/m^3, [29] the cyclone cut size will be:

$$d_{pc} = \sqrt{\frac{9 \times 75(10)^{-7} \times 0.0381}{2\pi \times 5 \times 20.22(2000 - 0.3)}}$$

$$= \underline{1.423\mu m\ for\ ash}$$

$$d_{pc} = \sqrt{\frac{9 \times 75(10)^{-7} \times 0.0381}{2\pi \times 5 \times 20.22(200 - 0.3)}}$$

$$= \underline{4.5\mu m\ for\ ash}$$

8.4.4. Calculation of Pressure Drop across the Cyclone

The cyclone pressure drop will be [29]:

$$\Delta P = \frac{0.065 \times \rho_G \times V_i^2 \times A_d}{D_e^2} \quad (68)$$

Where:-

A_d = inlet duct area ($B_c \times H_c$, = 0.0381m × 0.0762m)

$$\Delta P = \frac{0.065 \times 0.3 \times 20.22^2 \times 0.0381\text{m} \times 0.0762\text{m}}{0.0762^2}$$

$$= \underline{4mm\ H_2O}$$

It can be seen that this cyclone archives the desired particulate removal without excessive pressure drop.

8.5. Cooler 1 (Heat Exchanger)

It is essential to cool producer gas before admitting it in to the engine cylinder in order to overcome the difficulties of engine knocking, contamination problems at higher temperatures and overheating which results severe damage to the engine components. These problems can be avoided by making use of a heat exchanger with the required heat rejection capacity.

8.5.1. Heat Exchanger Selection

There are two successive producer gas cooling processes in this gasifier – engine set to be achieved by two coolers: cooler 1 and cooler 2.

The easily available and economical cooling mediums to take part in to these heat exchange processes are water (chilled) and ambient air. Using chilled water for both cases will require a very large heat exchanger that will provide very vast area for the heat exchange. Using ambient air as a cooling medium for both cases will not be economical by demanding a number of compact heat exchangers in series for the reason that the ambient air has a very low convection heat transfer coefficient compared to the speedy and hot producer gas. This conditions leads to the need of compact heat exchangers the will demand heat transfer area $>700 m^2/m^3$ in a single compact heat exchanger. Therefore the best way is to use cooling with chilled water in one of the stages (for cooler 1 at stage one) and cooling by ambient air on the next last step (for cooler 2 at stage two).

The available heat exchanger options for cooler 1 (cooled with chilled water) are the following [40]:

- Double tube heat exchangers
- Shell and tube heat exchangers
- Cross – flow heat exchangers
- Plate type heat exchangers
- Compact heat exchangers

Plate type heat exchangers and shell and tube heat exchangers are good choices from the available alternatives because double pipe heat exchanger needs very long piping and many fittings which will result in huge pressure drop plus it is difficult to open and clean. Cross flow and compact heat exchangers are used when one side of the fluids is gas, and cooling with ambient air is not a wise decision even if forced air is used, because it needs fins and very large heat transfer area on the piping, bigger fan etc … But shell and tube heat exchangers and plate type heat exchangers are efficient and relatively less costly for big temperature drop. [40]

8.5.2. Design of Shell and Tube Heat Exchanger for Producer Gas Cooling Applications (Cooler 1)

8.5.2.1.Thermal Design Consideration

Thermal design of shell and tube heat exchanger typically includes determination of heat transfer area, number of tubes, tube length and diameter, tube layout, number of shell and tube passes, type of heat exchanger (fixed tube sheet, removable, tube bundle arrangement …), tube pitch, number of baffles, its type and size, shell and tube side pressure drops etc [40].

The Shell

Shell is container for shell fluid and tube bundle is placed inside the shell. Shell diameter should be selected in such a way to give a close fit of tube bundle. The clearance between the tube bundle and inner shell wall depends on type of exchanger. Shells are usually fabricated from standard steel pipe with satisfactory corrosion allowance [47].

Tube

The outer diameter (OD) ¾ inch and 1 inch are very common to design a compact heat exchanger. The most efficient condition for heat transfer is to give the maximum number of tubes in the shell to increase turbulence. The tube thickness should be enough to understand the internal pressure along with adequate corrosion allowance. The tube thickness expressed in terms of BWG (Birmingham Wire Gauge) and tube outside diameter (OD). The tube lengths of 6, 8, 12, 16, 20 and 24 feet are preferably used. Longer tube reduces shell diameter at the expense of higher shell pressure drop. Finned tubes are also used when fluids with lower heat transfer coefficient flows in the shell side. Stainless steel, admiralty brass, copper, bronze and alloys of copper – nickel are commonly used materials [47].

Tube Pitch, Tube – Layout, and Tube - Count

Tube pitch is the shortest center to center distance between adjacent tubes. The tubes are generally placed in square or rectangular patterns as shown in the figure below [48].

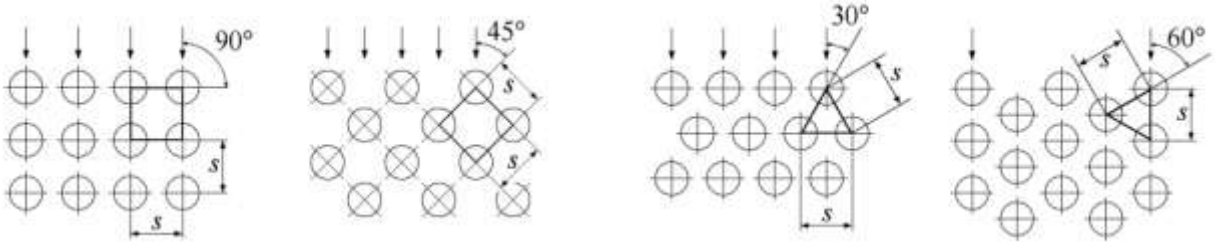

Figure 31: Standard Tube Arrangements: 90 and 45 Degree Square and 30 and 60 Degrees Triangular [48]

The widely used layouts are illustrated in the table below

Table 21: Common Tube Layouts [47]

Tube OD, inch	Pitch Type	Tube Pitch, inch
¾	Square	1
1		1 ¼
¾	Triangular	15/16
¾		1

The number of tubes accommodated in a given shell ID is called tube count. The tube count depends on the factors like shell ID, OD of tube pitch, tube layout, number of passes, type of heat exchanger and design pressure.

Tube Passes

The number of passes is chosen to get the required tube side fluid velocity to obtain greater heat transfer coefficient and also to reduce scale formation. The tube passes vary from 1 to 16. The tube passes of 1, 2, and 4 are common in application. The partition built in to exchanger head known as partition plate (also called pass partition) is used to direct the tube side flow [47].

Tube Sheet

The tubes are fixed with tube sheet that form the barrier between the tube and shell fluids. The tubes can be fixed with the tube sheet using ferrule and soft metal packing ring. The tubes are attached to tube sheet with two or more grooves in the tube sheet wall by 'tube rolling'. The tube metal is forced to move in to the groove forming an excellent tight seal. This is the most common type of fixing arrangement in large industrial exchangers. The tube thickness should be greater than the outside diameter to make a good seal. The recommended standards (15:4503 or TEMA) should be followed to select the minimum tube sheet thickness [47].

Baffles

Baffles are used to increase the fluid velocity by diverting the flow across the tube bundle to obtain higher heat transfer coefficient. It also supports tubes against flow induced vibration. The distance between adjacent baffles is called baffle spacing. The baffle spacing of 0.2 to 1 times the inside shell diameter is commonly used. Baffles are held in positioning by means of baffle spacers. Closer baffle spacing gives greater heat transfer coefficients by inducing

higher turbulence [47]. The pressure drop is more with closer baffle spacing. Various types of baffles are shown in the figure.

In case of cut segmental baffle, a segment (called baffle cut) is removed to form the expressed as a percentage of the baffle diameter. Baffle cuts from 15 to 45% are normally used. A baffle cut of 20 to 25% provides a good heat transfer with the reasonable pressure drop. The percent cut for segmental baffle refers the cut away height from its diameter.

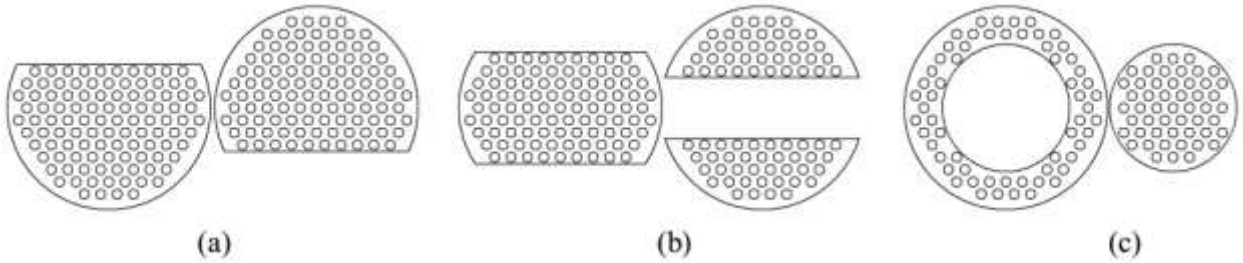

Figure 32: Some Basic Baffle Configurations, a) Single - Segmental Baffle, b) Double - Segmental Baffle, c) Disk and Doughnut Baffle [48]

8.5.3. Fouling Considerations

Most of the process fluids in the exchanger foul the heat transfer surface. The material deposited residues the effective heat transfer rate due to relatively low thermal conductivity. Therefore, the b=net heat transfer with clean surface should be higher to compensate the reduction in performance during operation. Fouling of heat exchangers increases the cost of [40]:

I. Construction due to oversizing
II. Additional energy due to poor exchanger performance
III. Cleaning to remove deposited materials

A spare heat exchanger may be considered in design for uninterrupted services to allow cleaning of exchanger. The effect of fouling is considered in heat exchanger design by including the tube side and shell side fouling resistances. Typical values for the fouling coefficients and resistances are summarized in table below [40].

Table 22: Typical Values of Fouling Coefficients and Resistances [40]

Fluid	Coefficient, $W/m^2\,^0C$	Resistance, $m^2\,^0C/W$
River Water	3000 – 12000	0.003 – 0.001
Sea Water	1000 – 30000	0.001 – 0.0003
Cooling Water (Towers)	3000 – 6000	0.0003 – 0.00017

Towns Water (Soft)	3000 – 5000	0.0003 – 0.0002
Towns Water (Hard)	1000 – 2000	0.001 – 0.0005
Steam Condensate	1500 – 5000	0.00067 - 0.0002
Steam (Oil Free)	4000 – 10000	0.0025 – 0.0001
Steam (Oil Traces)	2000 – 50000	0.0005 – 0.0002
Refrigerated Brine	3000 - 5000	0.0003 – 0.0002
Air and Industrial Gases	5000 - 10000	0.0002 – 0.0001
Flue Gases	2000 - 5000	0.0005 – 0.0002
Organic Vapors	5000	0.0002
Organic Liquids	5000	0.0002
Light Hydrocarbons	5000	0.0002
Heavy Hydrocarbons	5000	0.0002
Boiling Organics	2500	0.0004
Condensing Organics	5000	0.0002
Heat Transfer Fluids	5000	0.0002
Aqueous Salt Solutions	3000 – 5000	0.0003 – 0.0002

8.5.4. Selection of Fluids for Tube and Shell Side

The routing of the shell side and tube side fluids has considerable effects on the heat exchanger design. Some general guidelines for positioning the fluids are given in the table below.

Table 23: Guideline for Placing Fluids in Order of Priority [47]

Tube Side Fluid	Corrosive Fluid Cooling Water Fouling Fluid Less Viscous Fluid High Pressure Stream Hotter Fluid
Shell Side Fluid	Condensing Vapor (Less Corrosive) Fluid with Larger Temperature Difference (>40 ^{0}C)

8.5.5. Process (Thermal) Design

Shell and tube heat exchanger is designed by trial and error calculations. The design approach is adopted from **Kern Method** from [40].

Design Specifications:

Hot fluid inlet temperature (T_g) = 700^0C = 973K

Hot fluid outlet temperature (t_1) = 300 ^{0}C = 573K

Cold fluid inlet temperature (T_w) = 5 ^{0}C = 238K (Chilled Water)

Cold fluid outlet temperature (t_2) = 180 ^{0}C = 453K

Fouling factor of hot fluid (R_g) = 0.00035 m^2 ^{0}C/W (from table 12)

Fouling factor of cold fluid (R_w) = 0.000235 m^2 ^{0}C/W (from table 12)

Flow rate for hot fluid ($\dot{Q}_g$) can be calculated as:

$$\frac{\dot{Q}_1}{T_1} = \frac{\dot{Q}_g}{T_g} \tag{69}$$

Where:

$\dot{Q}_1$ = Volume flow rate at engine inlet = 65.14 Nm^3/hr.

T_1 = Temperature at the engine inlet = 300K

$\dot{Q}_g$ = Volume flow rate at of gas the heat exchanger inlet, Nm^3/hr.

T_g = Temperature at the heat exchanger inlet = 973K

$$\dot{Q}_1 = \frac{65.14\frac{Nm^3}{hr}. \times 973K}{300K}$$

$$= \underline{276.137 Nm^3/hr}. = \underline{0.0767\ m^3/s}$$

$\dot{Q}_W$ = Volume flow rate of water at the heat exchanger inlet, Nm^3/hr, will be calculated from the energy balance.

Calculation of Caloric Temperature

Hot Fluid		Cold Fluid	Difference
700 ^{0}C	High Temperature	180 ^{0}C	520 ^{0}C
300 ^{0}C	Lower Temperature	5 ^{0}C	295 ^{0}C
400 ^{0}C	Differences	175 ^{0}C	225 ^{0}C

The log-mean temperature difference (LMTD):

$$\text{LMTD} = \frac{\Delta T_2 - \Delta T_1}{\ln\frac{\Delta T_2}{\Delta T_1}} \tag{70}$$

$$\text{LMTD} = \frac{(300℃ - 5℃) - (700℃ - 180℃)}{\ln \frac{(300℃ - 5℃)}{(700℃ - 180℃)}}$$

$$\text{LMTD} = 397\ ℃$$

To find the LMTD correction factor, F_t, using the diagram in [Appendix A.5, Figure A.5.3]:

$$R = \frac{T_1 - T_2}{t_2 - t_1} \quad (71)$$

$$R = \frac{5 - 180}{300 - 700}$$

$$= 0.4375$$

$$S = \frac{t_2 - t_1}{T_1 - t_1} \quad (72)$$

$$S = \frac{180 - 5}{700 - 5}$$

$$= 0.252$$

From the above figure, at R = 0.4375 and S = 0.252, $F_t = 1$

$$\text{LMTD}_{\text{Corr.}} = 1 \times 397\ ^0\text{C} = 397\ ^0\text{C}$$

To determine the caloric temperature correction actor, F_c, referring to [Appendix A.5, Figure A.5.4]:

The ratio of cold fluid temperature difference to hot fluid temperature difference, r:

$$r = \frac{\Delta t_c}{\Delta t_h} \quad (73)$$

$$r = \frac{300℃ - 5℃}{700℃ - 180℃}$$

$$r = 0.567℃$$

$$K_c = \left|\frac{U_h - U_C}{U_C}\right| \quad (74)$$

Where, U_C= overall heat transfer coefficient to the cold end and U_h = overall heat transfer coefficient to the hot end.

From table 22:

U_C = 4500 W/m^2 ^{0}C

U_h =3500 W/m^2 ^{0}C

$$K_c = \left|\frac{3500 - 4500}{3500}\right|$$

$$K_c = 0.286$$

From [Appendix A.5, Figure A.5.4], at $r = 0.567$℃ and $K_c = 0.286$ and F_c = 0.44, Caloric temperature of the hot fluid, T_{hc}:

$$T_{hc} = t_1 + F_C\,(T_g - t_1) \quad (75)$$

$$= 300℃ + 0.44(700℃ - 300℃)$$

$$= 476℃$$

Caloric temperature of the cold fluid, T_{cc}:

$$T_{cc} = t_w + F_C\,(t_2 - T_w) \quad (76)$$

$$= 5℃ + 0.44(180℃ - 5℃)$$

$$= 82℃$$

Fluid properties at caloric temperature

- **Viscosity:**

μ_g = 1.57263 × 10^{-5} Ns/m^2 [38]

μ_w = 3.43 × 10^{-4} Ns/m^2 [38]

- **Thermal Conductivity:**

$K_g = 0.0344\ W/mK$ [38]

$K_W = 0.671\ W/mK$ [38]

- **Specific Heat Capacity:**

$C_{p,g}$ = 1249.61 J/kg. K [38]

$C_{p,w}$ = 4199 J/kg. K [38]

- **Specific Gravity:**

$SG_g = 1.033 \times 10^{-3}$

$SG_w = 0.974$

Energy Balance

Assuming no heat loss to the surrounding, heat released by the hot fluid (Q_g) is equal to heat absorbed by the cold fluid (Q_w).

Mathematically,

$$Q_g = Q_w \quad (77)$$

$$\dot{m}_g C_{p,g} \left(T_g - t_1\right) = \dot{m}_w C_{p,w} \left(t_2 - T_w\right)$$

The mass flow rate of the hot fluid ($\dot{m}_g$) can be calculated as:

$$\dot{m}_g = \rho_g \dot{Q}_g \quad (78)$$

$$= 1.03 \frac{kg}{m^3} \times 0.0767 \frac{m^3}{s}$$

$$= 0.079 \frac{kg}{s}$$

Mass flow rate of the cold fluid ($\dot{m}_w$) will be determined from the energy balance.

$$0.079 \frac{kg}{s} \times 1249.61 \text{ J/kg. K} (700℃ - 300℃) = \dot{m}_w 4199 \text{ J/kg. K} (180 - 5)$$

$$\dot{m}_w = 0.055 \frac{kg}{s}$$

The amount of cooling (rating of the heat exchanger), is therefore:

$$Q_g = Q_w = 39.487\text{kW}$$

Calculation of Heat Transfer Area and Tube Numbers

Iteration #1

The iteration started by assuming Single Shell and 1 tube pass, shell and tube heat exchanger with the following standards dimensions and considerations [Appendix A.5, Table A.5.1 and Table A.5.2].

- 1 inch OD tubes (14 BWG) on 1 ¼ in triangular pitch
- Outer tube diameter (d_o) = 1 inch
- Inner tube diameter (d_i) = 0.834 inch
- Tube length (L_t) = 12 feet
- Fixed tube plate
- Fluid arrangement: Producer gas is placed inside the tube because it has contaminants and has higher fouling tendency. Cooling water flows in the shell side.

Determining the Heat Transfer Area (A):

The average value of overall heat transfer coefficient of (U_{ov}, assumed = 26 W/m^2 ^{0}C) is assumed for heat exchanger of gases (hot fluid) and cold fluid (water) [Appendix A.5, Table A.5.3] to initiate the design calculation for the heat exchanger and will be checked later.

$$A = \frac{Q}{U_{ov,assumed} \times LMTD_{Corr.}} \quad (79)$$

$$= \frac{39487W}{26\ {}^{W}/_{m^2\text{°C}} \times\ 397\text{°C}}$$

$$=\ 4.37\ m^2$$

Calculating the number of tubes required, n_t:

$$n_t = \frac{A}{\pi d_o L_t} \tag{80}$$

$$n_t = \frac{4.37\ m^2}{\pi\ (0.0254m) \times\ 3.75m}$$

$$n_t = 15\ tubes$$

The closest shell ID to the calculated number of tubes is: Shell ID of 8 inch, 1 shell and 2 tube pass, fixed sheet shell and tube heat exchanger with tube OD of 1 inch and 1 ¼ triangular pitch. The standard number of tubes is:

$$n_t = 16\ tubes$$

Check for fluid velocity:

$$Re_g = \frac{4 \times \dot{m}_g \times \frac{n_p}{n_t}}{\pi \times d_i \times \mu_g} \tag{81}$$

$$Re_g = \frac{4\ \times\ 0.079 \times \frac{2}{12}}{\pi\ \times\ 0.0212\ \times\ 1.573\ \times\ 10^{-5}}$$

$$Re_g =\ 37703.58$$

$Re_g \gg 10^4$, which is not realistic (requires very high velocity of producer gas out of permissible limit), therefore the iteration proceeds

Iteration #2

The second iteration started by assuming Single shell, shell and tube heat exchanger with the following standards dimensions and considerations [Appendix A.5, Table A.5.4].

- 1 ¼ inch OD tubes (18 BWG) on 1 9/16 in square pitch
- Outer tube diameter (d_o) = 1 ¼ inch
- Inner tube diameter (d_i) = 1.15 inch
- Tube length (L_t) = 12 feet
- Fixed tube plate

- Fluid arrangement: Producer gas is placed inside the tube because it has contaminants and has higher fouling tendency. Cooling water flows in the shell side.

Calculating the number of tubes required, n_t

$$n_t = \frac{A}{\pi d_o L_t}$$

$$n_t = \frac{4.37\ m^2}{\pi\ (0.03175m) \times\ 3.75m}$$

$$n_t = 12\ tubes$$

The closest shell ID to the calculated number of tubes is: **Shell ID of 10 inch, 1 shell and 2 tube pass, fixed sheet shell and tube heat exchanger with tube OD of 1 ¼ inch and 1 9/16 square pitch**. The standard number of tubes is:

$n_t = 12\ tubes$

Checking for fluid velocity:

$$Re_g = \frac{4\ \times\ \dot{m}_g \times \frac{n_p}{n_t}}{\pi\ \times\ d_i\ \times\ \mu_g}$$

$$Re_g = \frac{4\ \times\ 0.079 \times \frac{2}{12}}{\pi\ \times\ 0.02921\ \times\ 1.573\ \times\ 10^{-5}}$$

$Re_g =\ 36509$, which is not realistic again.

Iteration #3

The third iteration started by assuming Single shell, shell and tube heat exchanger with the following standards dimensions and considerations [Appendix A.5, Table A.5.4].

- 1 ¼ inch OD tubes (18 BWG) on 1 9/16 in square pitch
- Outer tube diameter (d_o) = 1 ¼ inch
- Inner tube diameter (d_i) = 1.15 inch
- Tube length (L_t) = 12 feet
- Fixed tube plate

Fluid arrangement: Producer gas is placed inside the tube

Calculating the number of tubes required, n_t

$$n_t = \frac{A}{\pi d_o L_t}$$

$$n_t = \frac{4.37\ m^2}{\pi\ (0.03175m) \times\ 3.75m}$$

$$n_t = 12\ tubes$$

The closest shell ID to the calculated number of tubes is: **Shell ID of 10 inch, 1 shell and 1 tube pass, fixed sheet shell and tube heat exchanger with tube OD of 1 ¼ inch and 1 9/16 square pitch**. The second closest standard number of tubes is:

$$n_t = 16\ tubes$$

$$Re_g = \frac{4\ \times\ 0.079 \times \frac{1}{16}}{\pi\ \times\ 0.02921\ \times\ 1.573\ \times\ 10^{-5}}$$

$$Re_g = 13682$$

$Re_g > 10^4$, therefore it is acceptable.

The velocity of the tube side flow, V_g:

$$V_g = \frac{Re_g \times \mu_g}{d_i \times \rho_g} \quad (82)$$

Where, $n_p = number\ of\ tube\ passes\ and\ \rho_g = density\ of\ the\ producer\ gas$

$$V_g = \frac{13682\ \times 1.573\ \times\ 10^{-5}}{1.03 \times\ 0.02921}$$

$$V_g = 7.14\ m/s$$

$V_g > 1\ m/s$, the design velocity is within the acceptable range.

Determination of Heat Transfer Coefficients

The tube side heat transfer coefficient (h_i) is calculated from the correlation given in [40]:

$$J_H = \frac{h_i\ d_i}{K_g}\left(\frac{\mu_g \times C_g}{k_G}\right)^{-1/3}\left(\frac{\mu_g}{\mu_{Wall}}\right)^{-0.14} \quad (83)$$

Where, $\mu_{Wall} = viscosity\ of\ tube\ side\ fluid\ at\ wall\ temperature.$

$(Assuming\ mean\ gas\ temperature\ is\ equal\ to\ tube\ wall\ temperature, \frac{\mu_g}{\mu_{Wall}} = 1)$

J_H can be determined from [Appendix A.5, Figure A.5.5] as a function of Reynolds's number and L/D ratio:

At $Re_g = 13682$ and L/D = (3.75) / 0.02845 = 132, J_H = 41

$$J_H = \frac{h_i\, d_i}{K_g}\left(\frac{\mu_g \times C_g}{k_G}\right)^{-1/3} \quad (84)$$

$$41 = \frac{h_i\, 0.02845}{0.0344}\left(\frac{1.573 \times 10^{-5} \times 1249.61}{0.0344}\right)^{-1/3}$$

$$h_i = 41.13\ W/m^2{}^{\circ}\mathrm{C}$$

Shell side heat transfer coefficient (h_o):

Assumptions,

- 25% segmental baffles attached
- Baffles spacing; B = 0.5 × Shell ID = 5 inch = 0.127m

Equivalent diameter of the shell side, De: (for square pitch)

$$D_e = \frac{4\left(P_T{}^2 - \frac{\pi}{4} d_o^2\right)}{\pi d_o} \quad (85)$$

Where P_T= 1 9/16 inch (Pitch)

$$D_e = \frac{4\left(0.0397^2 - \frac{\pi}{4}\, 0.03175^2\right)}{\pi(0.03175)}$$

$$D_e = 0.03145\ m$$

Shell side cross flow area, a_s:

$$a_s = \frac{C \times B \times Shell\ ID}{P_T} \quad (86)$$

Where, C = tube clearance

$$\mathrm{C} = P_T - d_o \quad (87)$$

= 0.5625 inch = 0.0143m

$$a_s = \frac{0.0140m \times 0.127m \times 0.254m}{0.0397m}$$

$$a_s = 0.01137\ m^2$$

Mass velocity, G_s:

$$G_s = \frac{\dot{m_w}}{a_s} \quad (88)$$

$$G_s = \frac{0.055\ kg/s}{0.01137m^2}$$

$$G_s = 4.84\ kg/m^2 s$$

Shell side Reynold's number, Re_w:

$$Re_w = \frac{D_e \times G_s}{\mu_w} \quad (89)$$

$$Re_w = \frac{0.03145m \times 4.84\ kg/m^2s}{3.43 \times 10^{-4}\ \text{Ns/m}^2}$$

$= 443.78$

Now for the shell side,

$$J_H = \frac{h_o\, d_o}{K_w}\left(\frac{\mu_w \times C_w}{k_w}\right)^{-1/3} \quad (90)$$

From [Appendix A.5, Figure A.5.6], at $Re_w = 443.78$, with 25% cut segmental baffles:

$J_H = 11$

$$11 = \frac{h_o\ 0.03175}{0.671}\left(\frac{3.43 \times 10^{-4} \times 4199}{0.671}\right)^{-1/3}$$

$h_o = 300\ W/m^2\text{℃}$

Calculation of Overall Heat Transfer Coefficient (U_{cal})

$$U_{cal} = \left[\frac{1}{h_o} + R_w + \frac{A_O}{A_i}\left(\frac{d_o - d_i}{2K_{pipe}}\right) + \frac{A_O}{A_i}\left(\frac{d_o - d_i}{2K_{pipe}}\right)\left(\frac{1}{h_i}\right) + \frac{A_O}{A_i}R_g\right]^{-1} \quad (91)$$

$A_O = \pi d_o L_t$ = 0.374 m^2

$A_O = \pi d_i L_t$ = 0.335 m^2

Selecting Galvanized Steel

$$U_{cal} = \left[\frac{1}{300\frac{W}{m^2}\text{℃}} + 0.000235\ \frac{m^2\text{℃}}{W} + \frac{0.374\ \text{m}^2}{0.335\ \text{m}^2}\left(\frac{0.03175m - 0.02845m}{2\left(\frac{50W}{m}\text{℃}\right)}\right) + \frac{0.374\ \text{m}^2}{0.335\ \text{m}^2}\left(\frac{1}{41.13\frac{W}{m^2}\text{℃}}\right) + \frac{0.374\ \text{m}^2}{0.335\ \text{m}^2}\ (0.00035\ \frac{m^2\text{℃}}{W})\right]$$

$$U_{cal} = 32.11\ \frac{W}{\text{℃}\ m^2}$$

Checking for the design Criteria:

$$\frac{U_{cal} - U_{assumed}}{U_{assumed}} < 30\% \quad (92)$$

$$\frac{32.11\ \frac{W}{\text{℃}\ m^2} - 26\ \frac{W}{\text{℃}\ m^2}}{26\ \frac{W}{\text{℃}\ m^2}}$$

$= 23.52$ % ,Acceptable!

8.5.6. Pressure Drop Calculations

Tubes Side Pressure Drop Calculations

The tube side frictional pressure drop is given by:

$$\Delta P_{tube} = \frac{f\ G_t^2 L_t n_p}{7.5 \times 10^{12} \times d_i \times SG_G \times \varphi_t} \quad (93)$$

Where f is the frictional factor and can be determined from a curve in [Appendix A.5, Figure A.5.7]

For $Re_g = 13682$ the frictional factor, f = 0.00027 sq. ft / in^2 = 0.039 in^2/in^2

$$a_t = (number\ of\ tubes) \times \frac{(flow\ area\ per\ tube)}{number\ of\ passes} \quad (94)$$

$$a_t = (16\ tubes) \times \frac{(0.336\ m^2)}{1}$$

$$= 5.36\ m^2$$

The tube side mass velocity, G_t

$$G_t = \frac{\dot{m}_g}{a_t} \quad (95)$$

$$= \frac{0.079 \frac{kg}{s}}{5.36\ m^2}$$

$$= 0.0147\ \frac{kg}{m^2 s}$$

$$= 58.25\ \frac{lb}{ft^2 hr}$$

The tube side frictional pressure drop is calculated as:

$$\Delta P_{tube} = \frac{0.039 \times \left(58.25\ \frac{lb}{ft^2 hr}\right)^2 \times 12ft \times 1}{7.5 \times 10^{12} \times 0.016ft \times 1.033 \times 10^{-3}}$$

$$\Delta P_{tube} = 0.09Pa$$

Return Loss, ΔP_{rt}: (due to change in flow direction of the tube side fluid)

The return loss is given by:

$$\Delta P_{rt} = 1.334 \times 10^{-13} \left(2n_p - 1.5\right) \frac{G_t^2}{SG_g} \quad (96)$$

$$\Delta P_{rt} = 1.334 \times 10^{-13} (2 - 1.5) \frac{\left(58.25 \frac{lb}{ft^2 hr}\right)^2}{1.033 \times 10^{-3}}$$

$$= 0.00151 Pa$$

The Total Tube Side Pressure Drop, $\Delta P_{tube,tot}$:

$$\Delta P_{tube,tot} = 16 tubes \times \Delta P_{tube} + \Delta P_{rt} \quad (97)$$

$$\Delta P_{tube,tot} = 1.44 Pa$$

The pressure drop is within the maximum allowable value of 10psi, so it is Acceptable!

Shell Side Pressure Drop Calculations

From previous calculations for the shell side:

- Tube clearance, C = 0.25 inch = 0.0208ft
- Baffle Spacing, B = 5 inch = 0.4166ft
- $a_s = 0.01137\ m^2$ = 0.1224ft^2
- $G_s = 4.84\ kg/m^2 s$ = 3568.7 $\frac{lb}{ft^2 hr}$
- $Re_w = 443.78$
- $D_e = 0.03145\ m$ = 1.03ft
- $D_S = Shell\ ID = 10\ inch = 0.833\ ft$

Number of baffles, $n_b = \frac{Tube\ length}{Baffle\ spacing}$ (98)

$$n_b = \frac{12\ ft}{0.4166 \text{ft}}$$

$$= 29$$

At $Re_w = 443.78$, shell side friction factor for bundles with 25% cut segmental baffles, from [Appendix A.5, Figure A.5.8]: f = 0.004 sq. ft / in^2 = 0.576 in^2/in^2

The shell side pressure drop, ΔP_{shell}:

$$\Delta P_{shell} = \frac{f\ G_s^2 D_S}{7.5 \times 10^{12} \times D_e \times SG_w \times \varphi_t} \quad (99)$$

$$\Delta P_{shell} = \frac{0.576 \times \left(3568.7 \frac{lb}{ft^2 hr}\right)^2 \times (29+1)}{7.5 \times 10^{12} \times 1.03ft \times 0.974}$$

$= 0.2\ Pa$

The return loss for the shell side is zero in case of single pass flow.

Total shell side pressure drop, $\Delta P_{shell,tot}$: (Neglecting nozzle loss)

$$\Delta P_{shell,tot} = \Delta P_{shell} = 0.2\ Pa$$

The shell pressure drop is within the maximum allowable value of 7psi, so it is Acceptable!

Over Surface and Over Design Check – Up Calculations

$$\%\ Over\ surface = \frac{U_c - U_{cal}}{U_c} \times 100 \quad (100)$$

Where, U_c= Clean overall heat transfer coefficient, given by:

$$U_C = \frac{h_o \times h_{io}}{h_o + h_{io}} \quad (101)$$

Where, $h_{io} = h_i + \frac{d_i}{d_o} = 37.84 \frac{W}{^\circ C\ m^2}$

$$U_C = \frac{300 \frac{W}{^\circ C\ m^2} \times 37.84 \frac{W}{^\circ C\ m^2}}{300 \frac{W}{^\circ C\ m^2} + 37.84 \frac{W}{^\circ C\ m^2}}$$

$$U_C = 33.6 \frac{W}{^\circ C\ m^2}$$

The design criteria for acceptable over surface is $\%\ Over\ surface < 30\%$

$$\%\ Over\ surface = \frac{33.6 \frac{W}{^\circ C\ m^2} - 32.11 \frac{W}{^\circ C\ m^2}}{33.6 \frac{W}{^\circ C\ m^2}} \times 100$$

$\%\ Over\ surface = 4.43\%\ (Acceptable!)$

The %over design is calculated as:

$$\%\ Over\ design = \frac{A - A_{req}}{A_{req}} \times 100 \quad (102)$$

Where the A is design area of the heat exchanger when (n_t = 12) and A_{req} is the design heat exchanger area at (n_t = 16)

$$A = \pi \times d_0 \times L_t \times n_t \quad (103)$$

$A = \pi \times 0.03175m \times 3.75m \times 12\ tubes$

$= 4.5\ m^2$

$$A_{req} = \pi \times d_0 \times L_t \times n_t \quad (104)$$

$$A_{req} = \pi \times 0.03175m \times 3.75m \times 16\ tubes$$

$$A_{req} = 5.9\ m^2$$

$$\%\ Over\ design = \left|\frac{A - A_{req}}{A_{req}}\right| \times 100$$

$$\%\ Over\ design = \left|\frac{4.5\ m^2 - 5.9\ m^2}{5.9\ m^2}\right| \times 100$$

$\%\ Over\ design =$ 23.7% < 30%, Acceptable!

8.5.7. Summary of the Heat Exchanger

- Type: **1 ¼ inch OD tubes (18 BWG) on 1 9/16 in square pitch, single shell and one tube pass, shell and tube heat exchanger.**
- Sheel ID: **10 inch**
- Outer tube diameter (d_o) = **1 ¼ inch**
- Inner tube diameter (d_i) = **1.15 inch**
- Tube length (L_t) = **12 feet**
- **Fixed tube plate**
- Baffle Type: **25% cut segmental baffle**
- Number of baffles **= 29 baffles**

8.6. Plate Heat Exchanger (Cooler 2)

8.6.1. Selection of Off – the – Shelf Plate Heat Exchanger from Available Vendors

Specifications

Hot fluid inlet temperature (T_g) = 250^0C = 523K

Hot fluid outlet temperature (t_1) = $50\ ^0$C = 333K

Cold fluid inlet temperature (T_w) = $5\ ^0$C = 278K (Chilled Water)

Cold fluid outlet temperature (t_2) = 100^0C = 453K

Flow rate for hot fluid ($\dot{Q}_g$) can be calculated as:

$$\frac{\dot{Q}_1}{T_1} = \frac{\dot{Q}_g}{T_g} \quad (105)$$

Where:

$\dot{Q}_1$ = Volume flow rate at engine inlet = 65.14 Nm^3/hr.

T_1 = Temperature at the engine inlet = 300K

$\dot{Q}_g$ = Volume flow rate at of gas the heat exchanger inlet, Nm^3/hr.

T_g = Temperature at the heat exchanger inlet = 973K

$$\dot{Q}_1 = \frac{65.14 \frac{\mathrm{N}m^3}{\mathrm{hr}}. \times 523\mathrm{K}}{300\mathrm{K}}$$

= 0.0315 m^3/s

Mass flow rate of the hot fluid, $\dot{m}_g$:

$$\dot{m}_g = \rho_g \dot{Q}_g \quad (106)$$

$$= 1.03 \frac{kg}{m^3} \times 0.0315 \frac{m^3}{s}$$

$$= 0.03244 \frac{kg}{s}$$

$\dot{Q}_W$ = Volume flow rate of water at the heat exchanger inlet, Nm^3/hr, will be calculated from the energy balance.

Performing the energy balance, the mass flow rate of the cold fluid, $\dot{m}_w$ is calculated as:

$$\dot{m}_g \, C_{p,g} \left(T_g - t_1\right) = \dot{m}_w \, C_{p,w} \left(t_2 - T_w\right) \quad (107)$$

$$\dot{m}_w = 0.02 \frac{kg}{s}$$

The cooling capacity (Rating of the heat exchanger, Q) is therefore,

$$Q = 7.7 \, kW$$

CB200 plate type heat exchanger [Appendix A.5, Figure A.5.8]: qualifies for the required process.

8.7. Wet Scrubber [29]

Particles with diameters larger than 1μm settle by gravity and inertial as discussed on the previous sections. They are obeyed to Stock's law and can be captured by impaction, gravitational or centrifugal means

For particles smaller than 0.1μm, motion is dominated by molecular collusions. They follow Brownian motion principles, behave more like a gas and may be collected by diffusion in to a liquid surface.

Particles with diameters between 0.1 and 1μm fall within the so called 'Open Window'. They are the most difficult particles to capture, either by diffusion or inertial mechanisms. They are too large to diffuse and yet too small to settle. However, they can be made to grow in size, since small particles collide naturally and agglomerate into large particles that are easier to capture. Witted particles tend to stick together better when they collide, there by assisting agglomeration. Wet scrubbers have been used widely, especially in stationary applications for cleaning and cooling gas. Basic scrubber types and performance characteristics are summarized in the table [Appendix A.5, Table A.5.5].

8.7.1. Working Principles of Wet Scrubbers

A scrubber operates by creating conditions for maximum contact between the gas to be cleaned and a scrubbing medium.

Small difficult to capture droplets may be made to grow in size with time until they are large enough to be captured by simply providing adequate residence time in the scrubber volume. Particles grow in size by agglomeration and condensation. Agglomeration is particle growth through particle collusion. Almost all high – concentration clouds tend to have the same particle concentration with in one minute after formation.

Scrubber Equipment

It can be seen from table 11 that Venturi scrubber has a cut diameter (d_{p50}) of about 0.3μm which is good for fine particles and sticky materials.

The Venturi scrubber captures large particles by impaction and impingement and also rinses away droplet that might otherwise form. Some few particles are also captured hereby diffusion. High velocity flow through the low-pressure throat area causes atomizes the droplets. The low pressure at the throat causes condensation and the high relative velocity of droplets with respect to the gas captures larger particles by impaction.

The atomized droplets present a considerable surface area for fine particles to be captured by diffusion. Furthermore, condensation in the throat improves capture through diffusion because of the phenomenon of Stefan Motion. The atomized droplets rapidly agglomerate in the diffuser section, where collection through diffusion continues. Entrained droplets contaminating captured contaminants are separated initially from the cleaned gas. Liquid cycle requires cooling and removal of captured materials, or disposal and replenishment. The collection efficiency and droplet size are determined by pressure drop. Efficiency can be increased by reducing the throat area to raise the pressure drop.

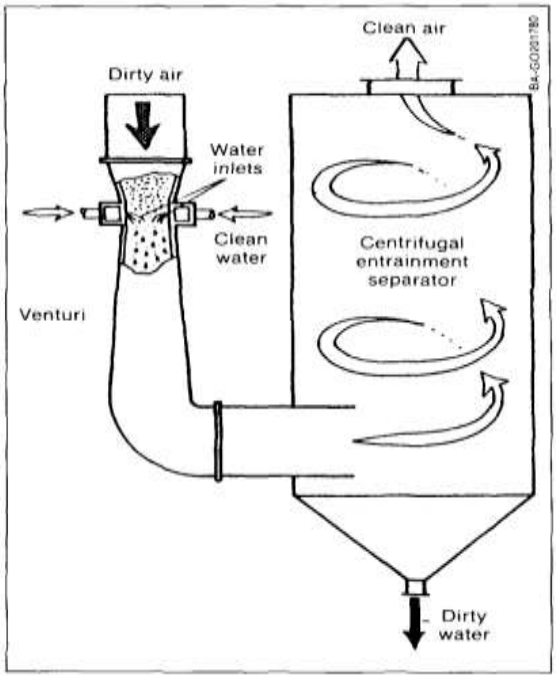

Figure 33: Venturi Scrubber with Centrifugal Entrainment Separator [20]

8.7.2. Design of Venturi Scrubber

The inlet temperature to the scrubber is assumed to be 200^0C (453K) which is the outer temperature from cooler 1. The gas volume flow rate at the inlet is:

$$\frac{\dot{Q}_3}{T_3} = \frac{\dot{Q}_2}{T_2} \tag{108}$$

Where:

$\dot{Q}_3$ = Volume flow rate at scrubber inlet, Nm^3/hr.

T_3 = Temperature at the scrubber inlet = 453K

$\dot{Q}_2$ = Volume flow rate at the engine manifold, 65.14 Nm^3/hr. = 0.0181m^3/s

T_2 = Temperature at the engine manifold = 300K

$$\dot{Q}_1 = \frac{0.0181 \frac{\mathrm{Nm3}}{\mathrm{s}}. \times 453\mathrm{K}}{300\mathrm{K}}$$

= 0.02733 m^3/s

Converting the gas volume flow rate of 0.02733 m^3/s to actual cubic feet per minute (ACFM),

$$\frac{0.02733 \frac{m^3}{s} \times 60}{(0.3048)^3} = 57.91\ ACFM$$

For this design, the inlet volume was 57.9 ACFM. The inlet temperature was estimated to be 200^0C (392 ^{0}F). The moisture content of the gas was assumed to be 0.00592 lb H_2O/lb of dry air [www.slyinc.com; 2009]. Thus for 57.9ACFM at 392 ^{0}F containing 0.00592 lb H_2O/lb of dry air, the chart [Appendix A.5, Figure A.5.10] indicates a correction factor of 0.425.

Inlet volume flow rate × Correction factor = Outlet volume flow rate (109)

$$57.91\ ACFM \times 0.425 = 24.6\ ACFM$$

The scrubber was sized for this saturated outlet volume using the data from the proportions given for the Venturi scrubber. The normal capacity range of 2600/3600 ACFM is closest to the value of 57.9ACFM for it is the smallest available in the catalogue [Appendix A.5, Figure A.5.11].

8.7.3. Dimensions of the Venturi Scrubber

- Normal capacity saturated CFM = 2600/3600
- Inlet and outlet (A) = 13×13
- Separation diameter (B) = 3’’
- Separation (C_1) = 6’’
- Vent (C_2) = 6’’
- Overall height (C_3) = 7’’
- Overall width (D) = 6’’
- Venturi width (E) = 2’’
- Separation cone (F) = 1’’
- Drain pipe (G) = 3’’
- Water pipe (H) = 2’’

- Venturi depth (J) = 1’’

8.8. Baghouse/Fabric Filter [29]

Baghouse filters (shown in figure 32) are used widely today to capture fine dust particles as to separate fly ash from combustion gases. A bag house filter consists of one or more fibrous. A bag house consists of one or more fibrous filter bags supported in metal cages enclosed in a chamber through which gases must pass.

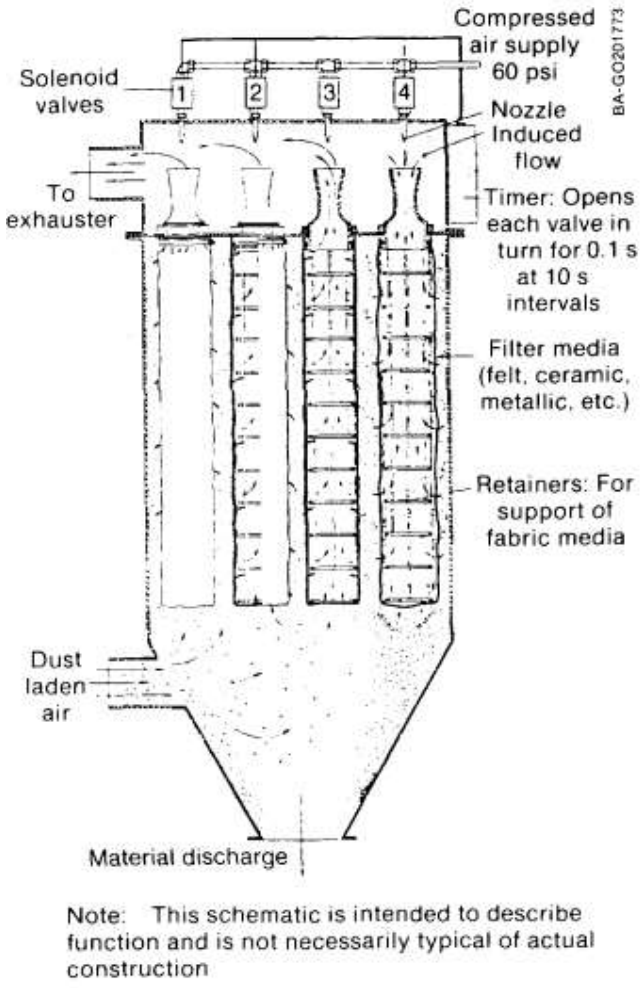

Figure 34: Bag Filter with Intermittent Reverse Pulse Cleaning [29]

8.8.1. Principles of Baghouse Filters

A deposit of separated particles soon builds up on the bag and establishes a dust cake of appropriate pole size through which additional particles cannot pass. As more is accumulated, the pressure drop increases. Fibrous filters have been found to be outstanding in the removal of particles down to submicron sizes. High efficiency capture of small particles is surprisingly independent of the size of openings in the filter weave. The fabric filter is no

doubt the most efficient device for fine cleaning; but for wood gas extensive precautions against condensation of tar or water are necessary.

Note that the cylinder wear is less for product gas with a fabric filter. During operation, the filter cake grows steadily in thickness, collection efficiency climbs and the pressure drop across the filter rises. When the filter cake has reached optimal thickness for removal, the filter cake must be removed.

8.8.2. Considerations in Design/Selection of Bag Filters

Bag filters are suitable only for removing dry particles; sticky or tacky materials do not release from filter bags. Therefore special provisions and precautions are required to maintain the bag filter temperature in order to prevent water vapor or tars from condensing on the filter bag. In particular, since tar – laden start up gases should be drawn through a cold bag filter.

Materials that have been used for bag filters include natural and synthetic organic fibers, glass fiber, ceramic and stainless steel. The properties of these materials are outlined in the table on [Appendix A.5, Table A.5.6]. Organic filters are limited to low temperatures requiring accurately controlled gas cooling.

Gas flow rate in to the baghouse filter is less than 0.05gpm, choosing standard FSPN vessel model with the closest flow rate, [Appendix A.5, Table A.5.6]

8.8.3. Summary of the Filter Vessel

Model number: FSPN – 20
Bag size No.: 1
Surface area per bag: 0.5ft^2
Surface area per vessel: 0.5ft^2
Inlet and outlet size: 1inch
Maximum flow rate: 15GPM

The bag filter data of the above model filter vessel give the physical dimension of the compactable bag [A Appendix A.5, Table A.5.7].

Surface area per bag: 0.05m^2
Volume per bag: 1.4gal/lit
Bag diameter: 10.2cm

Bag length: 20.9cm

8.8.4. Filter Bag

It can be seen that polypropylene has an excellent resistance to the contaminants with relatively fair cost. Off – the – shelf polypropylene filter bag (commercially known as BOS filter bag of item #BOS5PM2P) that has the following specifications is the closest bag that fulfills the physical dimensions demanded by the filter vessel is selected [Appendix A.5, Figure A.5.12].

8.8.5. Summary of the Filter Bag

Code: Polymicro seamless
Material: Polypropylene
Maximum operating temperature = 71^0C
Absolute (98%) micron rating = 3, 5, 10, 25, 35, 50, 75
Size: 17.8cm X 40.65cm
Effective surface area per bag: 0.05m^2
Volume per bag: 1.4gal/lit
Bag diameter: 10.2cm
Bag length: 20.9cm

Features:

- ✓ Seamless construction offers unequalled benefit of eliminating fluid by pass.
- ✓ Microfiber graded pore design provides lower initial pressure drop.
- ✓ Thermally – bonded microfibers contain no sizing, bounding adhesive, resin or silicone.
- ✓ Can be incinerated for easy disposal.

8.9. Gas Drier [29]

The gas emerging from the gas cooler and wet scrubber contains droplets of dirty water entrained in the gas stream. Most engine trouble is caused when these contaminants – borne form deposits on the engine parts. Therefore, they must be removed to finish the job of gas purifications.

8.9.1. Packed Bed Separators

Packed be separators are good for finer droplet removal. For example, figure 35 illustrates that a 6in deep bed packed with ½ inch diameter spheres will capture 50% of 2.5μm diameter droplets. From a superficial gas velocity at 1.5m/s. Deeper beds and finer packing will increase collection performance; however excessive gas velocity may cause re-entrainment deteriorating overall performance. The minimum packing size is limited by the fact that smaller particles more rapidly become plugged by viscous tar deposit. In these cases flow can be restored by stirring or replacing packing.

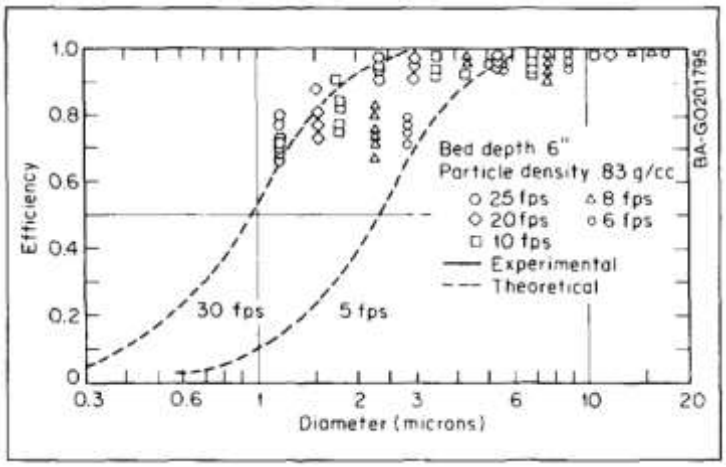

Figure 35: Entrainment Separator Collection Efficiency of Packed Bed for Droplet Removal [29]

8.9.2. Summary of the Gas Drier

The gas drier bed is composed of the following moisture absorbents in equal contents.

- ✓ Sand bed
- ✓ Activated carbon
- ✓ Silica jell

9. EXPERIMENTAL INVESTIGATION OF THE PILOT GASIFIER – ENGINE SETUP

In the preceding sections, design and sixing of downdraft gasifier with gas cleaning and condition system to meet IC engine requirements for its utilization has been performed. Based on the design and selection data, the pilot gasifier-engine setup has been manufactured in AAiT, SMiE-Mechanical Workshop. The manufacturing was done by dividing the tasks in to two phases. Phase one – manufacturing of gas producing unit (gasifier), Phase two – manufacturing and installation of gas cleaning and conditioning unit.

9.1. The Plant

The plant consists of a number of main components which are described as follows:

9.1.1. A Gasifier with Proper Feeding System and Grate

The gas production unit (gasifier) is made with lock hopper for feeding, upper chamber for drying and pyrolysis of the RDF and then on the bottom chamber, oxidation and reduction of the fuel will be carried out. Finally the grate is located on the bottom part. Hand holes for ash removal and gasifier start-up, air inlet nozzle and gas outlet lines are properly constructed. The figure below shows the gas production unit before it is covered with insulation.

Figure 37: The Gas Production Unit (Gasifier)

Figure 36: Gasifier Inner View

9.1.2. Gas Cooling and Cleaning (Conditioning) Unit

Once the gas is produced, cooling and cleaning will be preceded on the designed and installed cleaning system (as illustrated in the previous sections). It consists of cyclone, 2 stage cooling, bag house filter and catalytic gas drying. Some of the equipment's used in this unit are shown in the figure below.

Figure 39: Two Off-the-Shelf Heat Exchangers

Figure 38: The Bag Filter

Figure 41: Bag House Installation

Figure 40: The Gas Conditioning System

Figure 43: Silica Jell, Activated Carbon and Sand for Gas Drying

Figure 42: Bed Gas Drier Housing

Figure 44: Compressor for Air Supply

Finally all the units will be connected to the gas line and air supplying compressor is coupled with gasifier air inlet line to complete the installation of the set up. The final plant is shown in the figure below.

Figure 45: The Plant

9.2. The Feedstock

The feedstock (RDF) for the experiments is prepared from the nearby landfill in the AAiT location based on the mass fractions recommended on the RDF preparation and characterization section. As shown in the previous sections, the process design determines the feed rate to be 39kg RDF/hr and each tests use 19kg RDF/30min. The figure below shows the collected and prepared RDF for the tests.

Figure 46: 19kg of RDF feed for 30min Test Run

9.2.1. Moisture Content

The biomass fractions in the feed stock has to be checked for moisture contents as other constituents in the feed insignificantly affect the test by varying moisture content. As it is claimed by the modeling for best results, the moisture content in the feed must not exceed 6.25% and well drying was achieved to meet this condition. The feed for the test was measured o have an average moisture contents near to the valued demanded.

Figure 48: Moisture Content in the Biomass Fraction

Figure 47: Moisture Content in the Garden Waste

9.3. Experimental Investigation

The experimental investigation will be carried out for the following main objectives:

1. To characterize the producer gas at the gasifier outlet to validate experimental results with the modeling output for the optimal operating conditions determined by the computational technique from the equilibrium model.
2. To characterize the producer gas before and after the cleaning and conditioning system to evaluate the performance of the primary gas cleaning system.
3. To characterize the producer gas at the gasifier outlet after catalytic gasification to evaluate the performance of secondary purification method.

To do the gas sampling for the characterization, the set up was equipped with two sampling points (Sapling point 1 – at Gasifier outlet, Sampling Point 2 – at Engine Inlet).

9.4. Experimental Apparatuses Used

- Infrared Thermometer
- Moisture Meter
- Gas Velocity Meter for flow rate measurement
- KM9104 Gas Analyzer

- Testo 325 Gas Analyzer
- Methane Gas Analyzer

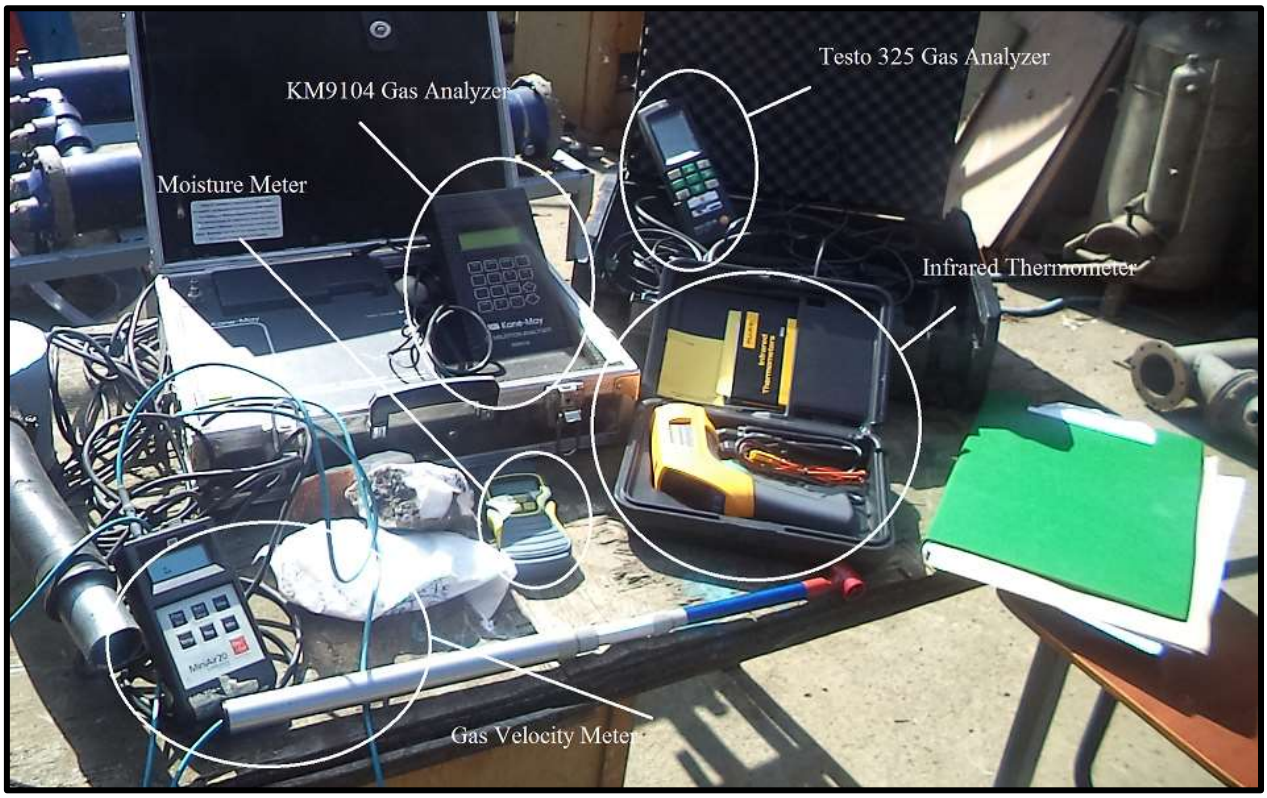

Figure 49: Experimental Apparatuses Used

Figure 50: Well Evacuated Gas Sampling Bags (Kits)

9.5. Experimental Procedures

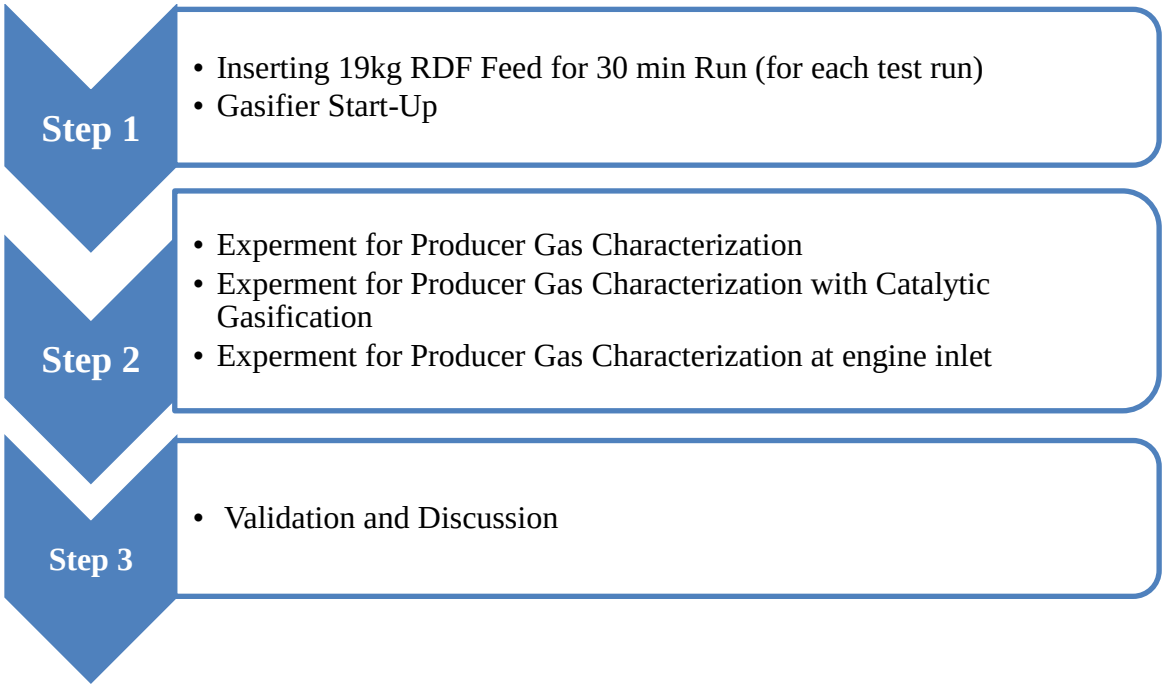

Figure 51: Experimental Procedures

Figure 52: Gasifier Start-Up

Test 1 – Characterization of Producer Gas (without catalytic Gasification) at gasifier outlet (Sampling Point 1) to validate results with computational/simulation results from the equilibrium modeling at optimal operating conditions.

Figure 54: Gas Composition Measurement

Figure 53: Measurement Data Reading

Table 24: Characterization of Producer Gas (without catalytic Gasification) at Gasifier Outlet (Sampling Point 1)

Test 1			
Start Time: 15:35	Operating Conditions	Results from Volumetric Fraction Analysis of Three Samples Taken	
End Time: 16:10	Gasif. Temp = 850 ^{0}C E.R = 0.2 Feed Rate = 19kg RDF/30min	Species in Producer Gas	Average Results in Volume Fractions
		CO	7ppm = 0.35
		CO_2	2ppm = 0.1
		CH_4	0
		O_2	2ppm = 0.1
		Tar	------
		Others	9ppm = 0.45
		Pressure (bar)	0.8
		Remark: CO_2 over estimated.	

Test 2 – Characterization of Producer Gas (without catalytic Gasification) at engine inlet (Sampling Point 2) to evaluate the performance of the primary gas cleaning and conditioning system. Comparison and contraction with result from test 1.

Table 25: Characterization of Producer Gas (without catalytic Gasification) at Engine Inlet (Sampling Point 2)

Test 2			
Start Time: 16:22	Operating Conditions	Results from Volumetric Fraction Analysis of Three Samples Taken	
End Time: 16:48	Gasif. Temp = 850 ^{0}C E.R = 0.2 Feed Rate = 19kg RDF/30min	Species in Producer Gas	Average Results in Volume Fractions
		CO	7ppm = 0.35
		CO_2	1ppm = 0.05
		CH_4	0
		O_2	0
		Tar	------
		Others	12ppm = 0.6

		Remark:

Test 3 – Characterization of Producer Gas (with catalytic Gasification using dolomite) at gasifier outlet (Sampling Point 1) to evaluate the performance of catalytic gas cleaning (secondary method). Comparison and contraction with result from test 1.

Table 26: Characterization of Producer Gas (with Catalytic Gasification using Dolomite) at Gasifier Outlet (Sampling Point 1)

Test 3			
Start Time: 17:12 End Time: 17: 44	Operating Conditions Gasif. Temp = 850 ^{0}C E.R = 0.2 Feed Rate = 19kg RDF/30min	Results from Volumetric Fraction Analysis of Three Samples Taken	
		Species in Producer Gas	Average Results in Volume Fractions
		CO	8ppm = 0.4
		CO_2	1ppm = 0.05
		CH_4	0
		O_2	1ppm = 0.05
		Tar	------
		Others	10ppm = 0.5
		Pressure (bar)	0.8
		Remark: Good result with respect to CO and CO_2	

9.6. Results and Discussion

A sample RDF prepared for the feed as per the proportions recommended on previous sections (shown in figure 46) is gasified in the gasifier to produce producer gas. The gas began to appear after few minutes from start-up. The gas was checked for its inflammability and well result was achieved with this respect.

Figure 56: The Produced Producer Gas - 1

Figure 55: The Produced Producer Gas - 2

The results obtained with the model implementation in this paper have been validated to experimental results from the test runs conducted on the pilot set-up. During the test runs, there were limitations on measuring equipment accesses for H_2, H_2O and tar in AAiT and other labs outside AAiT. Yet experimental and computational results confirm that studying the concentrations of CO, CO_2 and CH_4 is much worthy to investigate the process. During test 1, experimental characterization of the producer gas was done and results were compared with model out at optimal operating conditions for validation, shown on figure 57. Very similar results achieved on CO and CH_4 concentrations in the product gas. Both approaches estimate very small production of CH_4 and relatively higher CO. The very small concentration of methane in the product gas confirms the fact that, no chemical equilibrium can be achieved in reality, especially below 800^0C [51]. The methane formation reaction favors backward reaction and production of carbon and hydrogen gas (H_2) for the gasification temperature is below 900^0C, which is expected to have major share in other gases (collective gases remained in ppm). This makes insignificant amount of methane to be predicted in both cases. Therefore carbon is most dominant in the product gas in the form of CO, CO_2 and CH_4 and this result supports the investigation limited with the measurement of these species and can describe the kinetics enough. The experimental and modeling results show a very good agreement on the contents of CO, CH_4 and other collective gases with unexpected deviation on CO_2 content as shown on figure 57. The CO_2 content which is estimated to have less share in the product gas in both approaches has shown deviation one from the other, experimental result has overestimated the CO_2 content as the following gaps were identified on the experiment to attribute to the deviation.

- It was not easy to control the gasification temperature exactly at 850^0C. The experiments were conducted at various temperature ranges and sampling was taken only at temperatures near to 800^0C. The water gas shift reaction is a reversible reaction more active at temperatures > 800^0C. The reaction is forward reaction in the used temperature ranges and is characterized by increased mole fractions of CO_2.
- The air flow rate was measured well to meet the condition (E.R = 0.2), but to make a continued tastes, two air compressors was used interchangeably with repeated calibrations in the middle of the test each time air lines are changed. There is a possibility for the combustion zone to be air-rich in the meantime to contribute for the increased CO_2 content.

Using the second test, catalytic gas purification was evaluated by comparing the results with results of gasification without catalyst from test 1 as shown in figure 58. Using the above measured species, the tar cracking performance of the catalyst was estimated. The catalytic gasification is observed to yield more CO (very positive), and reduce CO_2 content. This effective reduction process is due to the tar cracking action imposed by the Dolomite catalyst in such a way that the waste gas shift reaction is a bit favored in reverse direction by the catalytic action and carbon in the tar is reduced to CO by same action. Experiment reveals slightly overestimated values for the other gases and the best analysis referred to this is case is increase of contents from broken compounds like NO_X for which the catalyst is sensitive too (as discussed in the previous sections). Results from the third test were used to evaluate the performance of the gas cleaning system to compare gas characterization after the cleaning with results obtained at gasifier outlet before the cleaning as shown in figure 59. The experiment gives well agreed results for CO, CO_2 and CH_4 contents before and after the cleaning process. This can be clearly seen that these species are more of sensitive to the methane formation and water gas shift reduction process in the bed of the gasifier than other thermal and filtration situations outside the gasifier to be unaffected. The oxygen content in both samples (before and after) is quiet low and yet much underestimated result was obtained from the sample after the clean-up. This might be attributed to favored oxidation of SO_X and other compounds at lower temperature after cooling stages which on the other hand, increases the parts of other gases in millions at the expense of used up oxygen gas.

The product gas flow rate at the engine inlet was so small due to unexpected pressure loss through the cleaning and cooling system beyond the values determined from theoretical calculations.. Gas characterization results reveal a quiet promising outcome from producer gas generator provided that there is a gas suction fan/compressor before the engine inlet to overcome the gas pressure drop as it passes through the cleaning and cooling equipment. This will be performed on the future work with other basic improvements. The model used an assumption of 1bar pressure and the pressure gauge at the outlet of the gasifier gave a reading close to 0.7-0.8bar, which makes the assumption valid as the amount of pressure drop observed supports the fact that downdraft gasifiers have relatively higher pressure drop.

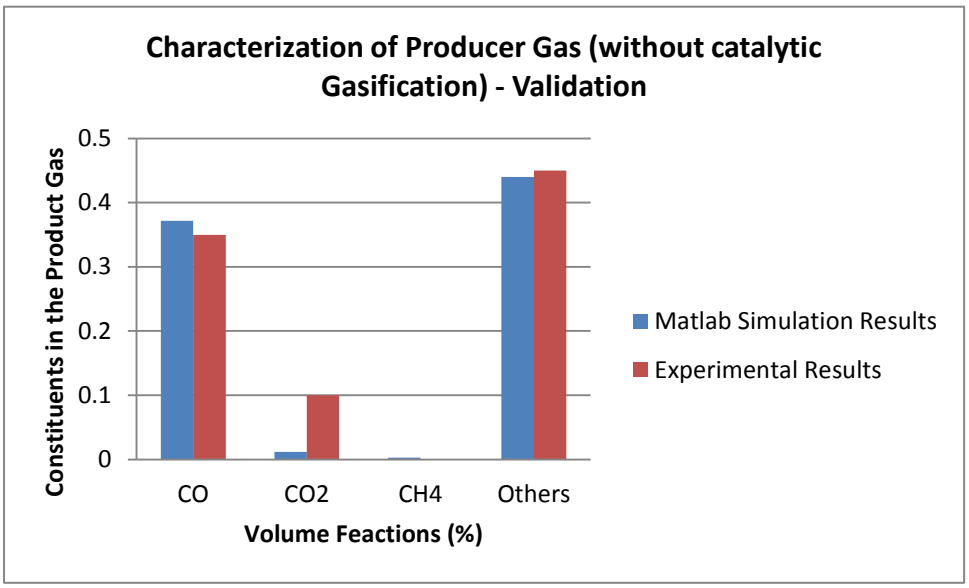

Figure 57: Characterization of Producer Gas (without catalytic Gasification) - Validation

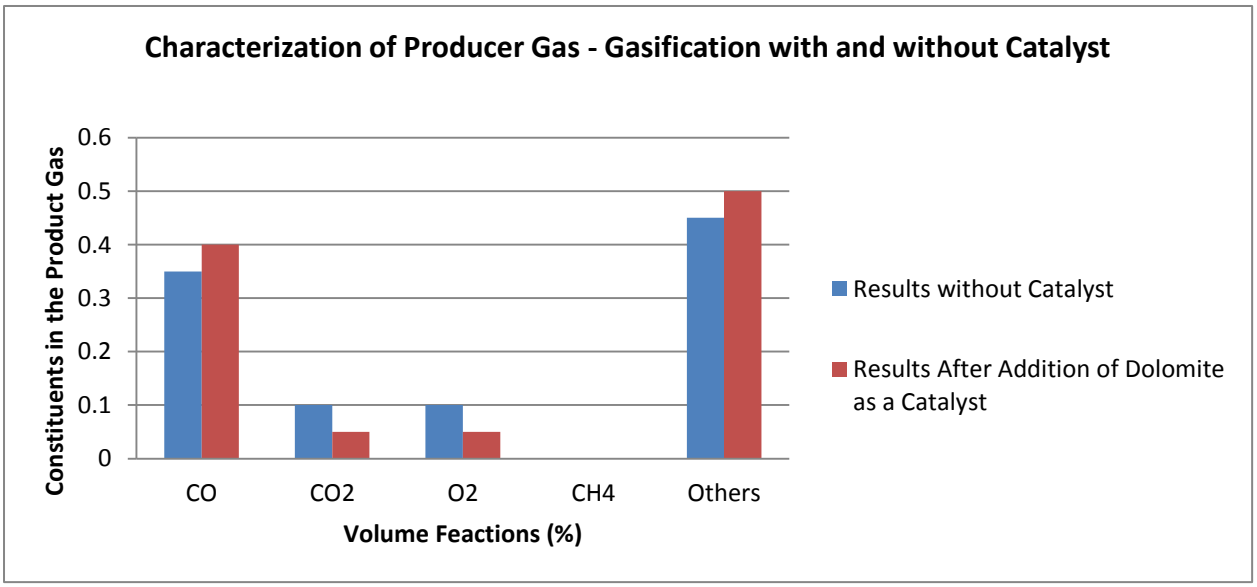

Figure 58: Characterization of Producer Gas - Gasification with and without Catalyst

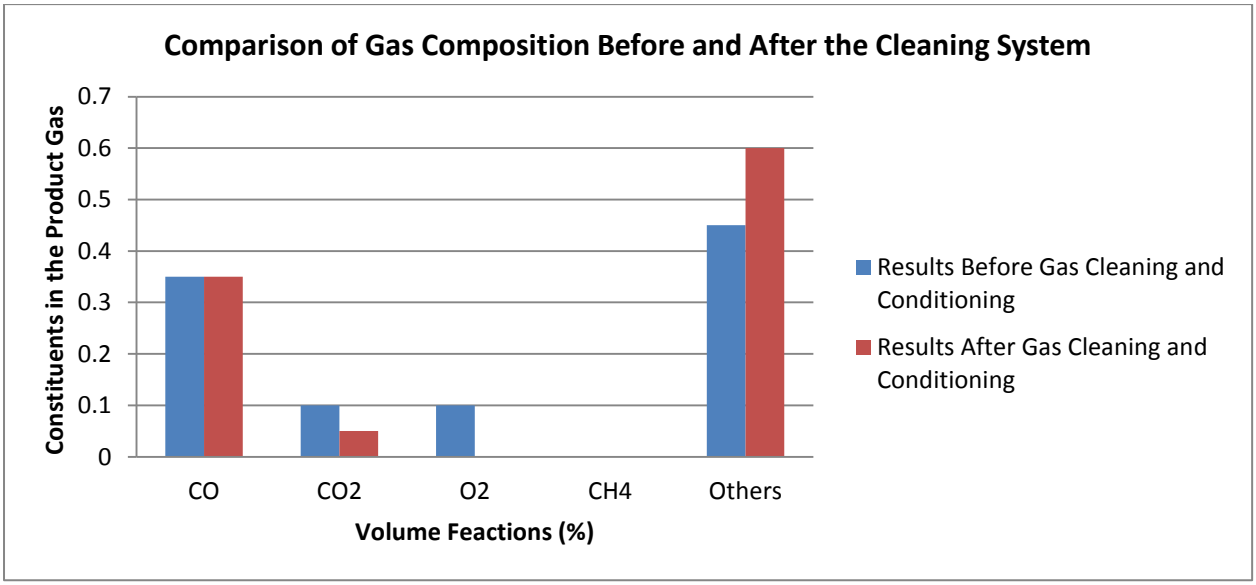

Figure 59: Comparison of Gas Composition before and after the Cleaning System

9.7. Conclusion

A good agreement between modeling and simulation results was achieved for gas characterization at the gasifier outlet. Catalytic gasification and the gas cleaning system give promising results for future advanced investigations on the use of Dolomite and the secondary gas cleaning. Even though test 2 and test 3 require more investigation with laboratory equipment that measure all possible product gases and tar, the results obtained so far give a satisfactory motive to do more improvements and conduct advanced tests. Both experimental and simulation results make electricity generation using a specific producer gas engine generator set based on the proven characterization of the gas (heating value and inflammability), provided that gas suction fun or blower or gas compressor is installed before it to meet the engine pressure requirements.

10.CONCLUSION AND RECOMMENDATIONS

10.1. Conclusion

Ethiopia is an east African country with a very limited electrical power supply to the vast majority of the rural areas from the main grid and there is hardly any off-grid power supply in the areas. Due to the daily backward and intensive life, the rural areas in the country to be retarded in there infrastructure and economic development and this calls for sound strategies to be implemented with respect to renewable and small scale electricity generations. As the country is also well known for high daily waster production rate with poor waste management, this study tried to address the problems all in one by taking measures to be implemented in terms of energy integrated waste management. This approach is designed for the use of solid, dry and combustible waste fractions in the municipal waste for electrification.

Even though gasification is an old technology, this and other published studies confirm the fact that gasification in downdraft gasifiers has been found to be a mature technology for small scale power generation application in ICEs.

A sample wastes collected from landfills in Addis Ababa were prepared to RDF based on the preparation guidelines provided by EU Directive 2000/76/EC and ultimate and proximate analysis results of the best sample RDF ensures it to be a typical well accepted RDF as it has LHV of 16.63MJ/kg. Various literatures range LHV of a good RDF to lie in 15 - 18MJ/kg according to the selection process and amount of high LHV constituents present.

The study used computational (simulation) and experimental approaches. A mathematical model to predict product gas compositions at various temperatures and E.Rs was developed based on non-stoichiometric thermodynamic equilibrium model. In the mathematical model, the gasifier is split in to three zones, namely the drying – pyrolysis, the oxidation and the reduction zones. There are corresponding mathematical sub – models which describe relevant chemical reactions and energy and mass balances in each zone. Implementation of the formulated model on MATLAB determines critical gasifier operating conditions and characterization of the producer gas at best operating parameters for best operation. The model predication appeared to be well accepted for applications on ICEs based on validations with published data. Validations of the theoretical gasification with and experimental results show a good agreement. Based on the two approaches used, it was possible to operate the

gasifier with feed rate of 38kg RDF/hr (which raises cold gas efficiency efficiency to 85%) with 6.2% moisture content gasified at E.R = 0.2 and gasification temperature of 850^0C, at nearly 85% cold gas efficiency to best output to produce a produce gas with LHV of 8MJ/kg to be utilized further in ICEs after clean up and conditioning.

In gasification, the most important objective is to produce a cleaner (low tar) gas with high heating value. To achieve the production of gas with relatively high heating value, it is important to convert carbon dioxide and water to as much carbon monoxide, hydrogen and methane as possible, as these constituents contribute relatively high heating values for the gas. Therefore it can be seen that it is desirable to give emphasis and encourage the two main reduction reactions (the Boudouard and Water Gas reaction).

Identification of gas contaminants and the respective cleanings along with conditioning techniques for applications in ICEs has given a good input to the design and conditioning of the gas cooling and condition system. According to the design, the cleaning system used thermal distraction and catalytic gasification to remove tar and filtering methods to avoid particulates from the gas. Cooling was also used for gas cleaning to make some hazardous compound inactive and to condition the gas temperature for ICEs.

Catalytic gasification and the gas cleaning system give promising results for future advanced investigations on the use of Dolomite and the secondary gas cleaning. Even though gas cleaning performance experimental tests require more investigation with laboratory equipment that measure all possible product gases and tar, the results obtained so far give a satisfactory motive to do more improvements and conduct advanced tests. Both experimental and simulation results make electricity generation using a specific producer gas engine generator set based on the proven characterization of the gas (heating value and inflammability), provided that gas suction fun or blower or gas compressor is installed before it to overcome the unexpected high pressure drop observed as the gas pass through the gas cleanup system to meet the engine pressure requirements.

In general, employing the principles of gasification of RDF for power generation in Ethiopia is found to be a fascinating solution to provide energy deficit rural areas with off-grid power from a simple and portable mini gasifier – engine set with a relatively higher output per unit area of the plant.

10.2. Recommendations

The results of this research from simulation and experimental approaches provide a satisfactory motive to deal with the work at more advanced levels. The following recommendations are devised to make developments for extending the work to next levels.

10.2.1. Catalytic Gasification

Catalytic gasification appeared to be a promising method to encourage gas reduction reactions at good tar cracking at the bed of the gasifier. Usage of dolomite as a catalyst has to be investigated more with the necessary, accurate and up to date gas analyzing equipment that can measure tar composition as well.

10.2.2. Environmental and Economic Evaluation of the Plant

All possible negative impacts of the plant on the environment have to be addressed and mitigation/solutions have to be implemented, if problems appear to be in the prohibited ranges. The plant must also be evaluated economically and should be proved cost wise for use in this particular application.

10.2.3. RDF Processing and Production Facility

The study revealed the importance of solid waste in the energy sector. A separate facility the processes waste and produces RDF for feed stock in the proportions recommended by this study or based on any other improvements in the energy content of the RDF must be accessible as this is what is meant by a sound measure to wards energy integrated waste management.

10.2.4. Laboratory Access and Set – Up Apparatuses

Producer gas (syngas) analyzer that can measure all contents in the gas including tar concentration like Gravimetric Gas Chromatography is strongly recommended for extended experimental works for gas characterizations and investigations on the clean-up. The experimental set - up is recommended to be equipped with a good control system that gives way to manage the intended air and gas flow rates, gasifier temperatures and other sensitive parameters by measuring and displaying values at different points of interest for effective and controlled experiment from what a more clear and valid results can be drawn. Availability of wet venturi scrubber in the gas cleaning line is a lot to mean for the clean – up level required and this device should be at hand for the upcoming investigations with a producer gas engine

– generator set with consumes the cleaned and conditioned gas directly without custom modifications on it for direct application for electricity generation provided that a gas suction device/gas compressor overcomes the gas pressure drop along its way to engine to meet the minimum requirements claimed by the ICE cylinders displaced volumes for effective combustion.

10.3. Future Works

So far, it has been observed that this paper produced results that invite to work more on advanced level for practical importance. Based on the recommendations devised and by making technical improvements on the set – up and filling gaps from deficiency of necessary lab access and equipment, a well-designed experimental set – up will be made. This research is enjoying a thematic research grant from AAU – Vice President for Research and Technology which will enable fulfilling of material accesses like proper gas analyzer, scrubber equipment and producer gas generator from the fund to be released for 2017/18 academic year. Design and installation of digital control system that worth 82,000ETB is almost finished with an automation company outside the university, to be used for further work. Environmental and economic analysis will be conducted in the meantime. Based on this ground, generation and quantification of electricity production will be performed based on the set – up with further efficiency improvement strategies implemented. So far, one scientific output titled '*Equilibrium Modeling of Refuse Derived Fuels (RDF) Gasification in Imbert Type Downdraft Gasifier*' accepted, from this study after a review by an open access journal for publication. More scientific outcomes are expected from further experimental investigations and performance analyses.

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APPENDIX

A.1 - RDF Characterization Data

Ultimate Analysis Result of the RDF, e-mailed from Dr. Yonas (AAU, Department of Chemistry) as emailing is the only way they give test reports.

Date: Thursday, June 03, 2017
Number of Samples: 2
Analysis: Elemental analysis: CHNS
Device: EA 1112 Flash CHNS/O- analyzer
Conditions: Carrier gas flow rate of 120 ml/min, reference flow rate 100 ml/min, oxygen flow rate 250 ml/min; furnace temperature of 900 C and oven temperature of 75 °C.
Calibration: 4 calibration points for every component. Samples were run **in duplicate** and the average values are to be taken.

Note: all three samples are not homogenous.

Sample Code	N(%)	C(%)	H(%)	S(%)
RDFS1a	1.197624	44.02082	6.360334	0
RDFS1b	0.87342	41.64986	5.907319	0
RDFS2a	0.441625	41.14566	5.92037	0
RDFS2b	0.379078	42.96608	6.130091	0
RDFS3a	0.274145	41.1352	5.984506	0
RDFS3b	0.256009	39.42715	5.4862	0

Proximate Analysis Result of the RDF from Geological Survey of Ethiop

Geological Survey of Ethiopia
Geochemical Laboratory Directorate
Hydrocarbon Laboratory analysis report format:Form GD0006
File ID 1267/17pvt
Originator:Dawit Musse.
Sample type:Municipal Waste
Number of Samples:3
Preparation required :60mesh
Element to be determined: (Moistur,Volatile matter, Fixed carbon and Ash) and Calorie .
Method of analysis:Proximate Analysis and Adiabatic Calorie Meter .

customer type:pvt
Date submitted 24/09/2009(06/02/2017)
Date completed 07/10/2009(06/14/2017)

Field No.	Lab No.	Moisture %	Volatile Matter %	Fixedcarbon %	Ash %	Calorific Value cal/gm
A.D.F.S-1	1267/17	6.10	72.42	11.84	9.64	4035.91
A.D.F.-2	1268/17	6.72	74.32	11.74	7.22	3996.72
A.D.F.S-3	1269/17	6.59	73.17	10.79	9.45	3927.68
A.D.F.S-3	1269/17Dup	6.84	72.56	11.06	9.54	3938.43

ANALYSTS:
Alemnesh
Haimanot Bayeh
Yoseph Mekonnen

CHECKED BY:
Alemnesh Abate

QUALITY CONTROL:
Awash Yerga

DATE REPORTED
08/10/2009(06/15/2017)

Page 1 of 1

A.2 - Matlab Code for Determination of Product Gas Composition

```
%THIS PROGRAM IS WRITTEN BY DAWIT MUSSE TO DETERMINE PRODUCER
GAS COMPOSITION IN
%DRY PRODUCER GAS BASIS FOR GASIFICATION OF RDF IN IMBERT
DOWNDRAFT GASIFIER.
function[final_comp]=eq_model_const(g_temp,ele_comp,m)
ele_comp=input('Please Enter Elemental Composition of RDF Sample = ')
%disp('elemental composition should be of the form [C, H, O, N, Ash]');
g_temp=input('Please Enter the Gasification Temperature Tg = ');
m=input('Please Enter the Equivalence Ratio = ');
format short
tol=0.00001;
maxit=100;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%disp('Initial guess is of the form [H2 CO CO2 H2O CH4] ')
xx0=[0.1,0.1,0.1,0.1,0.1]';
% Heat of formation of different compounds at 25 C, kJ/kmol
H_f_H2O_g=-241818;H_f_H2O_l=-285830;H_f_CO2=-393509;H_f_CO=-110525;
H_f_CH4=-74520;H_f_H2=0;H_f_O2=0;H_f_N2=0;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Function for finding sensible heat for various gases
%constants
C_p_H2O=[32.24 0.1923e-2 1.055e-5 -3.595e-9];
C_p_H2=[29.11 -0.1916e-2 0.4003e-5 -0.8704e-9];
C_p_CO=[28.16 0.1675e-2 0.5372e-5 -2.222e-9];
C_p_CO2=[22.26 5.981e-2 -3.501e-5 -7.469e-9];
C_p_CH4=[19.89 5.204e-2 1.269e-5 -11.01e-9];
C_p_N2=[28.90 -0.1571e-2 0.8081e-5 -2.873e-9];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding general equations for calculating k1 and k2
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
G_CO=[3.376 0.557e-3 0 -0.031e5 -110525 -137169];
G_CO2=[5.457 1.045e-3 0 -1.157e5 -393509 -394359];
G_H2O=[3.470 1.450e-3 0 0.121e5 -241818 -228572];
G_H2=[3.249 0.422e-3 0 0.083e5 0 0];
G_C=[1.771 0.771e-3 0 -0.867e5 0 0];
G_CH4=[1.702 9.081e-3 -2.164e-6 0 -74520 -50460];
delta_ws_final=[];
delta_meth_final=[];
for iii=1:6
delta_ws=G_H2(iii)+G_CO2(iii)-G_CO(iii)-G_H2O(iii);
delta_meth=G_CH4(iii)-G_C(iii)-2*G_H2(iii);
delta_ws_final=[delta_ws_final delta_ws];
delta_meth_final=[delta_meth_final delta_meth];
```

```
end
T_0=298.15;
%%%%%%%%%%%%%%%%%%%%%%%Continued
below%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
k1=exp(-((delta_meth_final(6)-
delta_meth_final(5))/(8.314*298.15)+(delta_meth_final(5)/(8.314*g_temp))...
+(int_eq_sp2(delta_meth_final,g_temp)/g_temp)-int_eq_sp1(delta_meth_final,g_temp)));
k2=exp(-((delta_ws_final(6)-
delta_ws_final(5))/(8.314*298.15)+(delta_ws_final(5)/(8.314*g_temp))...
+(int_eq_sp2(delta_ws_final,g_temp)/g_temp)-int_eq_sp1(delta_ws_final,g_temp)));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%function for calculating int_eq_sp
function int_for_gibbs_difff1= int_eq_sp1(difff,g_temp)
tau=g_temp/298.15;
int_for_gibbs_difff1=difff(1).*log(tau)+((difff(2).*T_0+...
((difff(3)*T_0^2+(difff(4)/(tau^2.*T_0^2)))*((tau+1)/2)))*(tau-1));
end
function int_for_gibbs_difff2= int_eq_sp2(var_sp,g_temp)
tau=g_temp/298.15;
int_for_gibbs_difff2=var_sp(1).*T_0*(tau-1)+...
var_sp(2)*0.5*T_0^2*(tau^2-1)+var_sp(3)*T_0^3*(tau^3-1)/3+...
var_sp(4)*(tau-1)/(tau*T_0);
end
%k1=9.72e-02;k2=1.4561;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%finding lambda and gamma for below
calculation%%%%%%%%%%%%%%%%%%%%%%%%
norm_1_C=ele_comp(1)/(12);
norm_1_H=ele_comp(2)/(1.008);
norm_1_O=ele_comp(3)/(16);
norm_1_N=ele_comp(4)/(14.007);
lambda=norm_1_H/norm_1_C;
gamma=norm_1_O/norm_1_C;
beta=norm_1_N/norm_1_C;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x0=xx0;
iter=1;
iter_m=1;
sol_final=[];
w=0;
Moisture_Content=[];
for N=1:length(w)
Moisture_Content=[Moisture_Content 18*100*w(N)/(24+18*w(N))];
```

```
end
Moisture_Content;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Main Loop for solving important equations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for iter_m=1:length(w)
while(iter<=maxit)
y=-df1(x0)\f1(x0);
xn=x0+y;
err=max(abs(xn-x0));
if(err<=tol)
x=xn;
else
%%%%%%%%%%%%%%%%%%%%%%%%%Continued
below%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x0=xn;
end
iter=iter+1;
end
iter=1;
sol_temp=x;
sol_final=[sol_final sol_temp];
iter_m=iter_m+1;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Multiplying m with 3.76 to get correct N2 mols
p=length(w);
frac_N2=[];
for l=1:p
frac_N2=[frac_N2 m*3.76];
end
final_comp=[sol_final(1:5,1:p);frac_N2];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
fin_rep=input('Do you want to find producer gas composition in dry basis(y): ','s');
fin_rep='n';
if fin_rep=='n';
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding total amount of product gas
total_frac_m=[];
for n=1:p
total_frac_m=[total_frac_m sum(final_comp(1:6,n))];
end
total_frac_m; %sum of all product gases
```

```
else
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%finding total amount of product gas on dry basis
%content
dry_final_comp=final_comp;
dry_final_comp(4,:)=[];
total_frac_m=[];
for n=1:p
total_frac_m=[total_frac_m sum(dry_final_comp(1:5,n))];
end
total_frac_m;
final_comp=dry_final_comp;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%expressing all the components in molar fraction or volumetric fraction
final_frac_comp=[];
for MM=1:length(total_frac_m)
final_frac_m=[];
if fin_rep=='y'
l_in=length(xx0);
else
l_in=length(xx0)+1;
end
%%%%%%%%%%%%%%%%%%%%%%Continued
below%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
for NN=1:l_in
final_frac_m=[final_frac_m;final_comp(NN,MM)/total_frac_m(MM)];
end
final_frac_comp=[final_frac_comp final_frac_m];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function f=f1(X)
x_1=X(1); x_2=X(2); x_3=X(3);x_4=X(4);x_5=X(5);
val_1=x_2+x_3+x_5-1;
val_2=x_1+x_4+2*x_5-w(iter_m)-(lambda/2);
val_3=x_2+2*x_3+x_4-2*m-gamma-w(iter_m);
val_4=-k1*x_1^2+(x_5*(x_1+x_2+x_3+x_4+x_5+3.76*m));
val_5=x_2*x_4*k2-x_1*x_3;
f=[val_1; val_2;val_3;val_4;val_5];
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function df=df1(X)
x_1=X(1); x_2=X(2); x_3=X(3);x_4=X(4);x_5=X(5);
```

```
df=[0,1,1,0,1;1 0 0 1 2; 0 1 2 1 0;-
2*x_1*k1+x_5,x_5,x_5,x_5,2*x_5+(x_1+x_2+x_3+x_4+3.76*m); -x_3 k2*x_4...
-x_1 k2*x_2 0];
end
end
```

A.3 - Matlab Output: Gas Composition and Heating Values for Wide Range of Temperatures and Equivalent Ratios

Molar Composition at E.R = 0.2														
Gasification temperature, K	573.15	673.15	773.15	873.15	973.15	1023.15	1073.15	1123.15	1173.15	1223.15	1273.15	1323.15	1423.15	1523.15
H_2	0.0592	0.2019	0.4436	0.659	0.7638	0.7872	0.8006	0.8081	0.8122	0.8143	0.8153	0.8156	0.8152	0.8144
CO	0.165	0.3343	0.6015	0.8176	0.9164	0.939	0.9545	0.9617	0.9676	0.9718	0.9749	0.9773	0.9807	0.9831
CO_2	0.441	0.3498	0.2098	0.1016	0.0536	0.0426	0.0355	0.0308	0.0274	0.0248	0.0227	0.021	0.0183	0.0163
H_2O	0.0039	0.0171	0.0298	0.0302	0.0273	0.0268	0.0271	0.0277	0.0286	0.0297	0.0307	0.0318	0.0337	0.0353
CH_4	0.3939	0.3159	0.1887	0.0808	0.0299	0.0184	0.0116	0.0075	0.005	0.0035	0.0024	0.0018	0.001	0.0006
N_2	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.752
Molar Fractions at E.R = 0.2														
H_2	0.0326	0.1024	0.1993	0.2699	0.3003	0.3068	0.3102	0.3123	0.3132	0.3136	0.3138	0.3137	0.3134	0.3130
CO	0.0909	0.1696	0.2703	0.3349	0.3603	0.3659	0.3698	0.3716	0.3732	0.3743	0.3752	0.3759	0.3771	0.3778
CO_2	0.2429	0.1775	0.0943	0.0416	0.0211	0.0166	0.0137	0.0119	0.0106	0.0095	0.0087	0.0080	0.0070	0.0062
H_2O	0.00215	0.0087	0.0134	0.0124	0.0107	0.0104	0.0105	0.0107	0.0110	0.0114	0.0118	0.0122	0.0129	0.0136
CH_4	0.2170	0.1603	0.0868	0.0331	0.0118	0.0072	0.0045	0.0029	0.0019	0.0013	0.00092	0.00069	0.00038	0.00023
N_2	0.4143	0.3815	0.3379	0.3080	0.2957	0.2930	0.2913	0.2906	0.29	0.2897	0.2894	0.2893	0.2891	0.2890
LHV_g (MJ/m^3)	9.285	8.997	8.677	8.327	8.211	8.187	8.176	8.164	8.158	8.155	8.154	8.154	8.154	8.154
Molar Composition E.R = 0.25														
H_2	0.062	0.2092	0.4502	0.6512	0.7361	0.7543	0.7615	0.7639	0.7637	0.7621	0.7599			
CO	0.0801	0.2628	0.5394	0.7573	0.858	0.8828	0.8993	0.9109	0.9197	0.9265	0.9321			
CO_2	0.5304	0.4302	0.283	0.1699	0.1161	0.1015	0.0909	0.0828	0.0762	0.0706	0.0659			
H_2O	0.01	0.0278	0.0455	0.0539	0.0609	0.0652	0.0698	0.0744	0.0789	0.0832	0.0871			
CH_4	0.3895	0.307	0.1776	0.0729	0.026	0.0157	0.0098	0.0063	0.0041	0.0028	0.002			
N_2	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94			
Molar Fractions at E.R = 0.25														

H_2	0.0308	0.0961	0.1848	0.2462	0.2689	0.2733	0.2748	0.2749	0.2744	0.2736	0.2726			
CO	0.0398	0.1207	0.2215	0.2863	0.3135	0.3199	0.3245	0.3278	0.3305	0.3326	0.3344			
CO_2	0.2636	0.1976	0.1162	0.0642	0.0424	0.0368	0.0328	0.0298	0.0274	0.0253	0.0236			
H_2O	0.0050	0.0127	0.0187	0.0204	0.0222	0.0236	0.0252	0.0268	0.0283	0.0299	0.0312			
CH_4	0.1936	0.1410	0.0729	0.0275	0.0095	0.0056	0.0035	0.0022	0.0015	0.0010	0.00072			
N_2	0.4672	0.4318	0.3859	0.3554	0.3434	0.3406	0.3392	0.3383	0.3378	0.3375	0.3373			
LHV_g (MJ/m^3)	7.781	7.619	7.405	7.257	7.199	7.187	7.186	7.182	7.186	7.168	7.186			
Molar Composition E.R = 0.3														
H_2	0.0641	0.2151	0.4541	0.6401	0.71	0.7196	0.7214	0.7193	0.7153	0.7105	0.7055			
CO	0.0282	0.2007	0.4808	0.6983	0.8002	0.8268	0.8456	0.8598	0.871	0.8802	0.888			
CO_2	0.5949	0.5033	0.353	0.2363	0.1774	0.1598	0.1462	0.135	0.1256	0.1175	0.1104			
H_2O	0.033	0.0437	0.0643	0.08	0.096	0.1046	0.113	0.1211	0.1287	0.1358	0.1422			
CH_4	0.3769	0.296	0.1663	0.0654	0.024	0.0134	0.0082	0.0052	0.0034	0.0023	0.0016			
N_2	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128	1.128			
Molar Fractions at E.R = 0.3														
H_2	0.0288	0.0901	0.1716	0.2274	0.2418	0.2437	0.2435	0.2423	0.2407	0.2389	0.2371			
CO	0.0127	0.0841	0.1817	0.2452	0.2756	0.2800	0.2854	0.2896	0.2930	0.2959	0.2984			
CO_2	0.2673	0.2108	0.1334	0.0829	0.0604	0.0541	0.0493	0.0455	0.0422	0.0395	0.0371			
H_2O	0.0148	0.0183	0.0243	0.0281	0.0327	0.0354	0.0381	0.0408	0.0433	0.0456	0.0478			
CH_4	0.1694	0.1240	0.0628	0.0229	0.0082	0.0045	0.0027	0.0018	0.0011	0.00077	0.00504			
N_2	0.5069	0.4726	0.4262	0.3960	0.3842	0.3829	0.3807	0.3800	0.3795	0.3792	0.3790			
LHV_g (MJ/m^3)	6.549	6.482	6.398	6.340	6.381	6.325	6.326	6.334	6.335	6.340	6.344			
Molar Composition E.R = 0.35														
H_2	0.0654	0.2194	0.4551	0.6257	0.6798	0.6834	0.6805	0.6745	0.6673	0.6597	0.6523			
CO	0.0134	0.151	0.426	0.6408	0.7431	0.7712	0.792	0.8082	0.8215	0.8328	0.8425			
CO_2	0.6313	0.5666	0.4193	0.3008	0.2377	0.2174	0.2012	0.1875	0.1757	0.1654	0.1562			
H_2O	0.075	0.0667	0.0864	0.1085	0.1326	0.1449	0.1567	0.1678	0.1781	0.1875	0.196			
CH_4	0.3553	0.2824	0.1547	0.0583	0.0193	0.0113	0.0069	0.0043	0.0028	0.0019	0.0013			
N_2	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316	1.316			

Molar Fractions at E.R = 0.35														
H_2	0.0266	0.0843	0.1592	0.2051	0.2173	0.2173	0.2158	0.2135	0.2113	0.2085	0.2061			
CO	0.0054	0.0580	0.1491	0.2101	0.2375	0.2453	0.2511	0.2559	0.2598	0.2632	0.2662			
CO_2	0.2570	0.2177	0.1467	0.0986	0.0759	0.0691	0.0638	0.0593	0.0556	0.0523	0.0494			
H_2O	0.0305	0.0256	0.0302	0.0356	0.0424	0.0461	0.0497	0.0531	0.0563	0.0593	0.0619			
CH_4	0.1446	0.1085	0.0541	0.0191	0.0062	0.0036	0.0022	0.00014	0.00088	0.00060	0.00042			
N_2	0.5357	0.5057	0.4605	0.4315	0.4206	0.4185	0.4173	0.4167	0.4163	0.4160	0.4158			
LHV_g (MJ/m^3)	5.543	5.534	5.540	5.550	5.564	5.469	5.576	5.538	5.59	5.593	5.599			

A.4 - Gasifier Sizing Charts and Gasifier Drawings

Figure A.4.1: Height of Nozzle Plane above Throat foe Various Throat Diameters [FAO]

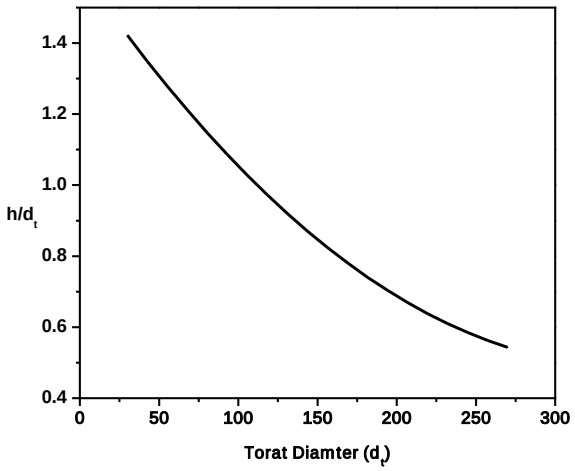


Figure A.4.2: Nozzle Area for Various Sizes of Gasifier Throat

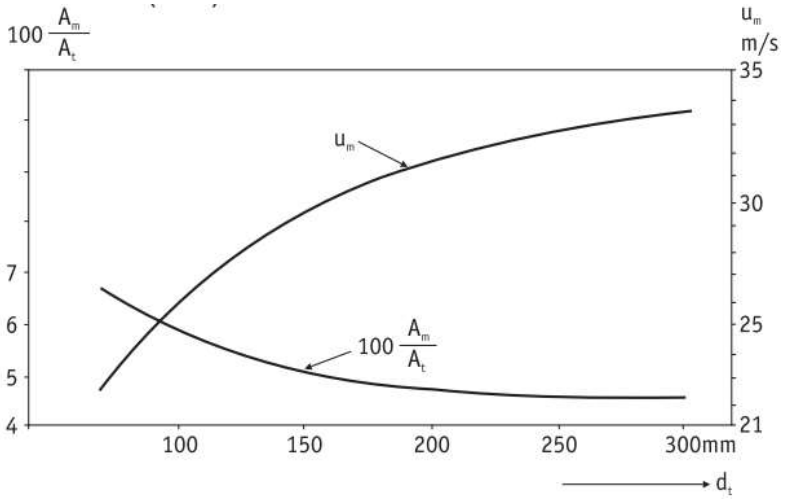


Figure A.4.3: Top Nozzle Rig Diameter as a Function of Throat Diameter

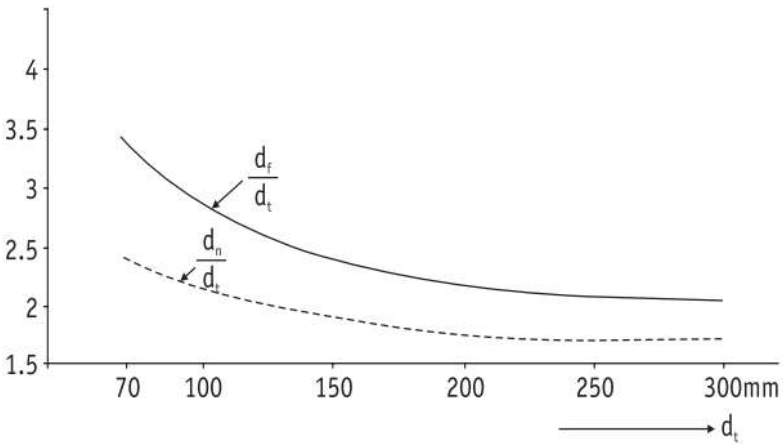


Figure A.4.4: Reduction Zone as a Function of Throat Diameter

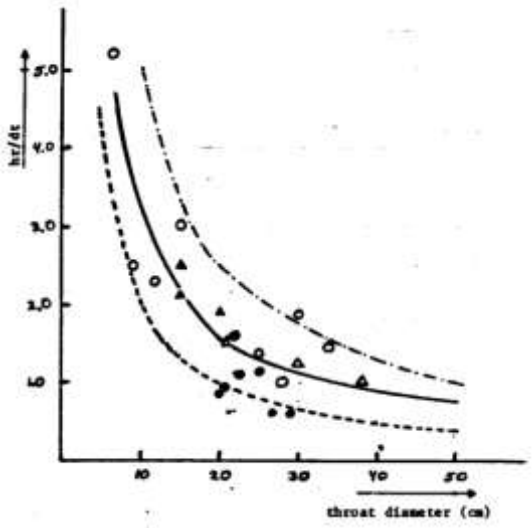


Table A.4.1: Gasifier Sizing Data for a Ranger of Gas Output

d_r/d_h	d_h mm	d_r mm	$d_{r'}$ mm	h mm	H mm	R mm	A No.	d_m mm	$\frac{A_m \times 100}{A_h}$	$\frac{d_r}{d_h}$	$\frac{h}{d_h}$	Range of Gas Output max. Nm^3/h	Range of Gas Output min. Nm^3/h	Maximum Wood Consumption kg/h	Air Blast Velocity Vm m/s
268/60	60	268	150	80	256	100	5	7.5	7.8	4.5	1.33	30	4	14	22.4
268/80	80	268	176	95	256	100	5	9.0	6.4	3.3	1.19	44	5	21	23.0
268/100	100	268	202	100	256	100	5	10.5	5.5	2.7	1.00	63	8	30	24.2
268/120	120	268	216	110	256	100	5	12.0	5.0	2.2	0.92	90	12	42	26.0
300/100	100	300	208	100	275	115	5	10.5	5.5	3.0	1.00	77	10	36	29.4
300/115	115	300	228	105	275	115	5	11.5	5.0	2.6	0.92	95	12	45	30.3
300/130	130	300	248	110	275	115	5	12.5	4.6	2.3	0.85	115	15	55	31.5
300/150	150	300	258	120	275	115	5	14.0	4.4	2.0	0.80	140	18	67	30.0
400/130	130	400	258	110	370	155	7	10.5	4.6	3.1	0.85	120	17	57	32.6
400/150	135	400	258	120	370	155	7	12.0	4.5	2.7	0.80	150	21	71	32.6
400/175	175	400	308	130	370	155	7	13.5	4.2	2.3	0.74	190	26	90	31.4
400/200	200	400	318	145	370	153	7	16.0	3.9	2.0	0.73	230	33	110	31.2

Variables not given in figure are defined as follows:
d_m = inner diameter of the tuyere.
A_m = sum of cross sectional areas of the air jet openings in the tuyeres.
A_h = cross sectional area of the throat.
A = number of tuyeres.
Source: Kaupp 1984a, Table 5; Fig. 75.

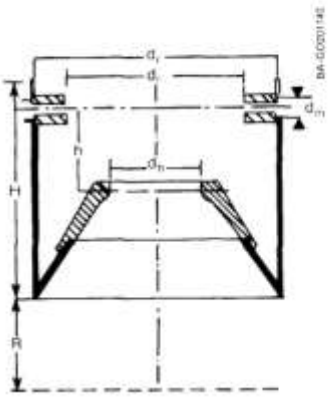
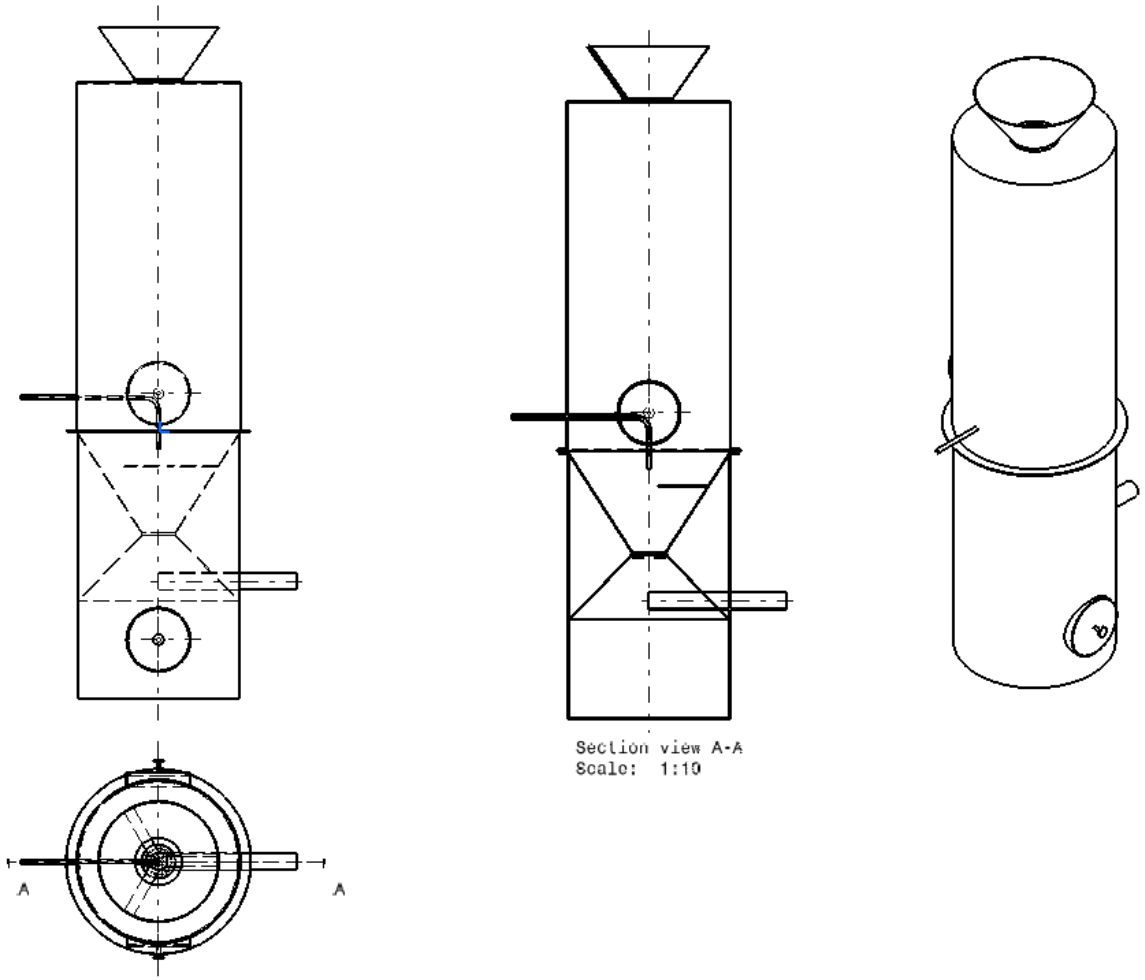


Figure A.4.5: Drawing of the Designed Imbert Type Downdraft Gasifier



A.5 - Gas Cleaning System Design: Components' Design Data

Figure A.5.1: High efficiency cyclone proportions - 2D and 3D

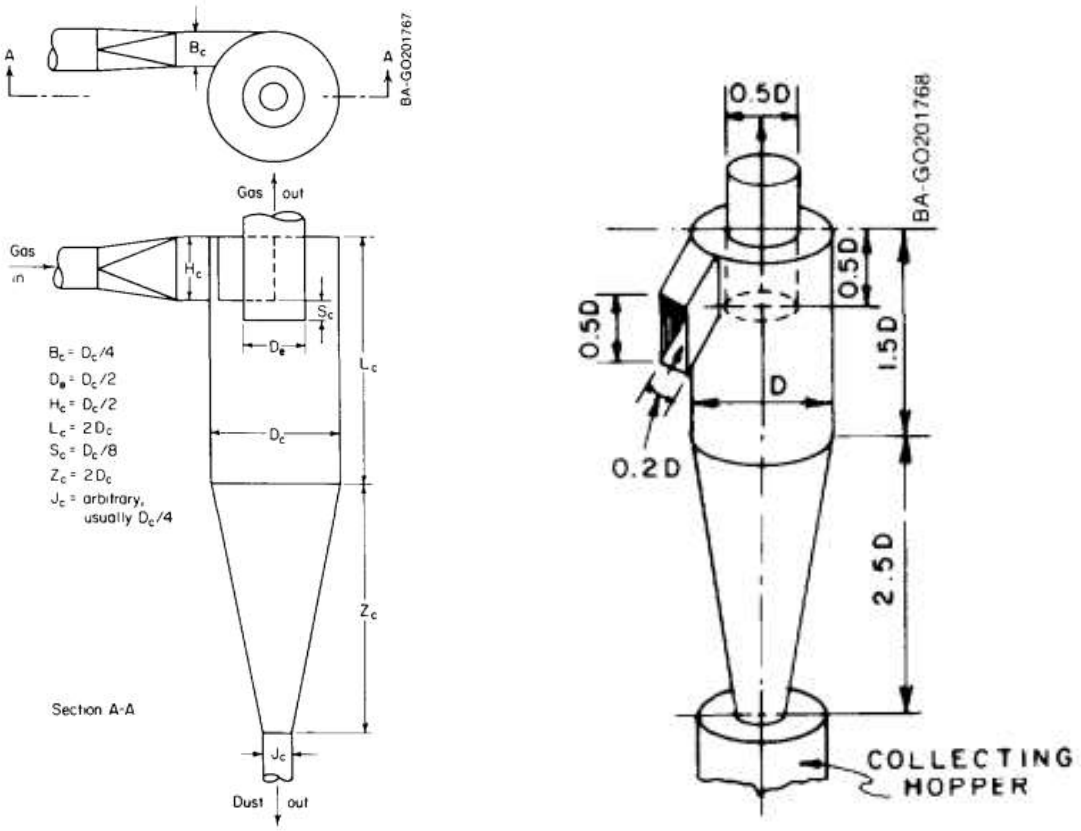


Figure A.5.2: The Variation of Gas Viscosity and Density with Temperature

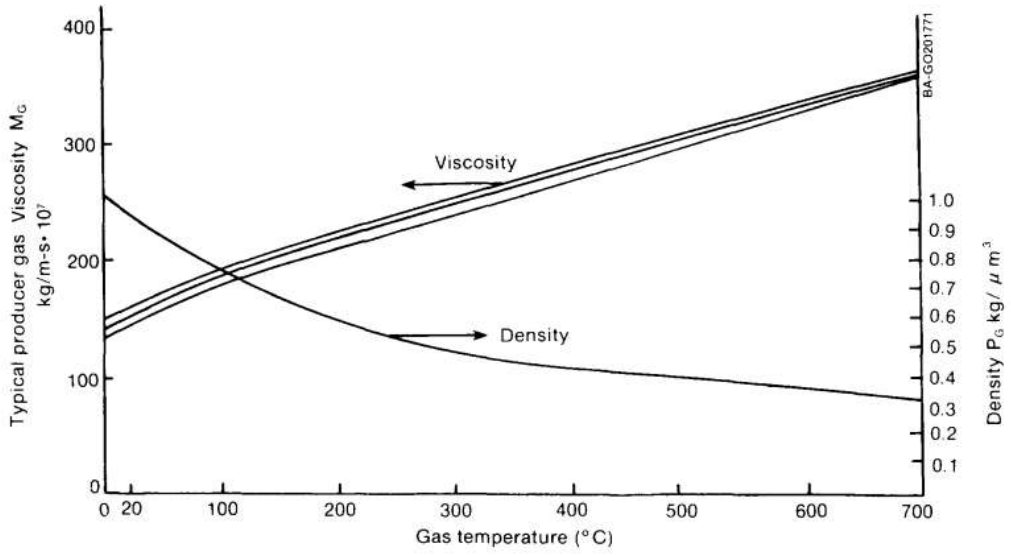


Figure A.5.3: LMTD Correction Factors, F_t

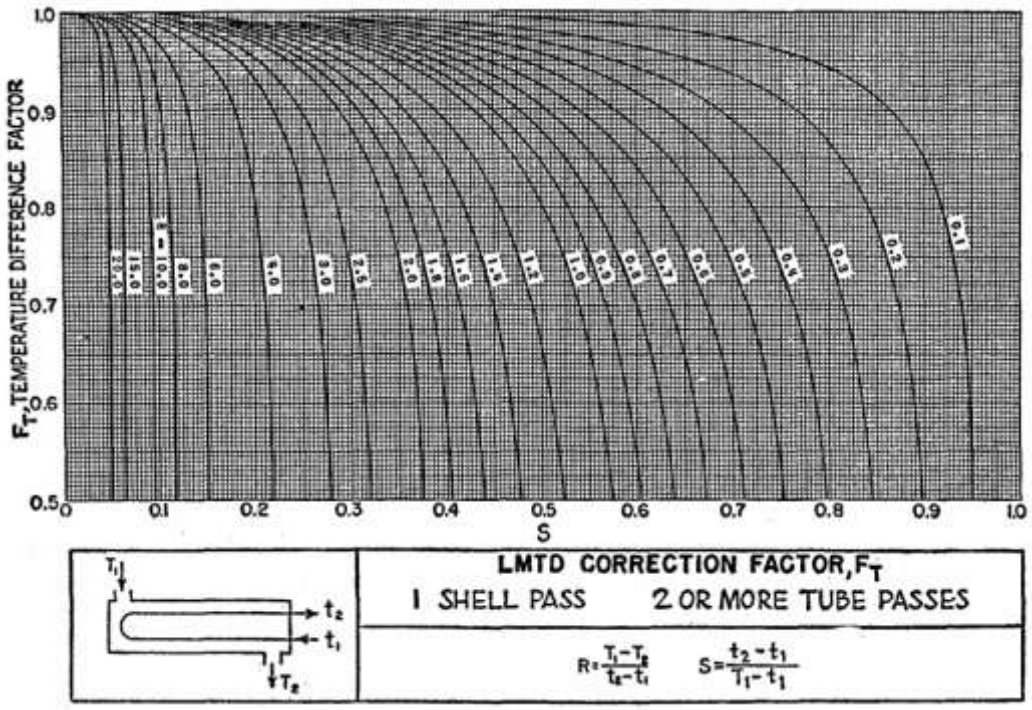


Figure A.5.4: Caloric Temperature Correction Factors, F_c

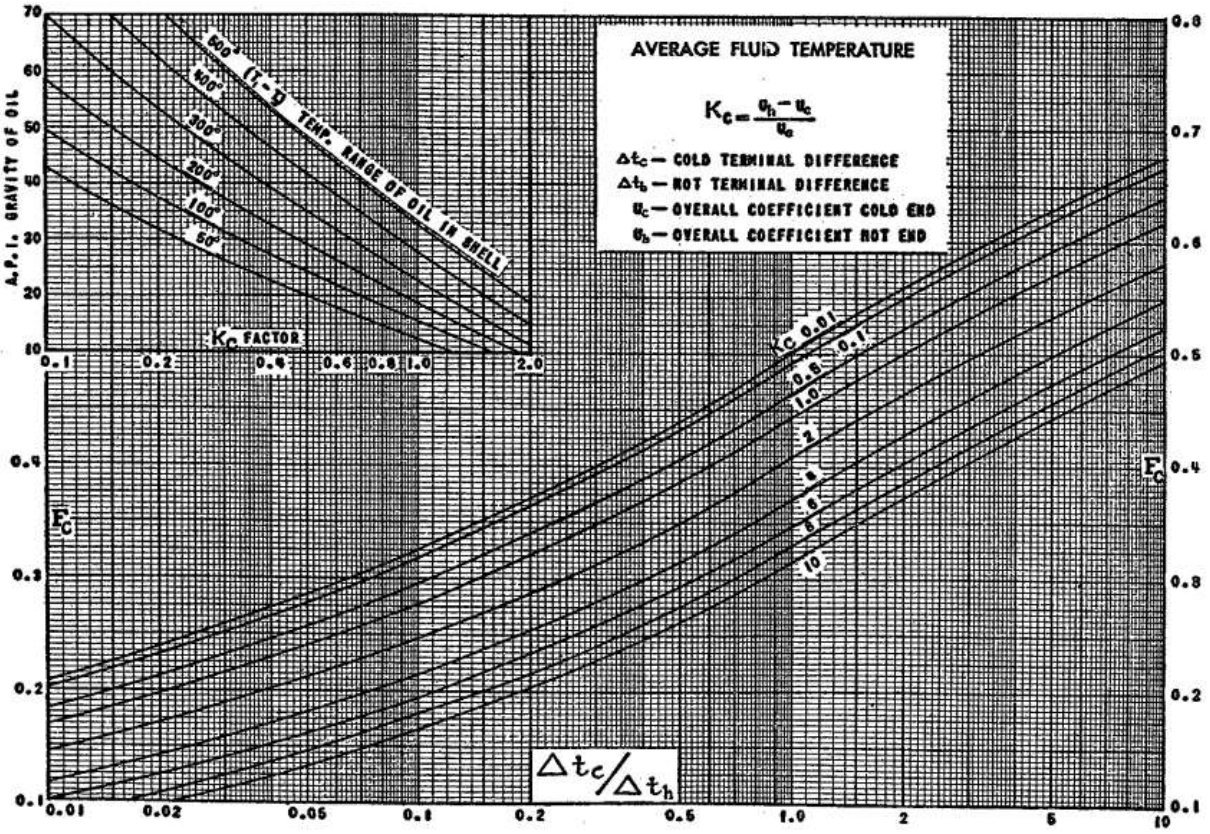


Table A.5.1: Tube Sheet Layouts (Tube Counts) – Triangular Pitch

1 in. OD tubes on 1¼-in. triangular pitch						1¼ in. OD tubes on 1 9/16-in. triangular pitch					
8	21	16	16	14		10	20	18	14		
10	32	32	26	24		12	32	30	26	22	20
12	55	52	48	46	44	13¼	38	36	32	28	26
13¼	68	66	58	54	50	15¼	54	51	45	42	38
15¼	91	86	80	74	72	17¼	69	66	62	58	54
17¼	131	118	106	104	94	19¼	95	91	86	78	69
19¼	163	152	140	136	128	21¼	117	112	105	101	95
21¼	199	188	170	164	160	23¼	140	136	130	123	117
23¼	241	232	212	212	202	25	170	164	155	150	140
25	294	282	256	252	242	27	202	196	185	179	170
27	349	334	302	296	286	29	235	228	217	212	202
29	397	376	338	334	316	31	275	270	255	245	235
31	472	454	430	424	400	33	315	305	297	288	275
33	538	522	486	470	454	35	357	348	335	327	315
35	608	592	562	546	532	37	407	390	380	374	357
37	674	664	632	614	598	39	449	436	425	419	407
39	766	736	700	688	672						

Table A.5.2: Heat Exchanger Tube Data

Tube OD, in.	BWG	Wall thickness, in.	ID, in.	Flow area per tube, in.²	Surface per lin ft, ft²		Weight per lin ft, lb steel
					Outside	Inside	
½	12	0.109	0.282	0.0625	0.1309	0.0748	0.493
	14	0.083	0.334	0.0876		0.0874	0.403
	16	0.065	0.370	0.1076		0.0969	0.329
	18	0.049	0.402	0.127		0.1052	0.258
	20	0.035	0.430	0.145		0.1125	0.190
¾	10	0.134	0.482	0.182	0.1963	0.1263	0.965
	11	0.120	0.510	0.204		0.1335	0.884
	12	0.109	0.532	0.223		0.1393	0.817
	13	0.095	0.560	0.247		0.1466	0.727
	14	0.083	0.584	0.268		0.1529	0.647
	15	0.072	0.606	0.289		0.1587	0.571
	16	0.065	0.620	0.302		0.1623	0.520
	17	0.058	0.634	0.314		0.1660	0.469
	18	0.049	0.652	0.334		0.1707	0.401
1	8	0.165	0.670	0.355	0.2618	0.1754	1.61
	9	0.148	0.704	0.389		0.1843	1.47
	10	0.134	0.732	0.421		0.1916	1.36
	11	0.120	0.760	0.455		0.1990	1.23
	12	0.109	0.782	0.479		0.2048	1.14
	13	0.095	0.810	0.515		0.2121	1.00
	14	0.083	0.834	0.546		0.2183	0.890
	15	0.072	0.856	0.576		0.2241	0.781
	16	0.065	0.870	0.594		0.2277	0.710
	17	0.058	0.884	0.613		0.2314	0.639
	18	0.049	0.902	0.639		0.2361	0.545

Table A.5.3: Heat Exchanger Design Coefficients

Hot fluid	Cold fluid	Overall U_D
Water	Water	250–500§
Methanol	Water	250–500§
Ammonia	Water	250–500§
Aqueous solutions	Water	250–500§
Light organics*	Water	75–150
Medium organics†	Water	50–125
Heavy organics‡	Water	5–75‖
Gases	Water	2–50¶
Water	Brine	100–200
Light organics	Brine	40–100

Table A.5.4: Tube Sheet Layouts (Tube Counts) – Rectangular Pitch

1¼ in. OD tubes on 1 9/16-in. square pitch						1½ in. OD tubes on 1⅞-in. square pitch					
10	16	12	10								
12	30	24	22	16	16	12	16	16	12	12	
13¼	32	30	30	22	22	13¼	22	22	16	16	
15¼	44	40	37	35	31	15¼	29	29	25	24	22
17¼	56	53	51	48	44	17¼	39	39	34	32	29
19¼	78	73	71	64	56	19¼	50	48	45	43	39
21¼	96	90	86	82	78	21¼	62	60	57	54	50
23¼	127	112	106	102	96	23¼	78	74	70	66	62
25	140	135	127	123	115	25	94	90	86	84	78
27	166	160	151	146	140	27	112	108	102	98	94
29	193	188	178	174	166	29	131	127	120	116	112
31	226	220	209	202	193	31	151	146	141	138	131
33	258	252	244	238	226	33	176	170	164	160	151
35	293	287	275	268	258	35	202	196	188	182	176
37	334	322	311	304	293	37	224	220	217	210	202
39	370	362	348	342	336	39	252	246	237	230	224

Figure A.5.5: Tube Side Heat Transfer Coefficient

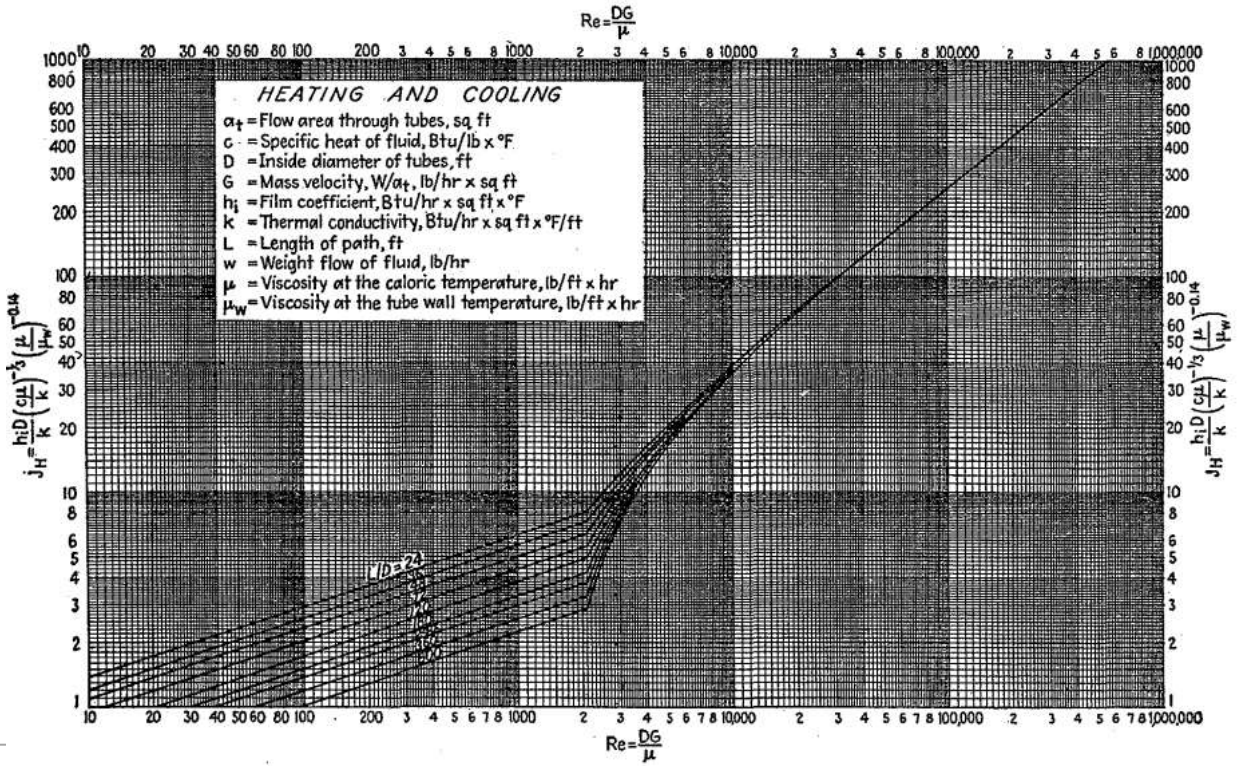


Figure A.5.6: Shell Side Heat Transfer Coefficient for Bundles with 25% Segmental Cut

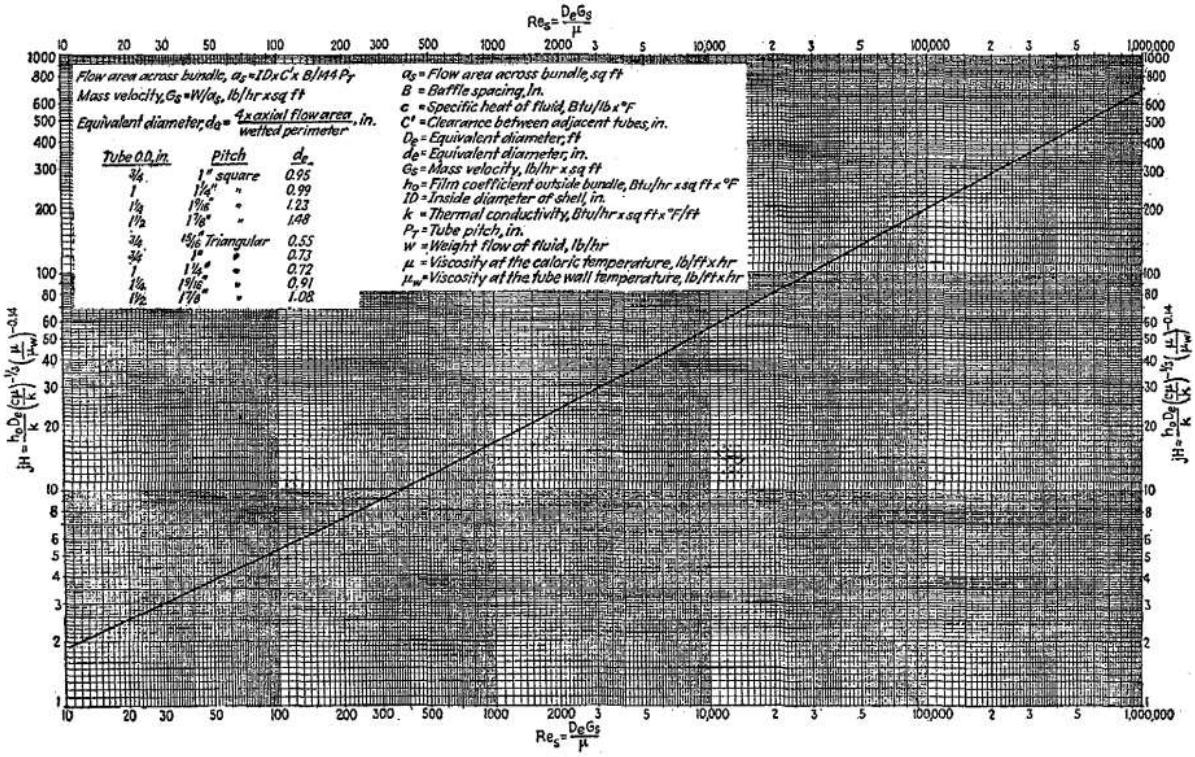


Figure A.5.7: Tube Side Friction Factors

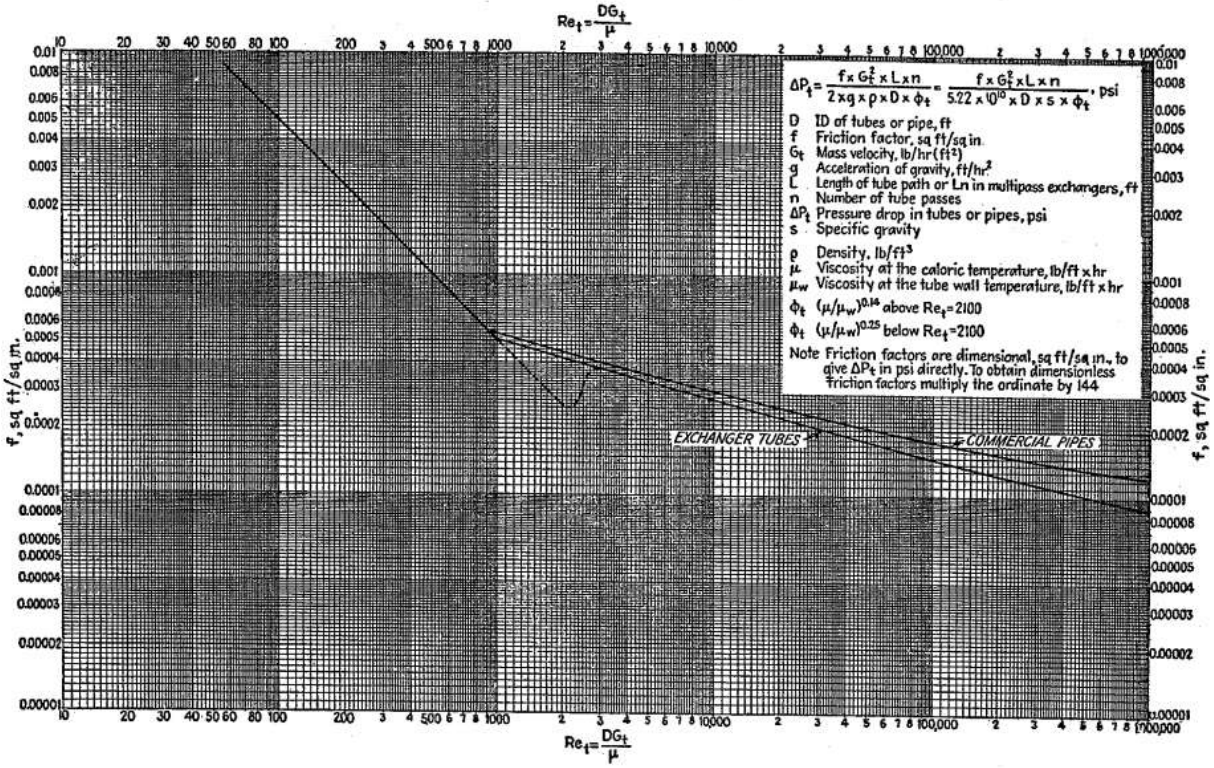


Figure A.5.8: Shell Side Friction Factors for Bundles with 25% Cut Segmental Baffles

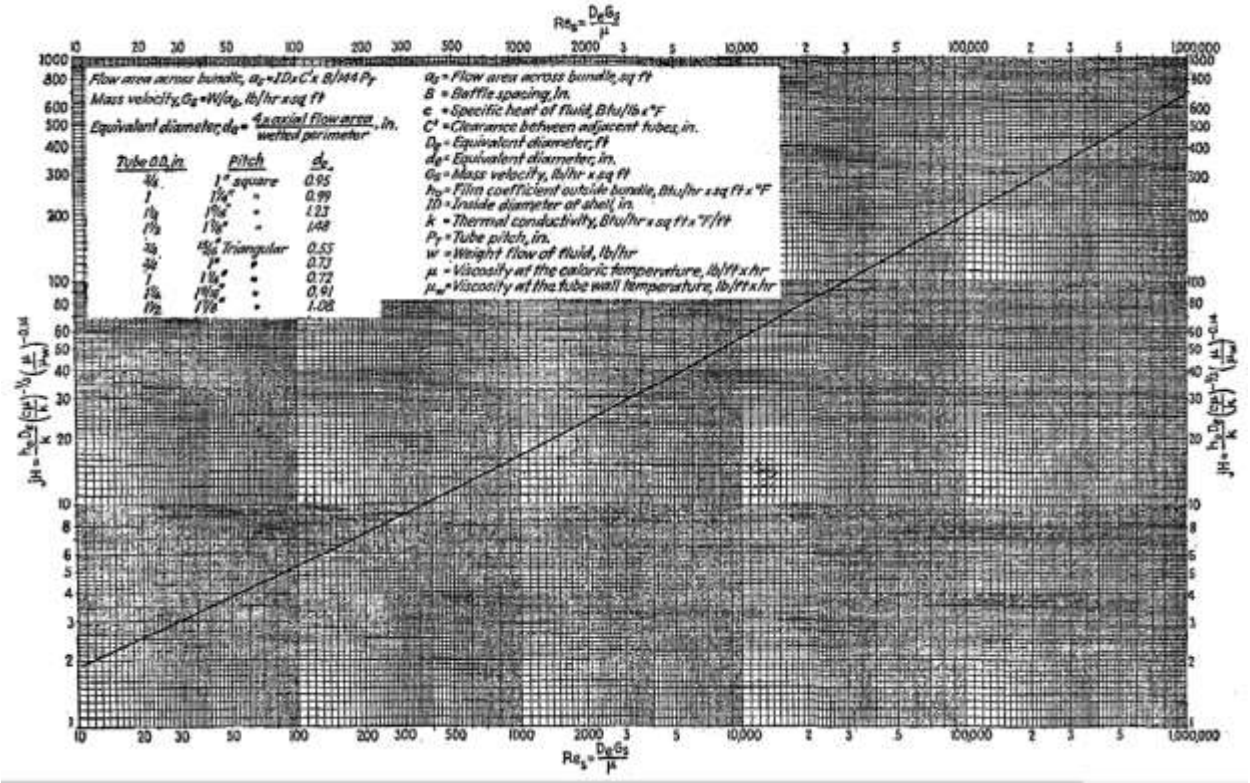
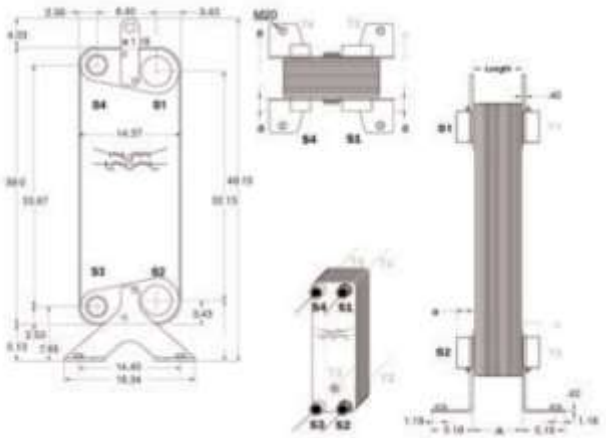


Figure A.5.9: CB200 – Plate Type Heat Exchanger (Cooler 2)



Specifications	CB200
Pressure Range (PSIG)	Vacuum to 435
Temperature Range (°F)	-256°F to 437°F
Max. Connection Size (in.)	3-1/2
Maximum Flow Rate (gpm)	615
Volume/Channel (gallons)	0.13
Height (in.)	31.48
Width (in.)	15.74
Length Calculations (in.)	.39 + (n*.111)
Weight Calculations (lbs.)	29 + (n*1.32)

n = number of plates

Table A.5.5: Scrubber Types and Performances

Method	Size Limit Particle Cut Dia. (dp_{50}) μm	Pressure Drop Water Column cm (in.)	Comments
Gravity Settling	>30	Low	Coarse separator; very large and bulky
Massive Packing	>5	1 cm/10cm of column height	Free draining coarse demister
Fiber Packing	1	10 cm	Viscous materials can cause plugging
Preformed Spray	>5	Low	High water consumption
Gas Atomized Spray Venturi and Sieve Plate Scrubbers	>5 >2 >1 Submicron	0.002 (0.001) 5.7 (2.2) 22.6 (8.9) 91 (35.9)	Good for sticky materials
Centrifugal	1-2	7.5-20 (3-8)	Compact; good for preliminary cleanup
Baffle Plate	20 (solids) 5 (mist)	2.5-7.5 (1-3)	Large coarse collector
Impingement	2-3	10-50 (4-20)	Recoil bounce; can reentrain
Entrainment Separator	5	32 (5)	Can be clogged
Mechanically Aided	1-2	Acts as a blower	High power and maintenance
Moving Bed	1	7.5-15 (3-6)	Good mass transfer
Fabric Filter	0.3	13 (5)	Excellent; can be clogged

Source: Compiled from data in Calvert 1972.

Figure A.5.10: Volume collection chart for sizing Venturi scrubber [SLY INC (2009)]

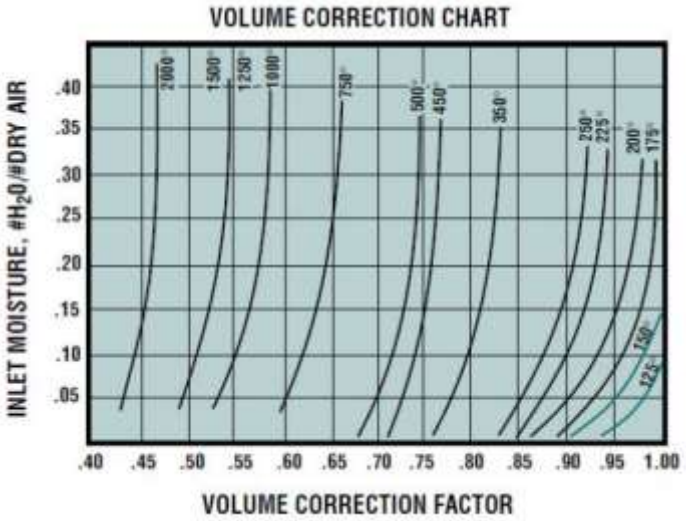
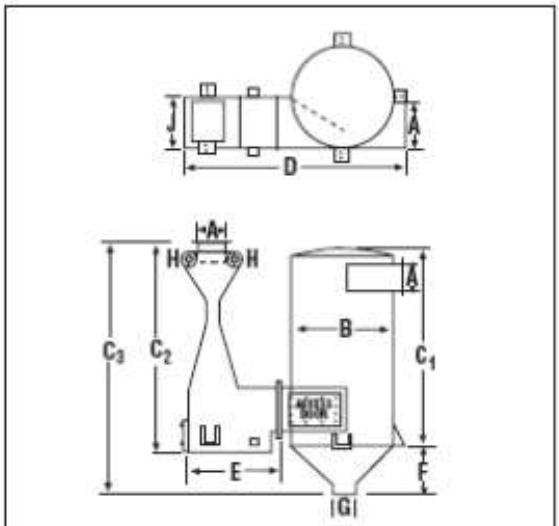


Figure A.5.11: Venturi Scrubber Capacity and Dimensions



Size	Nominal Capacity Sat. CFM	Inlet & Outlet A	Sep. Dia. B	Sep. C_1	Vent C_2	Overall Height C_3	Overall Width D	Venturi Width E	Sep. Cone F	Drain Pipe G	Water Pipe H	Venturi Depth J
1	2,600/3,600	13x13	3'-8"	6'-6"	6'-5 11/16"	7'-2 3/16"	6'-7 1/2"	2'-4"	1'-3 1/2"	3"	2"	1'-5"
2	3,600/4,700	15x15	4'-1"	7'-2"	6'-8 11/16"	7'-6 11/16"	7'-2 1/2"	2'-6"	1'-5"	4"	2"	1'-5"
3	4,700/6,300	17x17	4'-8"	8'-2"	7'-2 15/16"	8'-2 15/16"	7'-11 3/4"	2'-11"	1'-7"	4"	2"	1'-9"
4	6,300/8,500	20x20	5'-3"	9'-1"	7'-8 9/16"	8'-10 9/16"	8'-10 1/2"	3'-2"	1'-9"	4"	2"	1'-9"
5	8,500/11,500	23x23	5'-11"	10'-4"	8'-9 1/4"	10'-1 3/4"	9'-10 1/2"	3'-7"	1'-11 1/2"	6"	3"	2'-4"
6	11,500/15,000	26x26	6'-7"	12'-1"	9'-6 1/2"	11'-1"	10'-11 3/4"	3'-10 3/4"	2'-1 1/2"	6"	3"	2'-4"
7	15,000/20,000	30x30	7'-5"	14'-1"	11'-3 1/4"	13'-0 3/4"	12'-5"	4'-8 1/2"	2'-4 1/2"	6"	4"	3'-1"
8	20,000/27,000	35x35	8'-4"	16'-5"	11'-10 1/2"	14'-1 1/4"	13'-7 1/2"	5'-1"	2'-9 3/4"	8"	4"	3'-1"
9	27,000/36,000	40x40	9'-4"	19'-0"	14'-6 1/2"	16'-10 1/2"	15'-7 3/4"	6'-1"	2'-11"	8"	4"	4'-4 1/2"
10	36,000/48,000	46x46	10'-6"	22'-1"	15'-4"	18'-0 1/4"	17'-2 3/8"	6'-6"	3'-3 1/8"	10"	6"	4'-4 1/2"
11	48,000/60,000	52x52	11'-10"	25'-7"	17'-6"	20'-7 "	19'-3 3/8"	7'-5"	3'-8"	10"	6"	5'-10"

Table A.5.6: Fabric Filter Materials and Characteristics

Fiber	Operating Exposure (°F) Long	Short	Supports Combustion	Air Permeability[a] (cfm/ft²)	Composition	Resistance[b] to Abrasion	Mineral Acids	Organic Acids	Alkali	Cost Rank[c]
Cotton	180	225	Yes	10-20	Cellulose	G	P	G	G	1
Wool	200	250	No	20-60	Protein	G	F	F	P	7
Nylon[d]	200	250	Yes	15-30	Polyamide	E	P	F	G	2
Orlon	240	275	Yes	20-45	Polyacrylonitrile	G	G	G	F	3
Dacron[d]	275	325	Yes	10-60	Polyester	E	G	G	G	4
Polypropylene	200	250	Yes	7-30	Olefin	E	E	E	E	6
Nomex[d]	425	500	No	25-54	Polyamide	E	F	E	G	8
Fiberglass	550	600	No	10-70	Glass	P-F	E	E	P	5
Teflon[d]	450	500	No	15-65	Polyfluoroethylene	F	E	E	E	9

[a]cfm/ft² at 0.5 in. water gauge
[b]P = poor, F = fair, G = good, E = excellent.
[c]Cost rank, 1 = lowest cost, 9 = highest cost.
[d]Du Pont registered trademark.
Source: After Kaupp 1984a, Table 51.

Table A.5.7: Standard FSPN Filter Vessel Models

Standard FSPN Vessel Models

Model Number	FSPN 20	FSPN 35	FSPN 40	FSPN 85	FSPN 250	FSPN 355	FSPN 800	FSPN 1100	FSPN 2000	FSPN 2500	FSPN 3000	FSPN 3500	FSPN 4000	FSPN 4200	FSPN 4500	FSPN 4800	FSPN 5000
No. of Bags	1	1	1	1	2	3	4	6	8	10	12	14	16	18	20	22	24
Bag Size No.	3	4	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Surface Area per Bag, Ft	0.5	1.0	2.0	4.4	4.4	4.4	4.4	4.4.	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4	4.4
Surface Area per Vessel, Ft²	0.5	1.0	2.0	4.4	8.8	13.2	17.6	26.4	35.2	44.0	52.8	61.6	70.4	79.2	88.0	96.8	105.6
Inlet and Outlet Size	1"	1"	2"	2"	3-4"	3-4"	4-6"	4-6"	6-8"	8-10"	8-10"	10-12"	10-12"	10-14"	10-14"	10-14"	10-14"
Max Flow Rate, GPM	15	30	60	120	240	360	480	720	960	1200	1440	1680	1920	2160	2400	2640	2880

NOTE: The maximum flow rate GPM is the MAXIMUM FLOW RATE recommended through the vessel using a 10 micron felt filter bag (PONG10) filtering water. Any change in the micron rating, the type of filter, viscosity or specific gravity of the fluid may affect the maximum GPM calculation significantly. Please consult your FSI representative when sizing these vessels.

Table A.5.8: Standard Filter Bags Data

Filter Bag Data

Bag Size	1	2	3	4	X01	XL
Surface Area Per Bag (ft2/m2)	2.0/0.19	4.4/0.41	0.5/0.05	1.0/0.9	2.0/0.19	5.3/0.49
Volume Per Bag (gal*/liter)	2.1/7.9	4.6/17.3	0.37/1.4	0.67/2.5	2.1/7.9	5.5/0.51
Bag Diameter (inch/cm)	7.0/17.8	7.0/17.8	4.0/10.2	4.0/10.2	6.0/15.2	9.25/23.5
Bag Length (inch/cm)	16/40.65	32.0/81.3	8.25/20.9	14.0/35.5	22/55.9	32/81.3
FSI Filter Vessel Model Number	FSPN-40 CBFP-11	FSPN-85 FSPN-250 CBFP-12 and all multi-hole vessels	FSPN-20 BFN-13	FSPN-35 BFN-14	X100B	XL234

Figure A.5.12: BOS Filter Bag of Item #BOS5PM2P

Specifications

- **Available Materials**
  Polypropylene
- **Seamless Construction**
- **Maximum Operating Temperature**
  160° F (71° C)
- **Suggested Differential Pressure**
  35 PSIG maximum – dirty
  10-15 PSIG optimum change out
- **Absolute (98%) Micron Rating**
  3, 5, 10, 25, 35, 50, 75, 100
- **Sizes**
  #1: 7" x 16" (17.8 cm x 40.65 cm)
  #2: 7" x 32" (17.8 cm x 81.3 cm)
- **Plastic PolyLoc® Rings**
- **Available with NSF Standard 61 Certification**

SEAMLESS-ABSOLUTE RATED

BOS Filter Bags

Item # **BOS5PM2P**	
Code	BOS = Polymicro seamless
Micron Rating	See specifications
Cover	PM = Polypropylene
Size	1, 2
Ring	P = Polypropylene PolyLoc®

Item # **BOS5PP2P61**	
Code	BOS = Polymicro seamless
Micron Rating	See specifications
Cover	PP = Special NSF Construction
Size	2
Ring	P = Polypropylene PolyLoc®
Suffix	61 = NSF 61 Certified

A.6 - Technical Detail for the Procurement of a Selected Producer Gas Generator Set

(Link: https://wfhxdj.en.alibaba.com/contactinfo.html?spm=a2700.8304367.0.0.jGun7n**)**

From: Weifang Huaxin Electric Motor Co., Ltd.
China (Mainland) Manufacturer, Trading Company

Producer Gas Engine Generators of 10-1250KVA

1 Piece/Pieces (Min. Order)
Supply Ability: 2500 Piece/Pieces per Month
Port: Qingdao, China

Product Details

Place of Origin: **Shandong, China (Mainland)**
Brand Name: **HORIS**
Model Number: **H10GF**
Output Type: **AC Three Phase**
Speed: **1500RPM**
Frequency: **50Hz**
Rated Power: **12.5KVA/10KW**
Rated Voltage: **400/230**
Rated Current: **18A**
Certificate: **CE,ISO,EPA**
Function: **ATS AMF DSE7220 OR 5110 CONTROLLER**
Module: **GU620A**
Starting method: **electric start**
Regulator: **AVR**
Short circuit protection: **MCCB air switch**
Alternator: **STAMFORD MARATHON, LORY SOMER etc.**
Rated voltage: **220/380V,230/400V,240/415V,120/240V**
Ceritificate: **ISO CE**
Packaging & Delivery
Packaging Details: **Protection plastic + Plywood case,Export standard packing,**
Delivery Detail: **10-15days**

Specifications:

- ✓ Producer gas engine generator
- ✓ CE,ISO,EPA
- ✓ Well performed control system
- ✓ professional test
- ✓ Global Warranty:18month

Gas Generator - 50 HZ AT 1500/1000 RPM			ENGINE DETAILS			Alternator	DIMENSIONS	
Model	Rated Power	Standby	Model	R/Power	R/Speed	Brushless	LxWxH	Gross
						AVR	(A)	Weight

CQ	KVA	kW	KVA	kW	HIGH TECH	kW	rpm	Stamford	mm	Kgs
H8GF	10	8	11	8.8	H2100D	11	1500	HX164B	1600*700*1200	650
H10GF	**12.5**	**10**	**13.75**	**11**	**H2100D**	**14**	**1500**	**HX164C**	**1600*700*1200**	**650**
H16GF	20	16	22	17.6	H4100D	25	1500	HX184E	1750*720*1250	700
H20GF	25	20	27.5	22	H4100D	25	1500	HX184EF	1800*750*1300	820
H24GF	30	24	33	26.4	H4105D	38	1500	HX184G	1800*750*1300	900
H30GF	37.5	30	41.25	33	H4105D	38	1500	HX184H	1800*750*1450	950
H50GF	62.5	50	68.75	55	H6105D	58	1500	HX224E	2300*850*1600	1200
H75GF	93.75	75	103.125	82.5	H6140D	132	1500	HX274CS	2900*1100*1900	2100
H80GF	100	80	110	88	H6140D	132	1500	HX274C	2900*1100*1900	2950
H100GF	125	100	137.5	110	H6140D	132	1500	HX274E	2950*1150*1950	2780
H120GF	150	120	165	132	H6140D	132	1500	HX274F	2950*1150*1950	3000
H150GF	187.5	150	206.25	165	H12V135D	170	1500	HX274H	3350*1500*1900	3800
H200GF	250	200	275	220	H12V138D	230	1500	HCI444C	3400*1515*2110	4100
H250GF	312.5	250	343.75	275	H6190ZD	330	1000	HCI444ES	4900*1700*2200	8500
H300GF	375	300	412.5	330	H6190ZD	330	1000	HCI444FS	4900*1700*2300	8700
H400GF	500	400	550	440	H12V190D	450	1000	HCI544C	5120*2200*2312	11300
H500GF	625	500	687	550	H12V190ZLD	560	1000	HCI544FS	5120*2200*2680	11800
H700GF	875	700	962	770	H12V190ZLDW	800	1000	HCI634H1	5120*2040*2680	12800
H1000GF	1250	1000	1375	1100	H16V190ZLT	1200	1000	PI734A	5920*2200*2680	16500

Important:

The engine generator set to be procured is the one whose details are specified above in red color font in a shaded separate box.

The above generating set's Control Panel:

1. Key switch (manual type) control panel

Shock resist is fitted between control panel and generator set. Loose sheet is also fitted. The e quipment of control panel are Meters with Voltmeter, Ammeter, Frequency list, Water thermometer, Oil pressure gauge, Hour meter.

2. Control parts:

Start/stop key switch, start button, emergency stop button,voltage regulationresistance, speed regulation resistance. Voltage phase switch, Electric current phase selecting switch.

3. Protection setting for engine

For emergency shut down, overfeed, high water temperature, low oil pressure. ATS switch is optional components.

When some accidents appear, the digital Protector can shut down immediately, giving the bat tey voltage alarm andDC electrical source alarm. European extremity, steady wiring, and it ca n easily dismantle and install.

Advantages:

1. High profit: low operation cost, supply of electricity and thermal power at the same time, low maintenance cost
2. Longer life: Special design engine has longer life and overhaul time of 30000hours
3. Low operation cost: natural gas has a rich reserve with low cost and a high rate of return
4. Clean and environmental
5. GAS REQUIRED: Heat Value>5500KCAL , Gas Pressure range 0.8-10kpa.
6. Supply Scope: Gas generator set combine with engine and alternator, base frame, control box with Auto controller,ECU and spark system, Gas and Air Mixer,Radiator Fan,Fire protection system,Air filter, oil filter, Muffler

Advance:

1.	10-1250KVA Gas generator with Jichai, Cummins,Deutz,Steyr,Ricardo, Weichai,brand engine etc. Low displacement
2.	Alternator "STAMFORD" "MARATHON" "Leroy Somer" Brand 100% copper brushless alternator. Brushless excitation and "H" class insulation.
3.	Super silenced box, about 65d(B)A (L-7M)
4.	Longer life: Special design engine has longer life and overhaul time of 30000hours
5.	Moistureproof and derusting processing, effectively protect the generator from humid weather
6.	High quality steel
7.	Green environmental protection paint
8.	Cooling system: combined cooling water tank fitted to meet the requirement of radiation at ambient temperature 40°C
9.	Advanced reasonable structure, high efficiency, low vibration and noise, smooth running, good reliability, easy handling. It is widly used in national defense, telecommunications, field construction, high-rise buildings, commercial buildings, industrial and mining enterprisers, oil fields,roads, ports, villages, banks, hospitals etc.
10.	ISO, CE, SONCAP approval
11.	Global warranty: 18months

Service quality assurance:

1) Before-sale Service: we provide detailed product technical parameters for equipment choosing and system designing
2) Service quality assurance: our sale staffs are all experience and professional,who can provide the most proper system design and optimized equipment for the customers.
3) After sale maintenance service: We create files for end user and provide them follow-up service,regular return visit and permanent maintenance.
4) Spare parts supply: We provide all kinds of spare parts and technical support.
5) Main overhaul or maintenance service: We provide perennial major overhaul and maintenance service