“Mathematical Modeling and Experimental Investigations of Combustion of Biomass based Slurry Fuels in Oil Fired Furnaces”

THESIS

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CERTIFICATE

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LIST OF ABBREVIATIONS AND SYMBOLS

1. LDO- Light Diesel oil
2. CSP- Coconut shell powder
3. CWS- Coal Water slurry
4. COM – Coal oil Mixtures
5. SRC – Solvent refined coals
6. CWM – Coal water mixture
7. CFM – Coal Fuel mixture
8. DPM – Discrete phase model
9. CFD- Computational Fluid Dynamics
10. NPM- Non premixed model
11. FVM- Finite volume method
12. Re- Reynolds number
13. GAMBIT- Preprocessor and mesh generation software
14. FLUENT- Postprocessor, commercial CFD software
15. PDF- Probability density fraction
16. C_p = Specific heat
17. ρ = Density
18. Δh = Change in Enthalpy: Δs = Change in Entropy
19. K = Thermal conductivity
20. B5 = Blend of 5% of CSP and10% of Water to LDO
21. B10 = Blend of 10% of CSP and 10% of Water to LDO
22. B15 = Blend of 15% of CSP and 10% of Water to LDO
23. B20 = Blend of 20% of CSP and 10% of Water to LDO
24. B25 = Blend of 25% of CSP and 10% of Water to LDO
25. B30 = Blend of 30% of CSP and 10% of Water to LDO
26. IP = Indicated power
27. BP = Brake power
28. TFC = Total fuel consumption
29. BTE = Brake Thermal efficiency
30. ITE = Indicated thermal efficiency

ABSTRACT

Renewable energy sources are sustainable energy sources. They are gaining importance, as the fossil fuels are fast depleting and there is pressure for reduced emissions from combustion of fuels. Biomass turns out to be a good candidate as a renewable source of energy. The literature scan shows that the coconut shell powder has not been used in slurries to the extent it deserves in view of its reasonably high calorific value and tendency for low CO emission.

Coconut shell powder is being considered as the biomass component in the biomass slurry fuel. The properties of the slurries have been determined and simple correlations are developed. Based on the properties of the biomass slurry, the appropriate biomass slurry composition is selected for further studies. In this connection, a new guideline- fuel cost index is introduced to assist the selection of the suitable biomass slurry.

Computational fluid dynamics tool-Fluent is used, for the first time, to study the combustion of the biomass slurry in oil-fired furnace. The maximum temperature and the temperature distribution in the furnace are predicted. The emissions from the outlet of the furnace are also predicted. It has been observed that the maximum temperature in the furnace reduces with the increase in the percentage of coconut shell powder. It is also observed from the CFD analysis that the CO emission reduces with the increase in coconut shell powder in the slurry (up to 30%). The composition of the slurry investigated is varied from pure Light Diesel Oil to a maximum coconut shell powder percentage of 30%, along with 10% of water.

Experimental investigations of the combustion process using the biomass slurry based on the coconut shell powder, in the oil-fired furnace are carried out. The temperature distribution in the furnace and CO emission from the outlet of the furnace are measured. The predictions of the temperature and emissions from the CFD analysis agree reasonably with the experimental measurements. A simple correlation for determining the maximum temperature attained in the furnace as a function of the biomass slurry composition is

developed. The suitability of using the biomass slurry for melting aluminum and steam generation for subsequent power production is experimentally demonstrated. Coconut shell powder mixed with diesel oil is used in mobile Bullet Diesel engine successfully.

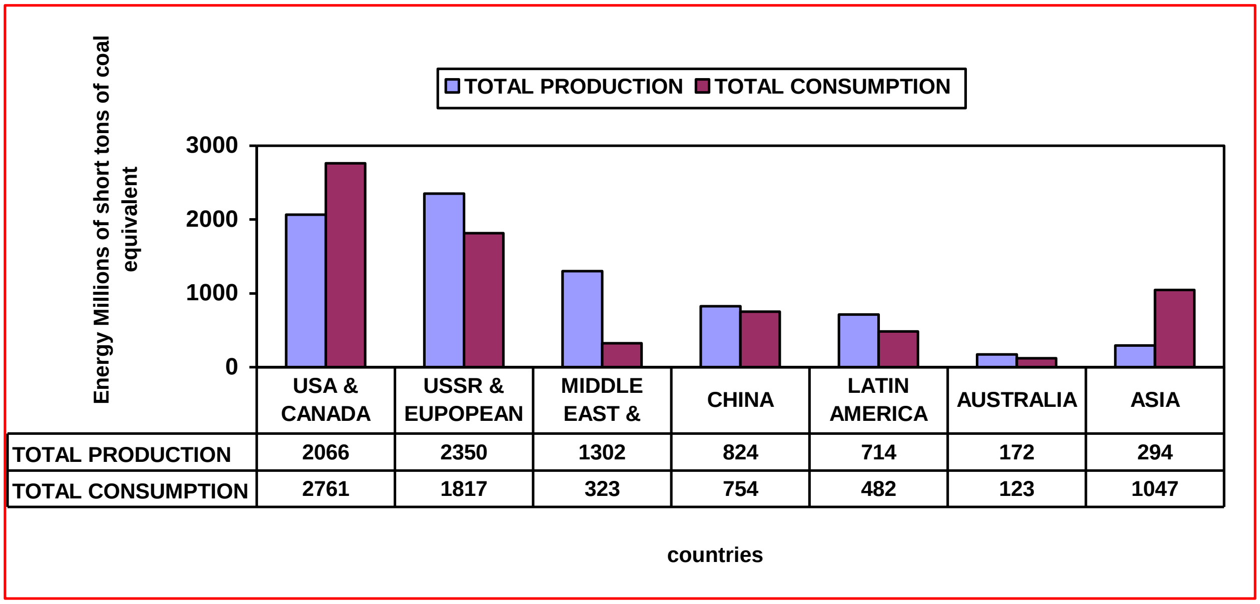
CHAPTER-1

INTRODUCTION

Energy is fundamental to the quality of our lives. Nowadays, we are totally dependent on an abundant and uninterrupted supply of energy for living and working. It is a key ingredient in all sectors of modern economies. We know that energy demand will increase significantly in the future. The research in the area of energy must answer how to meet the huge energy requirements of the future in an environmental friendly way. The present research on biomass-based slurry fuels is an effort in this direction.

1.1 World energy production and consumption

The energy production and consumption in the world alarms the sustainability of the present day activities. Figure 1.1 shows the total production and total consumption of energy in various countries, based on the present consumption rate [1]. It can be observed from Figure 1.1 that for USA, Canada and Asia, the total consumption exceeds the total production. While in USA and Canada, the deficit is only about 35%, in Asia the deficit is 300%. Thus, the need to look into the alternative sustainable source is more critical in Asia. Colin Campbell and the Uppsala Hydrocarbon Depletion Study Group have made a study of the world oil production and consumption, Figure 1.2 shows Production (Million barrels per day-Mbd) against Time (Years), based on Campbell’s data [2]. The four different lines correspond to different possible scenarios taking place from 1996 onward. It shows the oil production and usage in terms of actual usage, proposed usage and the minimum usage. It can be observed from the Figure 2.2, that the peak oil production turns out to be 2008. It can be seen that whichever scenario actually occurs, the result is almost the same. This is because more oil now means less in the future, whilst it may be possible to alter the shape of the curve, one cannot alter the area beneath it. The ‘premature peak’ in the early 1970s corresponds to the oil crisis of 1973. Now it is time to re-examine our approach to alternative fuels and it can be kept ahead of the oil depletion curve.



	USA & CANADA	USSR & EUPOPEAN	MIDDLE EAST &	CHINA	LATIN AMERICA	AUSTRALIA	ASIA
TOTAL PRODUCTION	2066	2350	1302	824	714	172	294
TOTAL CONSUMPTION	2761	1817	323	754	482	123	1047

Figure 1.1 Rate of production and consumption in different countries [1]

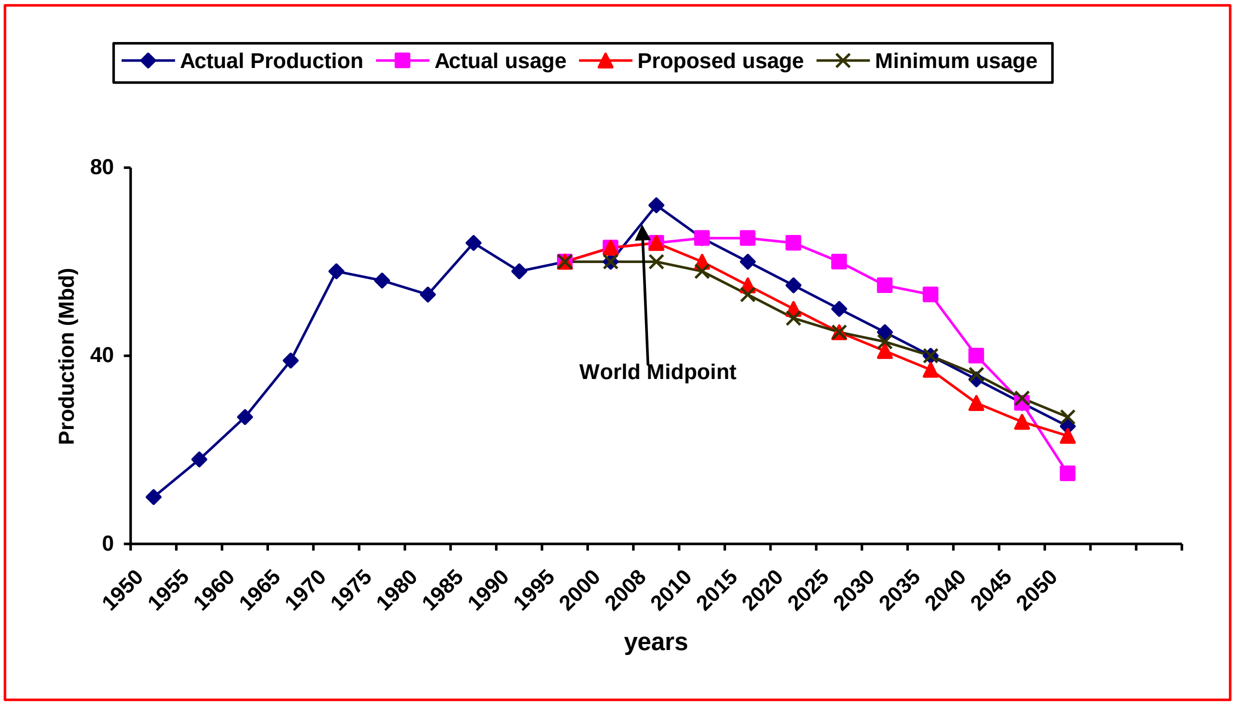


Figure1.2 Colin Campbell and the Uppsala Hydrocarbon Depletion Study Group2004- upgrade of the peak oil model [2]

1.2 Energy production and its impact on environment

The most important global concern today is the increase in the atmospheric carbon dioxide by 25-30% over the last 100 years and its potential to change the world climate. There is no doubt about the size of the changes in atmospheric carbon dioxide. Since 1960 there is lot of precautionary measures taken by the developed countries to control the pollution of the environment. The additional CO_2 is released to the atmosphere from the burning of fossil fuels and by the clearing of the forests. As population grows, the need for more and more energy is exacerbated. The increase in lifestyle and energy demand rise together and the wealthy industrialized economies contain 25% of the world's energy supply [3]. The problems with energy supply and use are related not only to global warming, but also to such environmental concerns as air pollution, acid precipitation, ozone depletion, forest destruction, and emission of radioactive substances. These issues must be taken into consideration simultaneously if humanity is to achieve a bright energy future with minimal environmental impacts. Much evidence exists, which suggests that the future will be negatively impacted if humans keep degrading the environment. Other environmental considerations have been given increasing attention by energy industries and the public. The concept that consumers share responsibility for pollution and its cost has been increasingly accepted. In some jurisdictions, the prices of many energy resources have increased over the last one or two decades, in part to account for environmental costs. World population is expected to double by the middle of the 21st century, and economic development will almost certainly continue to grow. Global demand for energy services is expected to increase by as much as an order of magnitude by 2050, while primary-energy demands are expected to increase by 1.5-3 times [4]. Simultaneously, concern will likely increase regarding energy-related environmental concerns such as acid precipitation, stratospheric ozone depletion and global climate change.

One solution to the impending energy shortage is to make much more use of renewable energy sources and technologies. This cause is sometimes espoused with a fervor, which leads to extravagant and impossible claims being made. Engineering practicality, reliability, applicability, economy, scarcity of supply and public acceptability should all be considered accordingly. Ultimately, of course, all energy supplies on earth derive from the sun. Solar energy provides a continuous stream of energy which warms us, causes crops to grow via photosynthesis, heats the land and sea differentially and so causes winds and consequently waves and, of course, rain leading to hydropower. In the light of preceding explanations, it can be pointed out the fact that energy is one of the main factors that must be considered in discussions of sustainable development. Several definitions of sustainable development have been put forth, including the following common one "development that meets the needs of the present without compromising the ability of future generations to meet their own needs [5].

There are many factors that can contribute to achieve sustainable development. One of the most important is the requirement for a supply of energy resources that is fully sustainable [6-9]. A secure supply of energy resources is generally agreed to be a necessary but not sufficient requirement for development within a society. Furthermore, sustainable development within a society demands a sustainable supply of energy resources and an effective and efficient utilization of energy resources. In this regard, the intimate connection between renewable energy sources and sustainable development emerges. Due to the usage of fossil fuels and the anticipated patterns of future energy use and consequent environmental impacts and to identify some solutions to the current environmental problems, focus on renewable energy sources and technologies and the linkage between renewable energy and sustainable development over fossil fuel is essential. During the past two decades, the risk and reality of environmental degradation have become more apparent. Growing evidence of environmental problems is due to a combination of several factors since the environmental impact of human activities has grown dramatically because of the sheer increase of world population, consumption, industrial activity, etc. Throughout the 1970s most environmental analysis and legal control instrument concentrated on conventional pollutants such as SO_2, NO_x, particulates and CO. Recently environmental concern has extended to the control of micro or hazardous air pollutants, which are usually toxic substances and harmful in small doses, as well as to that of globally significant pollutants such as CO_2. Apart from advances in environmental science, developments in industrial processes and structures have led to new environmental problems. For example in the energy sector, major shifts to the road transport of industrial goods and to individual travel by cars has led to an increase in road traffic and hence a shift in attention paid to the effects and sources of NOx and volatile organic compound (VOC) emissions. Detailed information on these gaseous and particulate pollutants and their impact on the environment and human bodies have been recently presented by Dincer [10].

1.3 Energy sources and sustainable development

A secure supply of energy resources is generally agreed to be a necessary requirement for development within a society. Sustainable development demands a sustainable supply of energy resources that, in the long term, is readily and sustainably available at reasonable cost and can be utilized for all required tasks without causing negative social impacts. Supplies of such energy resources as fossil fuels and uranium are generally acknowledged to be finite. If a breeder reactor is used, the depletion of nuclear fuel problem is eliminated [10]. Other energy sources such as sunlight, wind and falling water are generally considered renewable and therefore sustainable over the relatively long term. Wastes and biomass fuels are also usually viewed as sustainable energy sources. In general, the implications of these statements are numerous, and depend on how sustainable is defined. Environmental concerns are an important factor in sustainable development. For a variety of reasons, activities, which continually degrade the environment, are not sustainable over a time, e.g., the cumulative impact of the environment of such activities often leads over a time period to a variety of health, ecological and other problems. A large portion of the environmental impact in a society is associated with its utilization of energy resources. Ideally, a society seeking sustainable development utilizes only energy resources, which cause no environmental impact.

However, all energy resources lead to some environmental impact, it is reasonable to suggest that some of all the concerns regarding the limitations imposed on sustainable development by environmental emissions and their negative impacts can be in part overcome through increased energy efficiency. Clearly, a strong relation exists between energy efficiency and environmental impact. For the same services or products, less resource utilization is normally associated with increased energy efficiency. The exploitation of renewable energy resources and technologies is a key component of sustainable development. There are three significant reasons for it as follows

1. They have much less environmental impact compared to other sources of energy since there is no energy source with zero environmental impact. There are varieties of choices available in practice that a shift to renewable could provide a far cleaner energy system than would be feasible by tightening controls on conventional energy.

2. Renewable energy resources cannot be depleted unlike fossil fuel and uranium resources. If used wisely in appropriate and efficient applications, they can provide reliable and sustainable energy supply almost indefinitely. In contrast, fossil fuel and uranium resources are finite and can be diminished by extraction and consumption.

3. They favor power system decentralization and locally applicable solutions more or less are independent of the national network, thus enhancing the flexibility of the system and the economic power supply to small isolated settlements. That is why many renewable energy technologies are potentially available for us in urban areas.

In conjunction with this, the increasing world population requires the definition and successful implementation of sustainable development [10]. Some essential parameters that can help in achieving a successful sustainable development in a society are listed

- Public awareness of sustainable energy programs through media
- Information on energy utilization, environmental impact etc.
- Environmental education and training
- Using innovative energy strategies
- Promoting renewable energy resources
- Financing for sustainable energy development
- Monitoring and evaluation of data and findings.

1.4 Renewable energies for sustainable development

Global benefits from a rapid and progressive transition to renewable energies [10]:

(1) Global climate stability is a precondition for sustainable development. Renewable energies provide a timely gateway for global greenhouse gas emissions reduction. According to the assessments of the Intergovernmental Panel on Climate Change (IPCC), global emissions must begin to decrease at the earliest, to achieve global climate security.

(2) Sustainable development requires sufficient and low-cost energy supplies. Renewable energies provide worldwide secure access to inexhaustible energy resources, some already at low and all at further decreasing costs and energy security.

(3) Sustainable development is only possible with access to sufficient water. This is a worldwide problem. Renewable energies provide, particularly in the arid regions, the additional energy resources required for large-scale water desalination projects.

(4) Fossil fuel reserves are limited. In the coming decades, global energy shortages, rising prices, and risks of conflicts for resources undermining international security are imminent. Renewable energies can mitigate such threats.

(5) Renewable energies require the use of a variety of resources and many technologies: increased diversity for greater supply security.

(6) Economy and reliability of supply can be improved by inter-regional exchange: Enhanced cooperation will lead to understanding and peace rather than to armed conflicts.

(7) Renewable energies will reduce the dependence on a few oil and gas exporting countries and thus enhance geopolitical stability.

(8) Renewable energies allow preserving the scarce resources of oil and gas for their important non-energetic applications in the future can help to avoid the tremendous costs from climate Change.

(9) Renewable energies offer to countries in transition, the chance of Leapfrogging in development, straight into renewable technologies instead of detouring through

intermediate fossil fuel capacities. Technology transfer “North – South” and clean energy transfer “South – North” will interlink and stimulate these economies: partnership for mutual development.

Development of advanced renewable energy technologies serves as cost effective and environmentally responsible alternatives to conventional energy generation. An integrated set of activities such as R&D, technology assessment, standards development and technology transfer should be conducted.

1.5 Sustainable energy sources in India

India has today among the world's largest programmes for renewable energy. The activities cover all major renewable energy sources of interest to us, such as biogas, biomass, solar energy, wind energy, small hydropower. In each of these areas, we have programmes of resource assessment, R&D, technology development and demonstration. Several renewable energy systems and products are now not only commercially available, but are also economically viable in comparison to fossil fuels, particularly when the environmental costs of fossil fuels are taken into account. The Government and some private organisations are involved in the implementation of these programmes for development, demonstration and utilization of various renewable energy based technologies. Such as, solar, thermal, solar-photovoltaic, wind, power generation and water pumping, biomass combustion/co-generation, small, mini, & micro hydro power; solar power; utilization of biomass-gasifiers, briquette, biogas, improved Chula (cook-stove) geothermal for heat applications and power generation/energy recovery from urban, municipal and industrial wastes and tidal power generation. The Government also deals with other emerging areas and New Technologies such as, chemical sources of energy, fuel cells, alternative fuel for surface transportation, hydrogen energy etc. Among most of the renewable energies available, biomass is the only energy found more sustainable and not seasonal like most of the other renewable energies available. Gielen and urander, in their paper discusses the increasing cost and dependence of the oil in the Middle East and suggested alternative renewable fuels as substitutes [11]

1.6 Biomass an important sustainable energy source.

Biomass as the solar energy stored in chemical form in plant and animal materials is among the most precious and versatile resources on earth. It provides not only food but also energy, building materials, paper, fabrics, medicines and chemicals. Biomass has been used for energy purposes ever since man discovered fire. Today, biomass fuels can be utilised for tasks ranging from heating the house to fuelling a car and running a computer. The chemical composition of biomass varies among species, but plants consist of about 25% lignin and 75% carbohydrates or sugars. The carbohydrate fraction consists of many sugar molecules linked together in long chains or polymers. Two larger carbohydrate categories that have significant value are cellulose and hemi-cellulose. The lignin fraction consists of non-sugar type molecules [12]. Biomass (when considering its energy potential) refers to all forms of plant-derived material that can be used for energy: wood, herbaceous plants, crop and forest residues, animal wastes etc. Because biomass is a solid fuel it can be compared to coal. On a dry-weight basis, heating values range from 17.5 GJ per ton for various herbaceous crops like wheat straw, sugarcane bagasse to about 20 GJ/ton for wood. The corresponding values for bituminous coals and lignite are 30 GJ/ton and 20 GJ/ton respectively. At the time of its harvest, biomass contains considerable amount of moisture, ranging from 8 to 20 % for wheat straw, to 30 to 60 % for woods, to 75 to 90 % for animal manure, and to 95 % for water hyacinth [13]. In contrast, the moisture content of the most bituminous coals ranges from 2 to 12%. Thus, the energy densities for the biomass at the point of production are lower than those for coal. On the other hand, chemical attributes make it superior in many ways. The ash content of biomass is much lower than for coals, and the ash is generally free of the toxic metals and other contaminants and can be used as soil fertiliser.

It offers considerable flexibility of fuel supply due to the range and diversity of fuels, which can be produced. Biomass energy can be used to generate heat and electricity through direct combustion in modern devices, ranging from very-small-scale domestic boilers to multi-megawatt size power plants electricity (e.g. via gas turbines), or liquid fuels for motor vehicles such as ethanol, or other alcohol fuels. Biomass-energy systems can increase economic development without contributing to the greenhouse effect since biomass is not a net emitter of CO_2 to the atmosphere when it is produced and used sustainably. It also has other benign environmental attributes such as lower sulphur and NOx emissions and can help rehabilitate degraded lands. There is a growing recognition that the use of biomass in larger commercial systems based on sustainable, already accumulated resources and residues can help improve natural resource management.

The number of jobs created (for production, harvesting and use) and the industrial growth (from developing conversion facilities for fuel, industrial feedstocks, and power) would be enormous. For instance, the U.S. Department of Agriculture estimates that 17,000 jobs is created per every million of gallons of ethanol produced. The Electric Power Research Institute has estimated that producing 5 quadrillion Btu's (British Thermal Units) of electricity on 50 million acres of land would increase overall farm income by $12 billion annually (the U.S. consumes about 90 quadrillion Btu's annually). By providing farmers with stable income, these new markets diversify and strengthen the local economy by keeping income recycling through the community. Biomass is considered as a versatile source of energy and the key issues are being discussed in the article [14]. Olofsson et. al. review and evaluates the process technologies for systems suitable for cost efficient medium scale gasification for biomass to liquid fuels [15].

Jinyue yan suggests advanced biomass based systems that have the potential to contribute significantly to the energy supply in the future. The central goal for development is to create an economically and environmentally sustainable system, based on a fuel system infrastructure that will enable investment in modern high efficiency power production cycles [16]. Jagadish examines the total annual biomass growth in India including leaves, grasses and weeds. The strategy for a more efficient use of biomass resources has been discussed. Jagadish suggests a three-pronged approach, looking at biomass conversation, biomass generation and efficient conversion of biomass to biofuels, needed to improve the availability of useful energy in India [17]. Haripriya estimates the carbon contained in biomass of Indian forest for the year 1993, using species wise volume inventories for all forest strata in various states [18].

1.7 The biomass industry

Like hydropower, wind and solar power, biomass energy is not new. For centuries, people have recognized the energy value of animal and agricultural waste such as wood, peat and manure, and have burned it mostly for heat. This practice continues today in many less developed countries. As our world became industrialized, our need for power increased. Coal and oil were the most plentiful and efficient fuels but also the dirtiest. Many are now focusing full circle to rediscover biomass. Some fuels, can be introduced directly or co-fired with fossil fuels in generators as replacement fuels. However, many must be converted to either gas or some palletized form to achieve more efficiency to maximize heat productions. While research progresses to reduce any harmful emissions from the biofuels, it is understood that biofuels inherently give off far fewer harmful emissions than fossil fuels. Therefore, it makes a lot of sense to introduce biofuels as replacements for fossil fuels. Without a doubt, our fossil resource has been dramatically reduced as our demand for electricity has increased. Over the last couple of years, plans have been reviewed for several projects using a wide variety of biomass sources. For example, projects include anaerobic digesters on dairy and swine farms, landfill methane capture, rice hulls and fruit processing plant waste, chicken litter, wood product pelletisation and gasification, and ethanol production. Although technologies for burning solid and gasified fuels have been in operation for decades, the conversion processes from biomass to biofuels are constantly being tweaked to maximize energy output and reduce possible hazards. Additionally, equipment retrofits may be necessary to efficiently utilize some of the fuels. Most of the biomass materials are transformed into other forms to finally generate energy. The whole process is time consuming, expensive and labor oriented. Initially in the early seventies [19],because of oil crisis - to conserve petroleum fuel, coal in pulverized form was dispersed in diesel oil and burnt using burners in furnaces or by blower type fluidized bed combustion. Coal fines mixed with fuel oil mixture is known as coal slurry fuel. The liquid medium can be offered by oil, methanol, water or a mixture of any two. The main application of coal-oil mixtures was in boilers and industrial furnaces. Coal-liquid mixtures (CLM) enable the direct substitution of oil partly or completely by coal as an energy source. The crushing and mixing process involved in its preparation are far more economical than the energy expensive coal liquefaction and gasification processes. The CLM slurry is pumpable and hence can be readily used in the conventional oil-fired combustors with minimum hardware modifications and long distance transportation of the fuel is easy [20].

In India, there are more than 5000 foundary units, having an installed capacity of approximately 7.5 million tonnes per annum. The majority of the foundary units in India falls under the small scale industry. The oil fired foundary industry is catering to some specific end users like pump-sets castings, automotive castings, diesel engine castings, aluminum foil industries, tractors/ agricultural implements, food processing industries and some industries in northern Karnataka even exporting the castings. Most of these industries are using LDO, High speed diesel, furnace oil, diesel oil and certain petroleum blends. These industries can definitely think of alternative source of fuels like those that biomass blends, which reduces the cost, emission, and dependency on the fossil fuels [20a].

In many parts of the world and especially southern part of India coconut shell, groundnut husk, coffee husk etc. are available in abundance $12.5x10^9 m^3$/yr with a content of 182 EJ equivalents to 1.3 times the total world coal consumption. Most of the biomass sources are much more superior in quality compared to low rank coal that is available. Similar to coal pulverization, bio-husks can be pulverised and mixed with carrier medium like oil and water to form slurry. The resulting slurry is burnt efficiently as a slurry fuel, in boilers and industrial furnaces. Such fuels are named here as **Biomass based slurry fuels.** Since India is basically agricultural, country such type of slurry, fuels will definitely improve the Indian energy scenario and definitely the development of the nation. **This in fact is the motivation for under taking the present study**

CHAPTER.2

LITERATURE REVIEW

Coal was the main source of energy in the beginning of 20th century. Around the mid of 20th century petroleum oil became the main energy source as it a clean fuel and better control over its combustion can be exercised. However, the oil-stocks of 1970's have made many countries to think of moving back to coal. Coal is widespread geographically and its life is estimated for another 300years, where as oil and gas is estimated to be available until 2040. The present interest is to extend the life of the fossil fuels by augmenting to the fossil fuel with renewable energy sources, as they are sustainable energy sources. Biomass is one of the renewable energy sources playing an important role as a commercial energy source. The research addresses combustion of biomass like a liquid fuel in commercial applications. In the present chapter, a review has been made on methods of burning coal as a solid fuel and as slurry. Biomass is a solid fuel, based on the literature that is available for coal slurry; the research addresses the possibility of burning biomass as a slurry fuel to have the advantages of a liquid fuel.

2.1 Methods of coal burning

Various methods for coal-fired power generation are well established and widely used, and different steps are being taken to ensure that environmental requirements are satisfied. The methods include:

- Pulverised coal combustion (PCC) with sub critical steam driving a steam turbine, with various levels of flue gas cleaning to meet local requirements
- Cyclone fired wet bottom boilers with sub critical steam driving a steam turbine, again with various levels of flue gas cleaning to meet local requirements
- Stoker boilers for small applications, with sub critical steam, possibly using a low sulphur content coal

Various technologies are undergoing development in order to provide an environmentally satisfactory method of using coal as a basic fuel for power production in new plants. All methods, which meet environmental standards in different parts of the world, are included. Some are now commercially available, backed by large-scale operating experience in a number of countries. Others are still at the demonstration stage. These technologies include:

- PCC with supercritical steam driving a steam turbine, together with flue gas cleaning units
- Atmospheric pressure fluidized bed combustion (FBC) in both bubbling and circulating beds, mainly with subcritical steam turbines, together with sorbent injection for SO_2 reduction and particulates removal from flue gases
- Pressurized fluidized bed combustion (PFBC) currently uses bubbling bed boilers, in combined cycle with both a gas and steam turbine. Sorbent injection is used for SO_2 reduction and particulates removal from flue gases
- Integrated gasification combined cycle (IGCC), using different types of gasifier, and in combined cycle with both a gas and steam turbine. The syngas stream is cleaned of H_2S and particulates, before combustion and expansion of the combustion products through the turbine. Various levels of integration are used
- Combined heat and power (CHP) applications where the (subcritical) steam turbine is designed to produce both power and useful heat for process or district heating.

In the recent past, methods have been established to burn the coal as a slurry fuel.

2.2 Coal slurries

A colloidal fuel or slurry is obtained by dispersing the coal fines in fuel oil, and can be burnt like a liquid fuel with an added advantage. However, it is an added advantage of higher flame emissivity. Oil, water, methanol, or any two of them offer the liquid medium in the slurry. All technological problems appear to have been nearly solved for the coal- liquid mixtures (CLM) to be available alternative fuel to displace fuel oil and gas.

Coal-liquid Mixture (CLM) enables the direct substitution of oil partly or completely by coal as an energy source. The CLM slurry is pumpable and hence can be readily used in the conventional oil-fired combustors, such as utility boilers, industrial furnaces or an injection fuel in blast furnace with minimum hardware modifications. Consequently, there has been considerable interest in producing clean coal-derived liquid fuels, the major ones being solvent- refined coals (SRC). Coal–Oil Mixtures (COM) and Coal-Water Slurries (CWS). Coal-Water Slurries are also referred to as coal-water mixtures (CWM) and coal-water fuel (CWF) [21]. Both coal-oil mixtures and coal-water slurries are suitable for heating and steam raising applications generally as an alternative to heavy fuel oil although they can be used as engine fuels. Coarse coal (> 1mm diameter) water slurries can be used as feedstock for gasification plants and as a feedstock for direct coal injection into blast furnaces. The attraction of the coal–water slurry is its complete independence of an oil supply. Coal-oil mixtures are effectively a means of extending oil supplies.

Modern societies consume huge amounts of energy - to heat homes and offices, fuel transport systems, power industry and generate electricity. As our economy grows, so does our demand for energy. Today, most of this energy is produced using fossil fuels such as gas, oil, coal and peat. These are finite resources and eventually they will run out. Renewable energy resources, on the other hand, are constantly replenished through the cycles of nature. The sun, wind, running water, organic materials like wood and even wastes from domestic and agricultural activities are all potential sources of energy. Their supply will never be exhausted.

The rise in prices of the crude oil initially led to an alternative fuel like coal oil or coal-water fuel slurries, which can be used similar to oil. In addition, we have to depend on other countries for the fossil fuels like petroleum products. The alternative fuels at the same time has to satisfy the physical, thermal and chemical properties of the fossil fuels, which are very commonly used for heating, power-generation, transportation and at the same time it should be Eco-friendly(free of pollution). Burning fossil fuels releases vast quantities of carbon dioxide into the atmosphere. Under the Kyoto Protocol, countries have agreed to legally binding quotas to limit or reduce CO_2 emissions by the year 2010, other gases released in the fossil fuel combustion causes acid rain.

2.2.1 Coal-water slurry fuel system

The concept of using pulverized coal mixed with oil to form a fuel is not new, since the earliest patent on coal-oil mixtures is about 100 years old. Research into coal-oil mixture was undertaken in the 1940s. The development of coal-water slurries is more recent. Whilst some work on coal-water mixtures had been done during the 1960s in Germany and Russia, the major developments were made in Sweden, during the 1970s and considerable progress was made in developing and marketing a coal-water fuel [21]. The Swedish company Carbogel AB was set up to produce a coal-water fuel containing 70% by weight of coal for which the preparation process includes a froth floatation stage to reduce the ash and sulfur content of the coal so that coals of various ranks may be used in the preparation of the slurry. Over the last ten years, coal-water slurries have been tested in several industrial applications and pilot plants. Coal-water slurry combustion, and of slurry preparation, atomization and burning in industrial combustion systems such as furnaces and fluidized beds is considered [22, 23].

It is possible to mix high concentration of finely pulverized coal with water and a small amount of additive to produce a stable slurry fuel. The fuel can be burned similarly to heavy oil using combustion equipment of ordinary design. Research on the concept has been undergoing for sometime and involves development and combustion of slurries of coal in oil and in water [24]. The overall study consists of two steps. In step-I, highly loaded coal/oil, coal/oil/water and coal/water slurries are being formulated and tested for stability, rheological properties etc. In step-II, good candidate slurries chosen from step-I are burned in an experimental furnace and their combustion performance is evaluated.

2.2.2 Coal-slurry preparation

The key feature that has emerged from single slurry droplet combustion studies is that the small coal particles originally present in the slurry agglomerate together resulting in chars larger than if the original coal has been burned directly as a pulverized fuel. The implication is that a longer combustion time is required than for pulverized fuels or oil. Considerable attention therefore has been directed at both the slurry preparation technique and the atomization process in the hope that methods can be found in which the coal particles are thrown apart rather than sticking together during combustion. This might be achieved by using preheated slurries so that flash droplet vaporization occurs, or by using additives which disruptively break up the droplets (e.g. peroxides) or which lower the viscosity of the fluid so that, when atomized, very small droplets are produced. The viscosity of the fuel and the quality of atomization, which can be achieved, are therefore crucial factors.

The relative proportions of coal and water, which can form a suitable fuel, are restricted by several factors. The coal, being the only energy source in the slurry, must be present as a large fraction of the mixture, but, in the order to produce a practical flowing liquid fuel capable of being pumped and atomized, the presence of a certain amount of water is necessary. The highest coal loading, which will still provide slurry, which satisfies operational requirements, particularly flame stability criteria, appears to be less than 80%. For this reason, most of the coal-water slurries, which have been investigated so far, contain between 60% and 75% by means of pulverized coal.

Not only coal loading, but also the maximum size of the largest coal particles and the size distribution of the particles can affect both the rheology of the slurry and also the combustion efficiency. The ease of slurry handling gained by grinding the coal to a finer size are offset to a certain extent by the higher cost of pulverizing the coal. Therefore a typical coal-water slurry contains about 70% mass of coal pulverized to minus 200 mesh (i.e. 74 micrometer diameter) or finer, with about 1% by mass of an additive. Several different types of additives have been investigated. These are various dispersants, surfactants, neutralizers or stabilizers, which, when present in small concentrations, have the ability to alter the rheological properties of the liquid mixture and thus allow a larger coal loading. They also prevent the coal and water separating out by sedimentation during storage and prevent bacterial growth [24].

The first stage of CWS preparation is the grinding of the coal. Dry grinding has been used, with subsequent mixing with water, but in wet grinding, the water and the dispersant can be added before grinding begins, and beneficiation of the coal by froth floatation methods can be included in the grinding stage. If a flocculants is added to the water and ground coal mixture, the coal particles can be decanted. This process may be repeated if necessary and low ash levels of 2% and the removal of up to 95% of the sulfur may be achieved with some coals.

Traditionally, coal has been cleaned to remove sulfur and ash by washing with water and by density separation and flocculation processes. By incorporating the beneficiation process in with the wet grinding stage of slurry fuel preparation, the energy absorbing and thus costly dewatering stage necessary for dry coal cleaning, is no longer necessary and a reduction in the environmentally damaging sulfur and the boiler fouling ash is obtained.

Chemical Cleaning can also be incorporated to provide ultra- clean coal-water slurry suitable for burning in boilers without the need to add flue gas pollutant removal systems. Both one and two step grinding techniques in ball mills have been used to produce the required particle size distribution. The two-step process results in a bimodal particle size distribution. Clearly, a high proportion of fine-sized particles will maximize the coal loading without raising the viscosity to an unacceptably high level but the effect is offset by the increased cost of fine grinding the coal. The available surface area contributes to the rate of char combustion and slurry droplets containing many fine coal particles may agglomerate to a more closely filled and denser structure than those, which have a distribution of particle sizes. Combustion studies suggest that a CWS with coal particles with mass medium about 20-30 micrometer with about 70% or 80% less than 200 mesh yields higher combustion efficiency than do finer or coarser slurries.

2.2.3 Rheological properties of coal-slurries

Slurries with various rheological properties have been obtained depending on the additives used, many of which are proprietary substances. The first requirement is that the coal is well dispersed throughout the water. Coal surfaces have both hydrophobic and hydrophilic sites, the relative proportions varying from one coal to another. In water alone, parts of the surface of the coal articles can occur. Addition of a suitable surfactant decreases the surface tension of the fluid or modifies the electrostatic charges on the surface, the particles are rapidly wetted and the coal will be well dispersed in the liquid mixture. However, even in the presence of a suitable additive, the maximum coal loading which provides low viscosity slurry is about 60% with lignite's and (sub-bituminous coals) compared with about 75% for bituminous coals.

The other rheological property required is that the fuel should have a low viscosity, as a reduction in viscosity produces a more easily atomized fuel. Coal-water slurries are non-Newtonian fluids, that is the viscosity is not constant but a function of the applied stress and therefore a suitable additive should lower the viscosity at high shearing rates and improve the thermal stability. Various types of additives such as ionic salts, gums, clays and starches have been investigated. Ionic additives can have an adverse effect on combustion characteristics and non-ionic substances such as long chain fatty alcohol derivatives, especially polyethoxylates, are emerging as particularly suitable additives for coal-water slurries. The presence of about 1% of an additive has been found not to greatly affect combustion performance compared with combustion of similar slurry without the additive; carbon conversion efficiency was slightly lower with the additive present and atomization characteristics and the emission in the flue gases of particulates and SO_2, CO and NO_x were similar [24].

Adiga et. al. [25] have done a detailed investigation on Rheological properties of coal slurries in No. 2 oil and ethanol blends containing various amounts of water. Water is observed to increase the viscosity of the slurries. The slurries exhibited appreciable yield stress in the presence of water. The final subsided volume increased sharply and a decrease in critical solids concentration was observed up to 10% of water, above which these effects leveled off. In the case of low coal concentration slurries, the viscosity and the yield stress increased with increasing amounts of water and a critical shear rate was observed. Depending upon the concentration of water, the slurries behave as dilatant, Newtonian or pseudo plastic below the critical shear rate, in the lower shear rate region. In the higher shear rate region, they exhibited pseudo plastic behavior. The slurries containing higher coal loading were pseudo plastic at all water concentrations, and viscosity along with yield stress exhibited a maximum around 10% of water. The rheological parameters have been analysed using the power law and Bingham plastic models. The effect of water on the rheological characteristics has been explained on the basis of coal particle bridging by water, which is supported by the measured subsidence volumes and critical solids concentration.

2.2.4 Atomization of coal-water slurries

The atomization stage is a critical part, perhaps the most critical part of the process of coal-water slurry combustion, since both ignition delay and combustion efficiency are dependent upon the size of the droplets. Smaller droplets result in smaller agglomerates, and present a larger surface area for a given quantity of fuel than do larger droplets. This increase in surface area increases the ignition delay time, and facilitating more rapid char burnout. A more stable flame is possible with finer sprays, since fuel ignition would take place nearer the burner. It is probable that in order to achieve the desired carbon conversion efficiency it is only necessary to limit the number of droplets, which have a diameter greater than 300micrometer.

The fineness of the droplet size distribution depends on atomizer design, the properties of the fuel, its viscosity, temperature, and the mass flow rate of the atomising medium, which is either air or steam, usually preheated. The smaller the outlet orifice the finer the spray produced (although this is limited by the larger coal particle sizes), but also the greater the shear rate on the fuel necessary to achieve a particular firing rate; however some CWS fuels have a tendency to dilatancy, or an increase in viscosity at high shear rates. There appears to be no special relationship between the measured viscosity of the fuel and atomization quality, since each CWS fuel has a different relationship between concentration and temperature with viscosity. In some slurry viscosity decreases with temperature, while in others it increases.

However, it has been generally shown that fuel and atomizing medium preheat, and the dilution of the fuel with water, can improve atomization quality. However, atomization of slurries is a much more random and irregular process than the atomization of liquids. Sheet break-up results in large segments rather than well-ordered ligaments.

Atomizers designed for use with heavy fuel oils, are not automatically suitable for use with CWS fuels. Since, in regions where high velocities and change in flow directions exists, there is a tendency for the surfaces to experience erosion after only moderate use due to the abrasiveness of the coal, and there may also be clogging of any narrow passages by coal particles.

Erosion can be reduced by using lower slurry velocities or by replacing parts prone to erosion with harder materials such as ceramics. Several different types of atomizer suitable for use with coal-water slurries have been designed and tested. The initial contact of these flows occurs inside the nozzle and the fuel leaves the nozzle in an annular gap near the circumference of the tip. Spinning cup atomizers, of the type used for conventional fuel oil mixtures have also been used successfully. However, no single design of atomizer has yet appeared as a superior one for coal-water liquids [25].

2.2.5 Combustion mechanism of pulverised coal-water slurry

Coal is a heterogeneous mixture of organic compounds consisting mostly of C, H, O, N and S and other inorganic elements (ash). About two-thirds of the carbon and one-fifth of the hydrogen from condensed aromatic clusters consisting of one to three rings while the remaining carbon and hydrogen are likely in alkyl side chains. Coal probably has a polymeric structure consisting of monomer units, that is, the aromatic clusters with functional group side chains, held together by methylene and ether bridges. As the coal is heated, the weak bridges break to yield the monomers, which form the liquid tars, and some short side chains are split off to yield volatile gases such as methane, ethane and carbon monoxide [26].

At higher temperatures the liquid tars vaporise, possibly undergoing thermal cracking to lighter molecular weight hydrocarbons in the vapor phase and these products with the volatile gases ignite and burn with a diffusion flame surrounding the coal. As the coal devolatilises it forms a carbonaceous skeletal structure, or char, which subsequently undergoes surface combustion with the surrounding gases, leaving the mineral matter as an ash.

The combustion mechanisms of oil and coal-water slurry are similar, and in the following, the exact mechanism of coal-water slurry combustion is discussed further. Experimental studies, in which a single droplet of a coal-water slurry undergoing combustion is suspended by a supporting fiber or thermocouple so that it can be observed and monitored continuously over the droplet lifetime, have revealed details of the mechanism of slurry combustion.

These mechanisms in general also apply to large-scale practical situations in boilers and furnaces if the rate of heating is of the same order of magnitude. Clearly, there will be some differences between the two systems because of different conditions and the influence of droplet interactions but the general features have been found to be comparable. Therefore the single droplet studies have been used to provide much useful information about the behavior of various types of coal-water slurry as it has in the case of oil combustion.

Essentially a small droplet of slurry with a diameter of about 1mm or smaller is suspended on a fine fiber (of silica or a thermocouple), and heated by a furnace or laser. In order to monitor temperature changes, the droplet is suspended on the bead of a thermocouple and placed in the furnace maintained at a known temperature. The output from a photo-diode can be used to indicate the instant at which ignition occurs and the behavior of the droplet mass decreases with time can be obtained by heating in a furnace at known temperature a slurry droplet suspended on a quartz fiber attached to the arm of a microbalance [25]. Another technique is to allow a droplet, after ignition by a pilot flame, to fall through a vertical furnace and to observe through a vertical furnace and to observe through viewing ports the droplet as it falls. Alternatively, a single droplet may be injected in a flame and allowed to travel along with the hot gases.

In large-scale spray flame situations, a range of droplet sizes is present and the size and density of a droplet may affect its velocity and flow pattern within the combustion chamber. Clearly, the course of combustion may vary from one droplet to another depending on the size and position in the chamber, but the mechanism will essentially be similar to that observed for a single droplet.

2.2.6 Theoretical modeling of coal-water slurry combustion

As in the case of oil, droplet combustion a considerable amount of research has taken place to understand and theoretically model the chemical and physical processes of both the pyrolysis of coal in an inert atmosphere and gasification of coal char. If one considers a single coal-water slurry droplet entering a combustion chamber it heats up and vaporization of the slurry water takes place; this water contains a small amount of additive and possibly a few soluble components leached from the coal itself (which are assumed to have only a minor effect on the vaporization of the water and subsequent reactions).

The coal particles dry and agglomerate due to the surface tension effects and due to the stickiness of tar liquids, which are formed as the coal heats up to its plastic stage (600-850K). Non- caking coals have also been found to agglomerate to a certain extent. The effect of agglomerization as far as devolatilization of char combustion is concerned is to decrease the surface area available. Photographic studies on coal pyrolysis in an inert atmosphere have been shown that vapors and tar liquids can jet out of the walls of the coal particle and considerably increase the surface area by forming holes and craters; these jets can also cause the droplet to rotate. In the early stages of char combustion, depending on the initial droplet size, and while the agglomerated mass is large (i.e. > 100micrometer approximately) the rate of reactions will be the rate of diffusion by the gases. But as the mass burns away and the temperature increases, the reactions will proceed more rapidly and be chemically controlled.

The limitation of such models are due to a difficulty in predicting the surface area of the char accurately, due to both the random nature of the size and position of blowholes and to the available surface area due to the packing of the original coal particles, which is dependent on the size distribution of the original coal particles.

Another severe limitation, which occurs in all coal modeling, is that in order to simplify the mathematical solution of the set of equations derived to describe the physical and chemical mechanisms, the droplets and particles are assumed to be spherical, which is often an adequate approximation to the actual shape but not in all instances. Photographic evidence shows that char formed after coal devolatilization are in fact cenospheres and these are difficult to model accurately because of their random shape and lack of sphericity [26].

John P. Dooher [27] have presented herein the results of an investigation of theoretical models of atomization, which can be used for a phenomenological theory for coal slurry atomization. This investigation was conducted in several phases. The primary phase involved an intensive analysis of the rheological properties of coal slurry fuels. Analysis was performed including viscosity as a function of shear rate, the extensional viscosity, and the viscoelastic properties. During the second phase, atomization was studied over a sufficiently wide range of rheological properties. During this phase, simulated fluids as well as coal slurries were studied. The simulated fluids consisted of corn syrup solutions. In some blends, xanthan gum was used and both Newtonian and non-Newtonian simulated fluids were studied. The atomization properties of both coal slurries and simulated fluids were determined under a variety of spray conditions using a Malvern size analyzer. Three basic theoretical models were analyzed to determine the best approach to characterizing these complex fluids. The first model was a linearised Navier-Stokes equation for a cylindrical fluid stream breaking up into drops under the impact of a high-velocity air stream. The second model was a collisional model, by which the collision of the air stream and the fluid stream produced droplets. Energy and momentum conservation were used to derive relationships between the drop size and the relevant physical parameters. A third model studied was a statistical model using a Boltzmann-type transport equation for the propagation of drops under the interactions of a high-velocity airstream. The effects of drop coalescence and breakup are incorporated into this model. By comparing the various theoretical models with the atomization data and the rheological data, a phenomenological model was constructed that correctly predicted the trends of the Sauter mean diameter as a function of air/fuel ratio, rheological properties, and spray angle. An effective viscosity was defined that included the effects of viscous losses, extensional properties, and viscoelastic properties. In addition, the effects of yield point were incorporated and shown to be important in predicting atomization properties.

2.2.7 Coal-water slurry spray flames

The main stages occurring in a general liquid fuel spray combustion chamber are similar to those for oil [26]. The fuel is transported from the storage tank (which is fitted with a stirrer) by means of a pumping system and after mixing with air passes through an atomizer. The fuel leaves the atomizer in the form of small droplets which are injected into the combustion chamber where they are burned. The mixing of fuel and oxidant depends on the spatial distribution and momentum of the gas phase flow, as well as the combustion chamber geometry. The fuel vaporises and burns followed by mixing and re-circulation of the reacting hot gases. In the case where the liquid fuel is coal-water slurry the vaporizations step is replaced by vaporizations of the water, followed by the devolatilisation and agglomeration of the particles, and the droplet burning replaced by the char combustion stage.

2.2.8 Fluidised bed combustion of coal-water slurries

In a fluidized bed combustor, a flow of gas such as air through a bed of hot fine particles suspended and thus ‘fluidized’ [26]. The fuel to be burned is injected into the bed with the fluidising air and becomes rapidly heated due to large surface contact area between the fuel particles or droplets and the bed particles.

The combustion of coal-water slurries in fluidised bed combustors appears to be a very promising technique for a number of reasons. When burning dry pulverised coals in a fluidised bed, there can be problems with feeding the crushed coal into the bed, particularly with pressurised fluidised beds, and with elutriation of the fine particles. By comparison, the injection of the liquid slurry can be easily controlled and varied with changes in the firing rate and as agglomeration of the coal particles occurs as the slurry liquid evaporates, there are fewer problems with elutriation.

The extent of agglomeration depends on the type of coal used in slurry preparation and there is a tendency for some of the agglomerated particles to sink to the bottom of the bed material, which is denser than coal is used. If the fluidizing air velocity is high enough then the mixing of materials in the bed is good. Slurries with coal particle size distributions, which are coarser than that necessary for slurries used in other types of combustors, is burnt successfully in fluidized beds. Combustion efficiencies of 99% have been obtained with particle size distributions in which the largest diameter is 3mm and with coals with bed ash content. Sulfur retention and NO_x emission levels are as good as when dry pulverised coal is burnt. As beneficiation and fine grinding are unnecessary in the preparation of CWS liquids for fluidised bed combustors and with the improvement in fuel feeding over dry coal, coal-water mixtures are ideal for this method of combustion.

The Pennsylvania State University is conducting super clean coal- water slurry (SCCWS) program for the United States Department of Energy (DOE) and the Commonwealth of Pennsylvania with the objective of determining the capability of effectively firing SCCWS in an industrial boiler designed for oil [28]. Penn State has entered into a cooperative agreement with DOE to determine is SCCWS (a fuel containing coal with less than 3.0% ash and 0.9% sulfur) can effectively be burned in a oil-designed industrial boiler without adverse impact on boiler rating, maintainability, reliability, and availability. The project will provide information on the design of new systems specifically configured to fire these clean coal-based fuels. The project consists of three phases: (1) design, permitting, and test planning, (2) construction and start up and (3) demonstration and evaluation. The boiler testing will determine if the SCCWS combustion characteristics, heat release rate, fouling and slagging behavior, corrosion and erosion limits, and fuel transport, storage, and handling characteristics can be accommodated in an oil-designed boiler system. In addition, the proof-of-concept demonstration will generate data to determine how the properties of SCCWS and its parent coal affect boiler performance. Economic factors associated with retrofitting and operating boilers will be identified to assess the viability of future oil-to-coal retrofits.

Ryo Moriyama et. al. [29] has done an investigation into a new brown coal utilization process, combining the techniques of coal/water slurry (CWS) production and CWS in-line vaporization. In the process, brown coal was converted to CWS with high-pressure kneader under mechanical shear stress and moderate heating. Water in the CWS was vaporized with a special designed pre-heater, termed an in-line vaporizer, processing about 2.0 t/day (dry coal basis). Indonesian brown coal containing 22% moisture and Australian brown coal containing 59% moisture was successfully converted to CWS. The Australian brown coal CWS was pre-heated with the in-line vaporizer. The CWS converted has a coal/steam mixture without plugging of the feed tube and directly burned in a combustion furnace.

2.2.9 Coal-oil mixtures

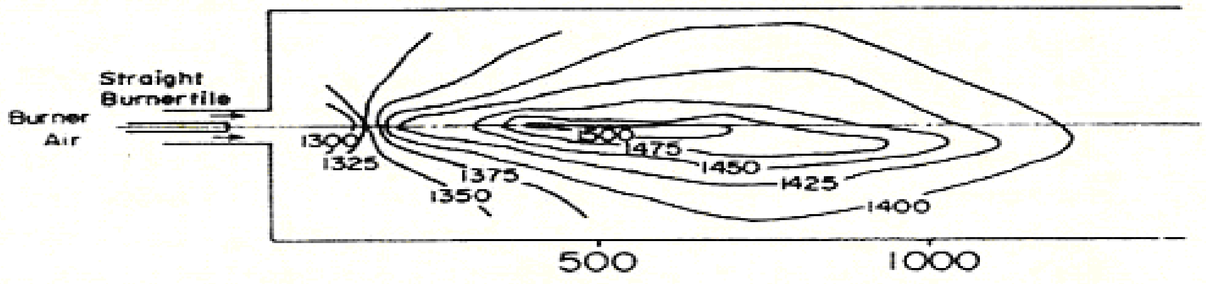
This technology by which mixtures of fine coal particles are dispersed in oil was developed in 1879 and there is an extensive literature [30]. Such mixtures have various terms including colloidal fuel. More recently, the term coal-oil mixture has been used. Whilst the fuel has been available for this long period, it has not been widely adopted for two reasons; firstly, it is not as easy to handle like coal or oil alone, secondly the grinding process and stabilisation process make it more expensive although, from an environmental viewpoint, the coal does become beneficiated during processing.

Although there is now a very considerable literature on COM to all intents and purposes, has been replaced by coal-water slurries, which are more economical. There are still some problems relating to handling, atomization and combustion. Consequently, COM is only dealt here in brief.

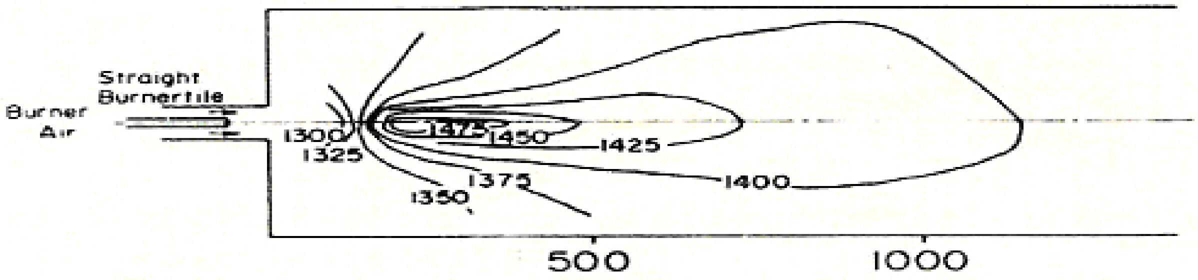
A suspension of powdered coal in oil is usually unstable and coal particles will deposit unless the mixture is ‘stabilised’. Coal-oil mixtures thus involve a complex formulation consisting of 50 wt % coal, 45 wt % oil and a cocktail of stabilising agents, particularly an electrolyte to provide a double layer of ionic charge around each coal particle to assist in stabilisation. Choice of oil and fitness of the coal particles are also important parameters.

Tomio Suzuki et. al. [31] has carried out work on pulverised coal-heavy oil combustion in high temperature furnaces for steel making. The combustion efficiency is measured in a furnace with 1m diameter and 4m long, a furnace temperature of 1300^0C and a combustion air temperature of $150\text{-}450^0$C. COM and pulverised coal combustion efficiency was determined and it is established that the efficiency of coal is lower than that of other fuels by 20-50%. An increase of the combustion air temperature, velocity and by changing the fuel injection position, promote the proper mixing and improve the combustion efficiency. The contours of the temperature distribution for various combinations of the fuel are shown in Figure 2.1.

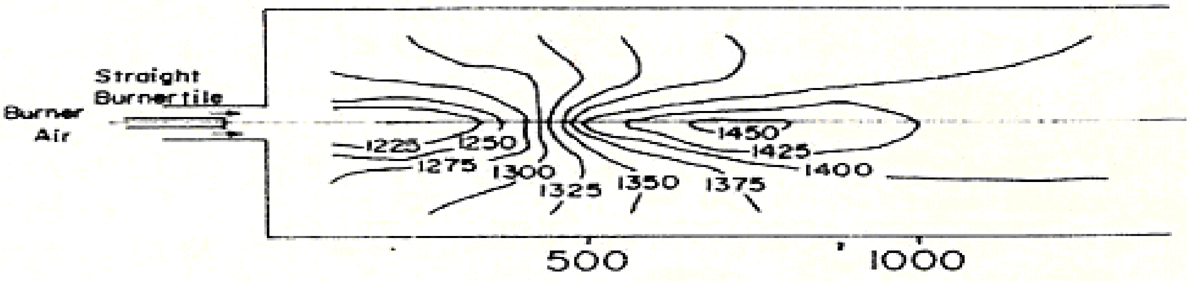
The COM produced is thixotropic in a similar manner to coal-water slurries. Problems can arise in the handling system from erosion because of the coal particles and this can seriously affect pumps and atomisers again increasing the cost. The thixotropic and generally more viscous nature of the mixture causes Plugging of filters. Further problems arise during combustion. Although the droplets produced during atomization are comparable, to that produced by conventional oil atomisers. Although the coal particles themselves are quite fine, it has been shown that during the combustion process, the time for combustion is longer than either for the oil droplets or the coal particles alone. The reason for this is that as droplets [32] become heated on entering the furnace, the oil component evaporates and the coal particles agglomerate.



(i) C – Heavy Oil (No.6)



(ii) COM (Coal 30 %)



(iii) Pulverized Coal

Figure 2.1 Isotherms in the Furnace for Heavy oil, COM and Pulverised coal [31]

The evaporative stage involves some disruptive ejection of material because as the surface temperature of the COM droplet increases the coal particles themselves pyrolyse (devolatilisation). However, the pyrolysing coal particles become coated with a viscous tar, which links the coal particles, by tar bridges. The agglomerated particles thus have sizes considerably larger than the original with a consequential increase in burnout time. Consequently, combustion equipment has to be derated. An attempt to overcome this has involved emulsifying water with coal-oil mixtures (40 wt % coal, 40 wt %oil, and 10-wt % water) with the intention of causing disruptive combustion.

Hori et.al. [33]. have carried out an investigation into ‘Coal slurry fuel as alternate petroleum fuel for IC engines’ has attracted interest recently. However, the compound fuel showed complicated fluidities and combustion characteristics, which were not seen in the single fuel. To use coal slurry fuel for heat engines, an experimental study to make clear the fundamental properties, that is, behaviors of evaporation, ignition, combustion on hot surface of CWM (coal water mixture), CMW (coal methanol mixture) and COM (coal oil mixture) fuels is described. Moreover, the effects of surfactants on them are shown. In experimental apparatus, SUS304 is used as hot surface, Fe as core for heat conduction

Brehob et. al. [34] have done an experimental investigation on Compression ignition characteristics of three coal slurry fuels and are compared with the diesel reference fuel in a diesel engine simulator. The three slurries are 45 wt % coals (5 micrometers mean diameter) in water, diesel No. 2, and methanol carriers. Each experiment is a single, isolated combustion event. Heat transfer losses to the cold walls and mass losses past the square piston seals reduce the compressed gas temperature. Air preheating to 400/sup 0/K for the diesel, to 450/sup 0/K for the coal/methanol and coal diesel, and to 525/sup 0/K for the coal/water fuels assures ignition. Activation temperatures (E/R) of 2330/sup 0/K, 2270/sup 0/K, 2670/sup 0/K, and 3430/sup 0/K for diesel fuel, coal/diesel, coal/methanol, and coal/water slurry, respectively, are found from ignition delay measurements.

2.2.10 Combustion of coal-methanol slurries

The combustion of CMS is a sequential two staged process [35], consisting of gas-phase combustion followed by solid-phase combustion. Scattering of pulverized coal takes place during the gas phase combustion. The effect of ambient air temperature on the apparent overall burning rate coefficient of CMS droplets is small. The apparent solid-phase combustion time of CMS droplets is shorter than that of COM, TCNM, etc., under the same conditions.

Currently, India is paying more than 50% of its import bill for oil alone. But, it has rich coal reserves as well a large biomass resource. So one can think of utilizing the rich coal reserves as well some of the biomass, which can be burnt in the slurry form either blending with oil or water, through the conversion may result in derating of oil fired furnaces and utility boilers.

The study on coal slurries shows clearly that the slurry fuels play a very important role in the future to come. In India, coal is available in abundance in some states; the coal must have low ash content to prepare the slurry to avoid erosion and to reduce the cost of combustion equipment required for ash removal system. The calorific values of most of the Indian coals available were low, which results in low energy density. The co-efficient of burning rate in turn depends on the solid carbonaceous residue. The agglomerate combustion mainly depends on the solid carbonaceous residue. These factors influence on droplet size and residence time inside the combustor. On the other hand biomass is available in all the other regions of India, with the ash content as low as 2-3% and volatile matter 78-80%. Obviously, they must show better combustion performance compared to coal. Since coal requires large heating time for agglomerate heating with LDO and high speed diesel. Many of the bio-mass products have very high volatile content and the slurries formed out of them almost behave like liquid fuels. They can form better slurry fuels with any of the carrier liquids like LDO and High speed diesel oil. These slurries will make a better fuel compared to coal slurries in comparison with Combustion, Emission and Cost of the slurry fuel as. To establish biomass slurry as a fuel for Furnace, Boilers and I.C. Engine, the study on Biomass based slurry fuel has been undertaken.

2.3 Bio-mass based fuel slurries

Historical recognition of the value of biomass is clear. But why in this technological age why are we interested in biomass again. This means environmental and economic concerns are making this ancient resource a potential renewable resource for a sustainable society. Burning new biomass contributes no new carbon dioxide to the atmosphere, because if we replant harvested biomass, carbon dioxide is returned to the cycle for new growth [36].

2.3.1 Biomass combustion methods

Bioconversion and thermal conversion techniques for transforming biomass into fuels are currently under development [37]. These new technologies will reduce our reliance on oil and coal with no net addition of carbon dioxide to the atmosphere. New thermal conversion techniques coupled with chemical catalysis are making it possible to exploit the previously discarded lignin fraction by converting it into valuable chemicals that we now get from non-renewable fossil sources.

The energy storage aspect of biomass and biofuels is of fundamental importance. The processes to be incorporated in conversion of biomass as fuel must have the aim of producing fuels at economical prices, for a full range of end uses. The net energy density available in combustion ranges from 10MJ/kg to about 40MJ/kg. Biomass is however mostly carbohydrate material with a heat of combustion of about 20MJ/kg dry matter. The details of heat of combustion of various biomass are given in Table 2.1

The thermo-chemical conversion of fuels into heat and power involves one of two processes, direct combustion or pyrolysis, for which any sufficiently dry combustible material can be used. Combustion entails direct burning to produce heat. In power generation, this heat is applied to boilers, which produce steam to drive turbines. For coal and biomass, combustion technology is well understood, fully commercial and widely used for district heating and power production. However, technical inefficiencies and pollution related problems have prompted new research into system optimization. Pyrolysis occurs when organic material is decomposed at high temperatures in an anaerobic reactor. Pyrolytic processes include slow, conventional and flash heating rates. These produce varying proportions of solid char, oil and gas. The oil and liquid alcohol created by liquefaction can be used as energy fuels for transport, while solid char can be mixed with water to make a slurry fuel for electric turbines. Problems associated with pyrolysis processes include unavoidable heat transfer into the feedstock, inadequate control of pyrolytic processes for optimizing product mixtures, and inefficient methods for separating the products, particularly the liquid fraction. Pyrolytic gasification is the most widely accepted and commercialized pyrolysis process. The development of gasification technology began about 150 years ago [38] and in power generation, gas or steam turbines can be used. Research and development projects now focus on optimizing issues such as emissions control, fuel mixing and fuel drying.

Joraphur and Rajvanshi [40] report the commercial scale (1080 MJ/hr) development of a low-density biomass gasification system for thermal applications and have been tested for more than 700 hours under laboratory conditions; subsequently they have used it in a metallurgical company where it was retrofitted to a specialty ceramic baking LDO fired furnace. The furnace was operated exclusively on the gasification system and the product quality was on par with, it not better than that obtained during LDO fired operation.

TABLE 2.1 Calorific values of various fuels [39]

Fuel	Gross calorific value MJ/kg
Fossil Fuels	
Methane	55
Petrol	47
Kerosene	46
Diesoline	46
Crude oil	44
Coal	27
Agricultural crops	
Wood	
Green	8
Seasonal	13
Oven dry	16
Vegetation	15
Crop Residue	
Rice Husk	
Bagasse	12-15
Cow Dung	
Peat	
Secondary Biofuels (byproducts)	
Ethanol	30
Methanol	23
Bio-gas	28
Producer gas	5-10
Charcoal	
Solid pieces	32
Powder	32
Coconut oil	39
Cocohol	39

2.4 Recent international developments

Nussbaumer [41] deals with combustion of biomass and suggests primary measures for emission reductions. European support for bioenergy research comes from the European Union's framework programme for research and technological development. Support is also available to developing countries, but funds must come from the appropriate programmes Regional electricity companies (RECs) must purchase a portion of their energy from renewable sources. RECs must pay more for this 'green' electricity than for that from fossil fuels, and these prices will change as the market develops.

Yorkshire Environmental's project ARBRE (arable biomass renewable energy) is developing a full scale biomass gasification system [42]. The project has received funding from the European Commission's THERMIE programme and has been included in the UK's NFFO list of renewable energy producers. Willows and aspen poplars are to be own on 2000ha of land, some of which is registered as set-aside land. The MAFF subsidies woodland establishment on such set-aside land using funds from the Farm Woodland Premium Scheme as well as the WGS. The technology employed is a biomass integrated gasification combined-cycle (BIGCC) system, which uses both gas and steam turbines for power production. The advantages are many: the unit capital cost of gas turbines is relatively low, and the complete BIGCC system offers higher electrical efficiency and reduced atmospheric emissions.

Power Generation, a UK power producer [43], has collaborated with International Combustion Limited to estimate the cost of biomass co-firing. This was done using the coal quality impact model, a PC-based computer model that accounts for varying coal qualities and associated impacts on power plant operations. The model is also applied to co-firing scenarios. Results show that costs of wood co-firing are significant due to expenses associated with wood supply, transport, handling and preparation before conversion. Research dealing with supply, transport and processing is therefore necessary. The performance of bioenergy technologies depends on local circumstances such as power production requirements, availability of fuel and delivered costs, as well as the chemical and physical characteristics of the fuel.

Shell International's Brazilian Biomass Power Project is a concrete example of how these local circumstances can make some systems more useful than others [44]. This project was aimed at implementing gasification technology in international energy industries. Collaborators included organisations representing biomass supply as well as electricity production and distribution. They are currently building a 30MW commercial-scale demonstration biomass integrated gasification gas turbine (BIGGT) system. The availability and accessibility of biomass in the area allow this larger system. At 30MW, a circulating fluidised bed gasifier becomes cost effective and, with a combined cycle power plant, is believed to be preferable to the less efficient and more costly conventional steam cycles. This project is valuable in that it has deployed a full-scale system, which, if successful, will contribute to the development of a healthy market.

Research into the reduction of atmospheric emissions has come a long way in recent years. Although emissions are already substantially lower than with fossil fuels, efforts to reduce them further have been successful. Assuming complete regeneration, biomass is a CO_2 neutral fuel, only releasing what it takes up in growth. Klaus Hein and Hartmut Spliethoff of the University of Stuttgart have assessed pulverized fuel combustion and fluidised bed combustion using combinations of combustion systems, fuel alterations, added biogenic fuels combined in varying ratios and feeding systems.

Within the EU clean coal technology programme (APAS), tests with biomass and coal revealed the effects of CO-combustion on emissions. Biomass additions decrease SO_2 emissions in proportion to the sulphur content of the mixtures [45]. Further, SO_2 can be partly captured in the ash by alkaline-earth fractions of the bio-mass ash. Due to higher levels of sulphur in sewage sludge, however, SO_2 emissions increase with such additions. In addition, the high volatile content of biomass makes it possible to achieve low NOx emissions by air staging and reburning [46].

The International Flame Research Foundation at IJmuiden, in the Netherlands, has analysed and interpreted results from coal and sewage sludge co-firing [47]. Fuel type, volatile matter content, burner types and operation all influence NOx emissions and flame characteristics. NOx emission is also substantially reduced when fuel injection is optimised using air and fuel staging. However, the high ash content of sewage sludge can produce operational difficulties caused by slagging and fouling. The University of Leeds is researching the formation and destruction of dioxin and furan species in combustion systems [48]. Results to date have shown that fuel composition and combustion/cooling temperatures are crucial determining factors in formation. Low chlorine content, high oxygen concentrations and post-combustion temperatures above 300°C decompose a large portion of dioxin and furan isomers.

China produces 600Mt/a of straw from crops such as corn and wheat [49]. This has sparked significant interest in using these crop straws as fuels for bioenergy production. The Energy Research Institute of Shandong Academy of Sciences in Jinan has developed a crop straw gasification unit that improves crop use efficiency and also increases the fuel efficiency of cooking methods in nearby villages.

Broek et. al. [50] gives the state of the art of biomass combustion power generation technologies with a capacity of power generation more than 10 MW. Biomass combustion technologies have been compared on a qualitative basis and a selection of individual biomass combustion power plant has been compared on a quantitative basis. Fluidised bed systems are found to have relatively high efficiencies and also flexible with regard to fuel properties.

Mukunda et. al. [51] gives classification of biomass in terms of woody and powdery (pulverized) forms along with comparison of its energetic of fossil fuels. They have also discussed the technologies involved namely gasified combustor, gasified-engine alternator combination, for generation of heat and electricity, are discussed for both woody biomass and powdery biomass in some detail.

Laux et.al. [52] presents the design considerations when biomass or opportunity fuels are to be fired in wall fired and tangentially fired pulverized coal boilers, installing a burner specifically designed for firing two or more dissimilar fuels, can optimize co-firing. Recent demonstrations of biomass co-firing have shown that biofuels are a viable option for cost effective reduction of green house gases and other emissions on coal fired utility boilers. Biofuels show significant differences in volatility, reactivity and ash characteristics when compared to coals. These differences need to be considered when compared when a bio-fuel firing system is to be integrated into the existing low NOx firing system.

Kostamo [53] discusses co firing tests with coarse sawdust and polish coal at FORTUM'S Nantali-3 power plant (315 MW fuel). During the actual cofiring test the proportion of sawdust in the blend varied between 4 and 10 percent by mass (1 to 4 percent from the fuel input). The cofiring tests were successful in many ways, but the behavior of the coal mills caused some problems, and therefore the simultaneous feed might not be the solution in long-term use.

Senelwa and Sims [54] have analyzed fuel characteristics of biomass from 12 tree species grown under a short rotation forestry regime, higher heating value ranged from 19.6-20.5 MJ/kg for wood, 17.4-20.6 MJ/kg for bark and 19.5-24.1 MJ/kg for leaves. Wood basic density ranged from 250-500kg/m^3, ash content 0.7-1.4 %, volatile matter content 91.5-95.1%, fixed carbon content 4.2-7.3% and extractive content 3.3- 11.9%.

Babu and Chaurasia [55] have carried out the simulation of Pyrolysis process by which a biomass feedstock is thermally degraded in the absence of air/oxygen. It is used for the production of solid (charcoal), liquid (tar and other organics) and gaseous products. The work involves the estimation of optimum parameters in the pyrolysis of biomass for both non-isothermal and isothermal conditions. The modeling equations are solved numerically, using the fourth order Runge-Kutta method over a wide range of heating rates and temperatures. The simulated results are compared with those reported in the literature and found to be in good agreement quantitatively in the range of operating conditions covered, but some very interesting trends are found, especially with respect to the effect of net heating rate and temperature on final pyrolysis time. The final pyrolysis time first decreases at lower values of net heating rate or temperature and then decreases as net heating rate or temperature is further increased, providing an optimum value of net heating rate or temperature at which final pyrolysis time is minimum. This interesting phenomenon, which was not reported by investigators earlier, is well explained by means of the pyrolysis kinetics.

Babu and Ramkrishna [55a] have made a study on the optimum utilization of waste oil for improved thermal efficiency of bagasse. A combination of bagasse and waste oil, which is usually recovered in the industry from the effluent drains or at the machinery sections, is studied to generate a high CV fuel relative to the low CV bagasse fuel alone. The associated technical aspects such as excess steam generation, stack height requirements, economical returns due to the fuel mix are theoretically assessed in this study.

Chaurasia and Babu [55b] have made a study on the product yield, density, heating conditions and conversion on pyrolysis of biomass. Biomass is an attractive option as a fuel for power generation. The pyrolysis process consists of the thermal degradation of biomass feedstock in the absence of oxygen/air. In the present study, the simultaneous chemical kinetics and heat transfer model is used to predict the effects of heating conditions, density of biomass, product yields and conversion on pyrolysis of biomass fuels. Finite difference pure implicit scheme utilizing Tri-Diagonal matrix algorithm is employed for solving heat transfer model equation.

Babu and Chaurasia [55c] have done a study on optimization of pyrolysis using differential evolution approach. Differential evolution is an evolutionary optimization technique, which is exceptionally simple, significantly faster and robust at numerical optimization and is more likely to find a function’s true global optimum. Pyrolysis of biomass is an important and promising chemical process in the area of renewable energy sources. In the present study, the modeling and simulation of the above process is coupled with the optimization of a nonlinear function using differential evolution. The objective in this problem is to estimate optimal time of pyrolysis and heating rate under the restriction on concentration of biomass. It serves as an input to the coupled ordinary differential equations to find the optimum values of volatiles and char using runge-kutta fourth order method.

Babu and Chaurasia [55d] have done a study on the pyrolysis of shrinking cylindrical biomass pellet. In this study, the impact of shrinkage on pyrolysis of biomass particles is studied employing a kinetic model coupled with heat transfer model using a practically significant kinetic scheme consisting of physically measurable parameters. The numerical model is used to examine the impact of shrinkage on temperature profile and pyrolysis conversion time considering cylindrical geometry. Finite difference pure implicit scheme is utilized for solving heat transfer model equations. The impact of shrinkage reflects on pyrolysis in several ways. The temperature profile of the particle changes due to increased density and decreased distance across the pyrolysis region. The magnitude of the temperature gradient is more for shrinking particle as compared to non-shrinking particle. Shrinkage affects the pyrolysis time in thermally thick regime. Pyrolysis conversion process is fast for shrinking particle as compared to non-shrinking particle.

Wahlund et. al. [56] have made a study that emissions of greenhouse gases such as CO_2, need to be greatly reduced to avoid the risk of a harmful climate change. One powerful way to mitigate emissions is to switch fuels from the fossil fuels to renewable energy, such as biomass. In this paper, we systematically investigate several bioenergy processing options, quantify the reduction rate and calculate the specific cost of reduction. This paper addresses the issue of which option Sweden should concentrate on to achieve the largest and most long-term sustainable CO_2 reduction would be achieved by refining the woody biomass to fuel pellets for coal substitution, which have been done in Sweden. Refining to motor fuels, such as methanol, DME and Ethanol, gives only half of the reduction into pellets enables transportation over long distances and seasonal storage, which is crucial for further utilization of the woody biomass potential.

Enden and Lora [57] have designed an approach for a biomass fluidized bed gasifier using the comprehensive simulator for fluidized bed equipment (CSFB) is proposed. Performance parameters such as air factor, feeding point position and bed height are determined looking for maximum gasifier efficiency and gas heating value and minimum tar content in the gas. Other parameters optimized by using the CSFB software are the pressure drop, the bubble diameter and the gas velocities in the bed.

Lundgren et. al.[58] have done an experimental study in a newly developed furnace suitable for small district heating networks. The fuel is wood-chips with moisture content in the range of 30-58%. One of the unique features of this new furnace is the broad thermal output span, which makes it possible to run the boiler down to 10% of maximum heat load, with maintained low emissions of CO and total hydrocarbons. The aim of the study has been to evaluate the performance of the combustion chamber during steady-state operation in the complete thermal output range. The experiments show very good results over the entire thermal output range. In the range 60Kw up to 500Kw, the average CO content in the stack gases is typically below 25mg Nm^{-3} (20 ppm) and the NO_x concentration below 195 mg Nm^{-3} during steady state conditions. At lower thermal outputs, the average CO content is below 105 mg Nm^{-3} (84ppm).

Mukhopadhyay [59] has done an evaluation on socio economic and environmental impact of the Biomass Gasification based power plant (BGBPP) in Chottomollakhali islands of Sunderbans set up by West Bengal Renewable Energy Development Authority (WBREDA). Four villages of Chottomollakhali Island are benefited with electricity from the power plant, which serves 225 consumers comprising household, commercial and industrial sectors. A simple cost benefit analysis has been used to estimate the impact of BGBPP. The findings of the study indicate that BGBPP has made a very positive impact on the life of the villagers of Chottomollakhali Island. This has led to an increase in economic activities and more profitable turnover for the commercial consumers, improves quality of life for the household sector. All of them showed willingness to pay a higher price to get 24h of power supply. From the cost benefit analysis it has been found that, the benefit cost ratio, internal rate of return and pay back period of the project are 1.68, 19% and 7 years respectively. But environmental awareness is very poor among the villagers.

Neidel et. al. [60] has done research on Mix Combustion of Coal/Biomass in Fluidised Beds, where fluidized beds are qualified for mix combustion of coal/Biomass. The fluidized beds are qualified for mix combustion of coal/biomass. The research group of the authors realized experimental investigations of mix combustion coal/biomass in stationary and circulating fluidized beds. The reason for using biomass as an energy source is specially the CO_2 –neutrality of their burning. This is very important for the stability of the earth climate.

Andries et. al. [61] has done a study on co-combustion of Biomass and coal in a pressurized Bubbling Fluidised Bed combustor. The objective of the study is to decrease the CO_2 concentration in the atmosphere and the possible negative effect on the global climate requires immediate action. Therefore, apart from a more economical use of fossil fuels, the application of regenerative sources for energy conversion should be advanced. As one of the alternatives, to decrease the net CO_2 emissions, cultivation and the combustion of biomass is considered. In addition, the thermal conversion of biomass as a regenerable energy source preserves the diminishing resources of coal. In order to achieve a noticeable CO_2 reduction and fossil fuel substitution, it is necessary to use a large quantity of biomass for energy production. An exclusive biomass firing would result in the erection of many biomass fired small power plants. The time to construct these plants and the costs would be immense. Considering the seasonality of biomass production and heat or electricity production a corresponding stock would be necessary for exclusive firing.

Mclendon et. al. [62] has done an experimental study on high-pressure co-gasification of coal and biomass in a fluidized bed. Mixtures of coal and biomass were co-gasified in a jetting, ash-agglomerating, fluidized bed, pilot River Basin sub bituminous and Pittsburgh No.8 bituminous coals were mixed with sawdust and pneumatically conveyed into the gasifier at an operating pressure of 3.03 MPa. Feed mixtures ranged up to 35% by weight biomass. The results of gasification tests of sub bituminous coal/sawdust mixtures showed few differences in operations compared to sub bituminous coal only tests. The bituminous coal mixture had marked differences. Transport properties of coal/biomass mixtures were greatly improved compared to coal only.

Kingston [63], CEO of DynaMotive a Canadian based company is seeking to establish itself as a major player in the green fuels sector. The company's aim is to make a major impression in global energy markets by developing and commercializing fuels produced from biomass. While it is too easy to say whether it will be successful, the firm is attracting considerable attention from both the private and public sectors.

Vos [64], Green prices.com report-Green power represents a volume of about 400 billion kWh a year in the EU-25. Market stimulation alone is arguably still not sufficient to meet the EU's target of 21% green power markets into one internal EU market should reduce costs and help meet this target, and 2005 looks set to become a milestone to measure progress in this regards.

Westwood [65] from Douglas-Westwood ltd and Bruce Knight, from Innovation Management, present the conclusions of the recently published study ' The World Biomass Report' stating that the commercial biomass market is a dynamic one that is forecast to show significant growth over the next decade as the present environmental and agricultural drivers are increasingly supported by commercial ones.

Mogg [66] refocus correspondent describes that Thailand is fostering a new scheme to manufacture and distribute ethanol, distilled from the country's vast harvest of starch-rich indigenous agricultural crops for use in transport applications.

2.5 Biodiesel as an option for energy security

India ranks sixth in the world in terms of energy demand accounting for 3.5% of world commercial energy demand in 2001 [67]. The energy demand is expected to grow at 4.8%. A large part of India's population, mostly in the rural areas, does not have access to it. At 479 kg of oil equivalent per capita, energy consumption is very low. Hence, a program for the development of energy from raw material, which grows in the rural areas, will go a long way in providing energy security to the rural people.

The growth in energy demand in all forms is expected to continue unabated owing to increasing urbanization, standard of living and expanding population with stabilization not before mid of the current century. The demand of Diesel (HSD) is projected to grow from 39.81 million metric tons in 2001-02 to 52.32 million metric tons in 2006-07 @5.6% per annum. Our crude oil production, as per the Tenth Plan Working Group, is estimated to around 33-34 million metric tons per annum even though there will be increase in gas production from 86 million standard cubic meters per day (2002-03) to 103 million standard cubic meters per day in (2006-07). Only with joint venture abroad. There is a hope of oil production to increase to 41 million metric tons by (2016-17). The gas production would decline by this period to 73 million standard cubic meters per day. The increasing gap between demand and domestically produced petroleum is a matter of serious concern.

Our dependence on import of oil will increase in the near future. The Working Group has estimated import of crude oil to go up from 85 million metric tons per annum to 147 million metric tons per annum by the end of 2006-07 correspondingly increasing the import bill from $ 13.3 billion to $ 15.7 billion at today's prices. Transport sector remains the most problem sector as no alternative to petroleum based fuel has been successful so far. Hence petroleum based fuels especially petroleum diesel (HSD) will continue to dominate the transport sector in the foreseeable future, but its consumption can be minimized by implementation of Biodiesel program expeditiously. Many plants produce oil, as means of storing energy they absorb from the sun. Sunflower, Soya, rape, Limseed, Maize, olives, dates- all of these are grown commercially for their oil. Usually that oil is used for food purposes, but any of it could be used as fuel instead. In energy terms, vegetable oil is very much like any other oil. It can be burnt directly but more significantly with a little upgrading. It can be used to run diesel engines. Plantation based oil that has been chemically altered to give a performance similar to conventional diesel is known as biodiesel [68].

The main obstacle presently, regarding commercial use of biodiesel is one of the economics. It currently costs more than twice as much to produce bio-diesel as it does to produce diesel. Targets need to be set up for biodiesel production to achieve blending ratios of 5, 10 and 20 percent in phased manner. The estimated biodiesel requirements for blending with petroleum diesel over the period of next 5 years are given in Table 2.2

Table 2.2 Biodiesel requirement for blending [68]

Year	**Diesel demand million tons**	**Biodiesel requirement for blending million tons**		
		@ 5%	@10%	@20%
2001-02	39.81	1.99	3.98	7.9
2002-03	42.15	2.16	4.32	8.6
2003-04	44.51	2.28	4.56	9.1
2004-05	46.97	2.35	4.70	9.4
2005-06	49.56	2.48	4.96	9.9
2006-07	52.33	2.62	5.24	10.48

Super efficient diesels-In February-2006 [69], Volkswagen of Germany released its 80 miles per gallon (33.7 kilometers per liter) lupo car. The lupo has a turbo direct injection (TDI) diesel engine. It has similar acceleration and power to other cars in its class, while maintaining emission levels well below new EU emissions standards. In conjunction with US department of energy, Ford has developed a ‘green diesel’ family car called P2000. The P2000 diesel gets 63 miles per gallon (26.5 kilometers per liter) and weighs only 2000 pounds (908 kilograms). The P2000 has a super efficient direct injection (D.I) Diesel engine.

Cloin [70] south pacific Applied Geoscience’s Commission reports state that, there are great opportunities to utilize coconut oil as a fuel in the pacific. Coconut oil can be blended with diesel fuel and under certain conditions totally replace it. Coconut oil in pacific islands countries is increasingly used in both transport and electricity generation through its lower local cost. Other benefits include the support of local agro-industries and a decrease in emissions.

2.6 Comparison of properties of various fuels

Comparison of preparation of various fuels have been made

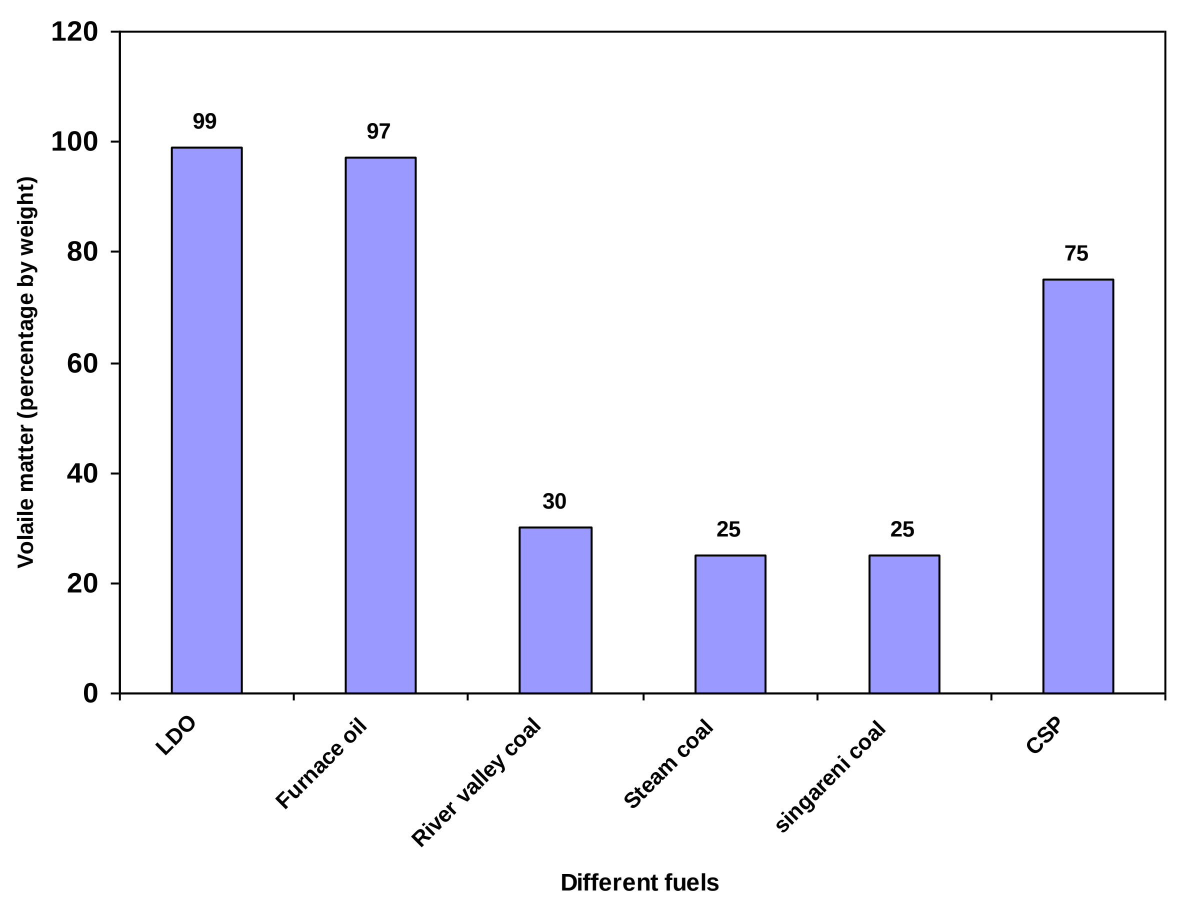


Figure 2.2 Volatile Matter v/s Different fuels [71]

Figure 2.2 shows the volatile matter for different fuels like LDO, Furnace oil, River valley coal, steam coal, singerani coal and coconut shell powder. It can be observed from Figure 2.2 that CSP has better volatile matter than most of the Indian coals that are available. It is also observed that it is about 75% of the value for LDO and furnace oil. Whereas the available Indian coals does not exceed 30% by weight.

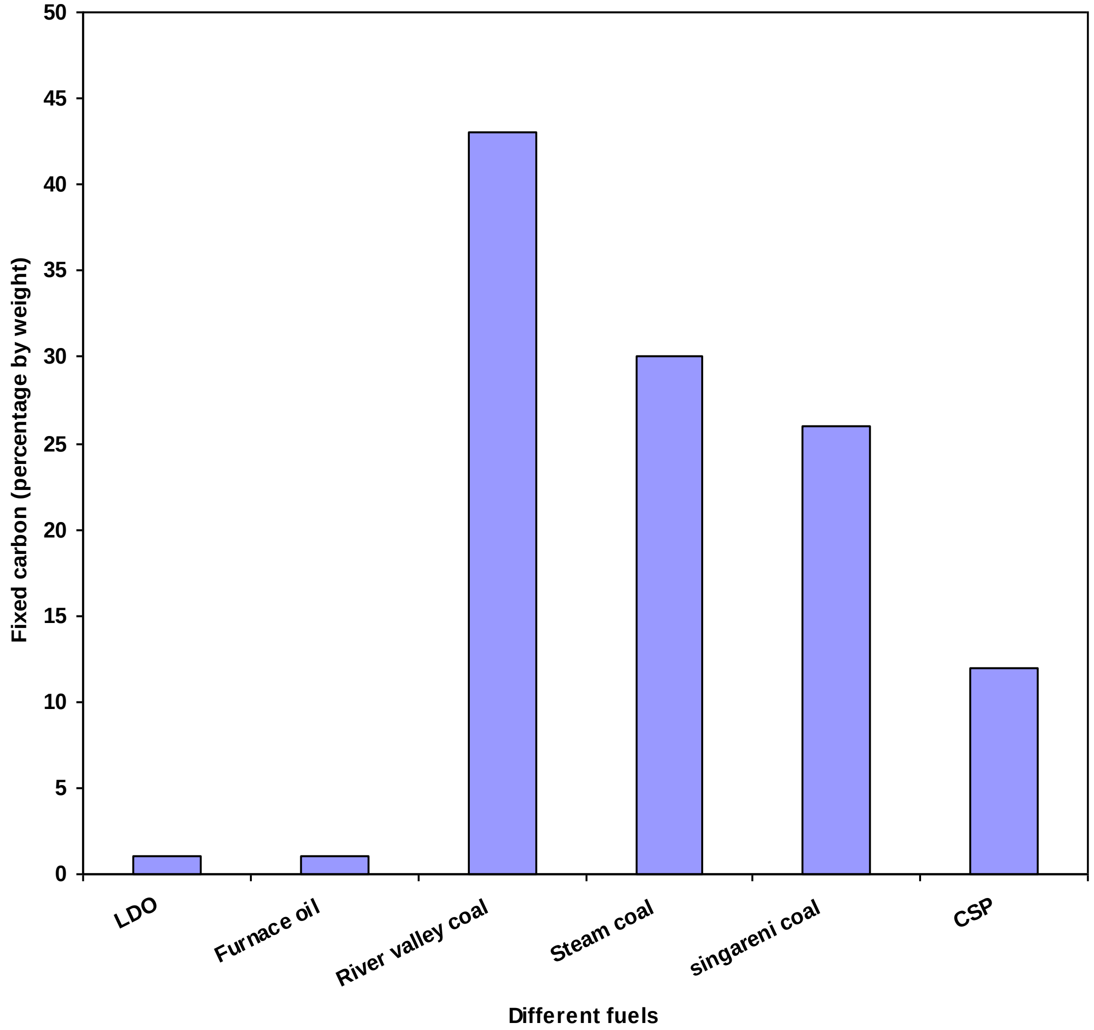


Figure 2.3 Fixed Carbon Percentages of Different Fuels [71]

Figure 2.3 shows the fixed carbon for the same fuels. It can be observed from Figure 2 that the carbon percentage of the coconut shell powder is less than that of the available coals and thus is considered suitable for blending.

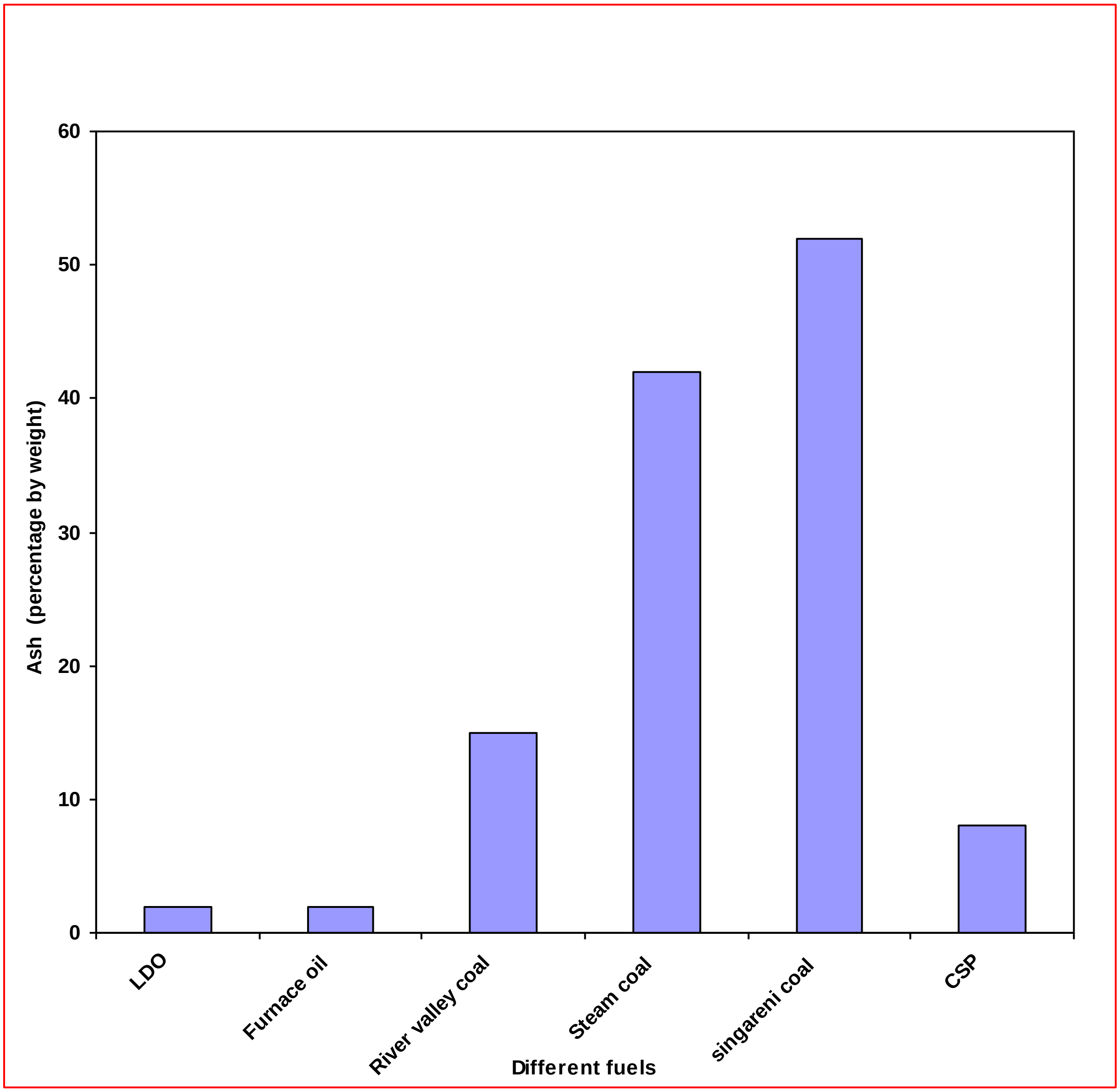


Figure 2.4 Ash Percent in Different Fuels [71]

Figure 2.4 shows the variation of percent of ash content for the same set of fuels mentioned earlier. It can be observed from the figure that the ash content of coconut shell powder is much lower compared to the available fuels. However, CSP's ash content is higher than LDO and furnace oil, as expected.

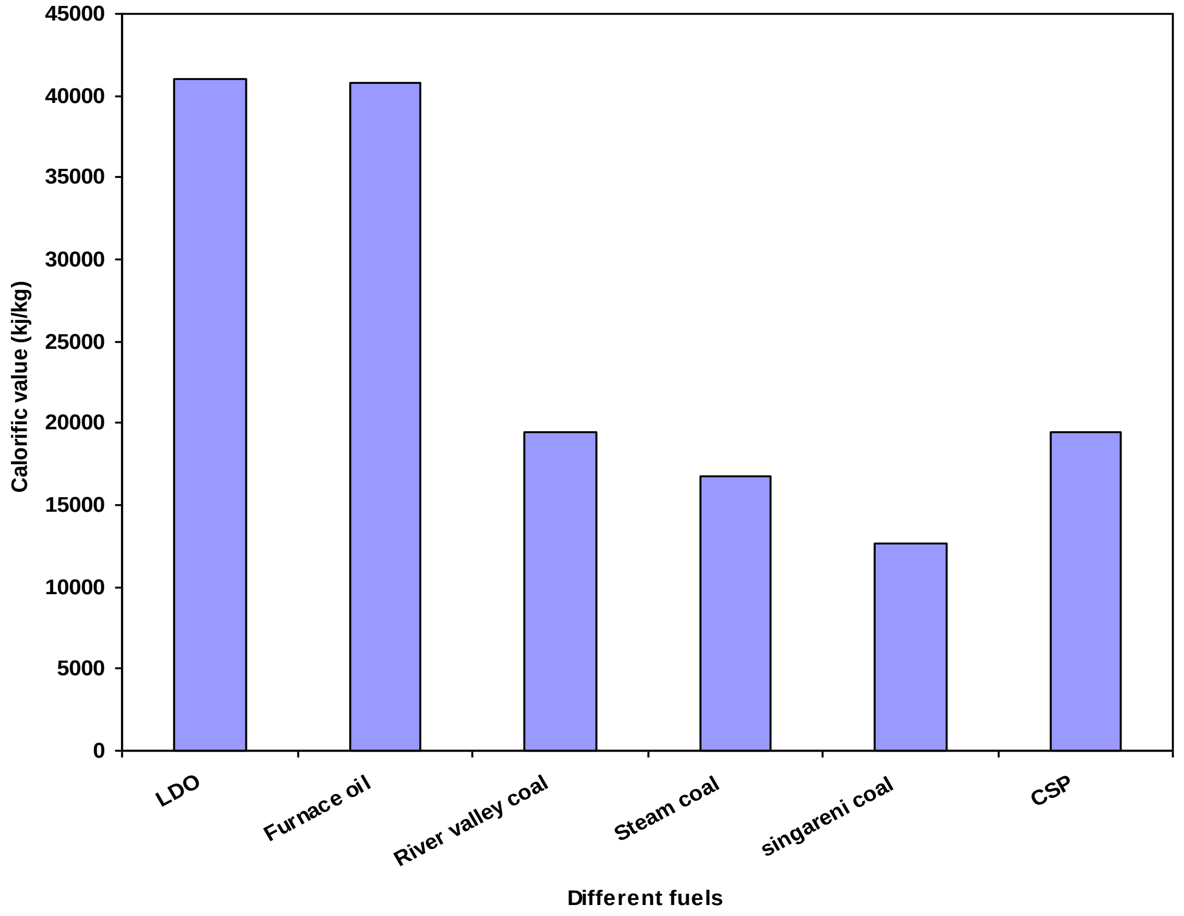


Figure 2.5 Calorific value of Different Fuels [71]

Figure 2.5 shows the Calorific Value of Different Fuels mentioned earlier. It can be observed that the calorific value of coconut shell powder is better than any of the available Indian coals, although its calorific value is about 50% of that of LDO and furnace oil.

The above-mentioned properties clearly shows that the Biomass fuel - coconut shell powder is a better substitute for fossil fuels like coal and on this basis Coconut shell powder slurries were prepared and the combustion analysis was carried out in the present investigation.

2.7 Biomass based slurries

Benter [72] has investigated the production of a biomass slurry fuel made from a mixture of oil and finely ground biomass. The types of oil investigated were diesel and kerosene. Biomass was represented by radiata pine (pinus radiata). The wood was prepared with the convertech process, which is being developed to continuously wash, autohydrolyse and dry wood chips. Finely ground wood particles settle in fuels such as diesel or kerosene due to their greater density and thus need to be stabalised if long-term storage is needed. It was found that autohydrolysed wood particles can be prevented from settling by emulsifying the oil particle mixture with a polar liquid. In this context, it was discovered that certain mixtures of kerosene, ethanol, water and wood form a stable emulsion without any additives (stable for more than 30 days). Various additives for the stabalisation of pure wood powder oil mixtures were also tested. Whereas no stable additive of the surfactant type could be identified, a castor oil-based thickener was found to successfully stabalise the slurry. The apparent viscosities of some of the slurry that were stable for at least 30 days were also measured. All slurries showed pseudo plastic properties. The thickener stabalised slurry was found to have the lowest viscosity at shear rates above 50 $s^{-1.}$

Agarwal and Agarwal [73] have mentioned that the biomass oil slurry fuels are made from a mixture of oil and finely ground biomass. It has many applications such as district heating, industrial furnaces and possibly stationary diesel engines and domestic boilers. The stability of the mixture is the most critical stage in the entire utilization procedure of the slurry fuels. The rheological properties of a fluid determine the suitability for the preparation of a slurry fuel. The slurry fuel stabalisation, the apparent viscosity of the oil is to be increased, to achieve these properties several methods can be applied all have the use of one or more additives in common, which have either directly or indirectly induce interaction between the particles and thereby prevent them from settling. Another concept is to add a polar liquid such as water or oil, a short chain alcohol to the fuel oil, wherever required with the help of surfactants to form an emulsion. In this case, the particles get caught preventing coalescence of droplets.

Shankapal [74] has done experimental investigations on combustion analysis of coconut shell based slurry fuels. Single fuel-slurry droplets, were suspended on micro thermocouples and burned under room temperature as well as in a hot stream of air at atmospheric pressure. The general combustion behavior was observed photographically and transient temperature history was recorded. Parametric effects of solid fuel fraction in the slurry, droplet size, water addition, oil volatility, air temperature and velocity on the slurry droplet were studied systematically.

Droplet combustion of pulverized coconut shell based slurry fuel has been carried out using the suspended droplet technique. The observations made and the results of the experiments conducted are discussed. The results include burning behavior of fuel droplets, effect of droplet diameter on temperature profile, droplet diameter history, variation of ignition delay and droplet peak temperature with ambient temperature. Verification of square law of inlet droplet diameter, effect of ambient temperature, fraction of solid fuel in the slurry, addition of water, air flow rate and oil volatility on burning rate coefficients have been carried out.

In the second part, the application of the fuel slurry, as a potential fuel in oil fired foundary furnace, oil fired steam generators and diesel engines are discussed. Using finite element analysis, time taken for preheating the furnace, the temperature distributions along the thickness of the furnace wall have been predicted. Using 3-dimensional modeling concept, the flow inside the furnace, the velocity distribution, pressure distribution, temperature distribution and particle tracing have been predicted. Temperature distribution inside the furnace during the combustion of different slurries has been measured and plotted. By introducing a coiled steel tube of suitable length, it was tested for steam generation and its efficiency was calculated.

2.8 CFD analysis in furnaces

Development and optimization of biomass grate furnaces and boilers by CFD analysis has been carried out [75]. During the past 20 years, the numerical simulation of heat transfer and turbulent flow phenomena in combustion systems has developed rapidly concurrently with the development of new and more powerful computers. These mathematical models were originally used only within professional R & D environments such as universities. Among experts, these programs are designated CFD codes/programs. Following this development, commercial CFD programs have been developed for use in project planning, optimizing and diagnostic tests of plants. The CFD programs are advanced calculation tools for computations of 3-dimensional turbulent flow with heat and mass transfer. Temperature distribution, Heat transfer – radiation, convection and conduction, Gas velocity, flow distribution (velocity vector components), Pressure distribution and turbulence, Combustion, concentrations and Particle trajectories.

Davis et. al. [76] have carried out the simulation of saw dust co-firing in a pilot scale furnace , using CFD tools and shows that reasonably accurate predictions of heat release, reduction of CO_2, NOx and SO_x emissions can be made. In addition, under certain circumstances, fuel costs can be decreased and optional benefits in areas such as flame stability, heat balance, corrosion and fuel efficiency are possible. They also mention the level of detail provided by the simulations can be a valuable aid in understanding mechanisms by which saw dust cofiring effects the combustion process and its impact on NOx formation and reduction. The impact of co-firing on the combustion process can be particularly unpredictable. This work focuses on the application of CFD simulation as a tool provides understanding and guidance in the evaluation of various biomass co-firing injection strategies.

Kaer et. al. [77] one of the main results of the Joint Project for Biomass has been the development and implementation of a CFD-based deposition model, which integrates the growth of deposits on furnace walls and superheater tubes in the heat transfer rates determined by the CFD code. Based on the commercial CFD code FLUENT, the model is fully implemented through the user defined functions. The model is configured entirely through a graphical user interface integrated in the standard FLUENT interface. The model considers fine and coarse mode ash deposition and sticking mechanisms for the complete deposit growth, as well as an influence on the local boundary conditions for heat transfer due to thermal resistance changes. The model is applied to the straw-fired Masnedo boiler. Results are in good qualitative agreement with both measurements and observations at the plants. Poor mixing is predicted in the furnace and a discussion is offered of the potential operational implications.

Charles et. al. [78] has done a study on stating that, Biomass makes up a steadily increasing part of the fuel mix in Denmark, and the Danish electricity companies have, throughout the past 10 years, established and commissioned several large-scale straw- and wood chip-fired CHPs based on grate combustion technology. In an attempt to improve the theoretic basis of designing tomorrow’s grate combustion plants the leading players from industry, electric utilities and universities have joined in a generic development work. The project objective is to develop a substantially improved CFD model describing the processes of importance to the performance and design of a biomass boiler; such as deposit formation, sulphur chemistry, nitrogen chemistry, movement and combustion of non-spherical particles in the gas phase. The objective is that the CFD model can become a substantial part of the boiler supplier’s design tools, which the CFD model can contribute to documenting a designs environmental performance and used for trouble shooting.

From the literature review the following conclusions were made

1. Biomass can be burnt in the form of a slurry, just like coal slurry
2. Burning biomass as slurry gives the advantage of a liquid fuel.
3. A wide varieties of biomass can be pulverised and mixed with a carrier medium like oil or water, and slurry can be prepared
4. The biomass based slurry acts as a pseudo plastic fluid
5. Biomass slurries can be better than coal based slurries prepared using low-grade coals, as biomass has higher volatile matter, low ash content and comparable calorific value
6. The slurry can be pumped, atomised and burnt in retrofitted oil fired furnaces and steam boilers

However, systematic investigation on biomass slurry preparation, rheological properties, thermal properties, atomisation of slurries, flow analysis and spray combustion of slurry fuels needs to be done. In the present investigations, effort has been made to prepare biomass-based slurry by mixing with light diesel oil and water. The rheological properties were studied and correlation has been established. Computational fluid dynamic analysis of a small aluminium-melting furnace was carried out using slurry as a fuel to establish the flow path for better combustion and the experimental investigations were carried out to validate CFD results. The emissions from slurry fuel are comparatively lower than the emission from pure fossil fuels. The slurry fuel was burnt in an oil-fired furnace to demonstrate that the slurry can be used in commercial applications.

CHAPTER.3

PRESENT WORK

3.1 Aim of the present investigation

The literature survey shows that there is a need for a renewable energy source, which can replace or supplement the existing fuel oils. Biomass slurry seams to be a possible candidate for this. From the literature, it is seen clearly that a solid fuel to be burnt in a slurry form in furnaces and boilers must have low ash content, high volatile matter and a high calorific value similar to coal. It has been shown from the literature that the coconut shell powder satisfies the above criterion. It is also available in plenty especially in India, thus the objective of the present work is to investigate the combustion principle of the coconut shell powder (CSP) based slurry fuel, which is a combination of light diesel oil (LDO), coconut shell powder (CSP) and water. The investigations are carried out both experimentally and computationally using the computational fluid dynamics (CFD)-Fluent software. The heat generated by the combustion of the slurry in furnace is utilized in melting aluminum and in generating steam. The CSP based slurry is also tested in diesel engine.

3.2 Objective of the proposed research

To realize the aim the following objectives were set

- **Preparation of biomass based slurries (coconut shell Powder)**
- **Establishing the properties of the slurries and selection of suitable Slurries for further studies**
- **CFD analysis to study the flow and combustion behavior in melting furnaces**
- **Experimental investigation of combustion of biomass based slurry fuels in melting furnaces and steam generators**
- **Performance analysis of diesel engine using biomass based slurry fuels**

3.3 Methodology

The methodology followed in this Thesis, is indicated in the following sections:

3.3.1 Preparation of slurries and studying their properties

This includes:

1. Particle size distribution of coconut- shell powder
2. Proximate analysis of the pulverised coconut shell powder
3. Preparation of:
    a. Pulverised coconut shell
    b. Pulverised coconut shell and light diesel oil slurry
4. Proximate & ultimate analysis of different composition fuel slurries
5. Determination of calorific value, density, specific heat, viscosity and thermal conductivity of slurry samples.
6. Establishing a correlation for the above properties in terms of its constituents.

3.3.2 CFD analysis to study the flow and combustion behavior in melting furnaces

The furnace was modeled according to the existing oil-fired Foundary Furnace dimensions that existed in the Foundary and meshed. The pre-processing CFD software Gambit was used to model the furnace and mesh the same for further analysis.

3.3.2.1 Steps involved in the application of CFD-tool

The following steps are involved in the application of the CFD tool-Fluent 6.0 to the combustion process of biomass slurry in the Furnace.

1. Geometrical modeling and discretisation of the combustion zone in the furnace is carried out using Gambit.
2. The biomass slurry properties cannot be fed directly to the fluent, thus a prePDF (probability density function) file is created, which can be fed to the Fluent for

studying the combustion behavior of the biomass slurry. The calculations are carried out in two steps

    a. Adiabatic calculations
    b. Non adiabatic calculations

3. Next step is the input to the Fluent which consists of
    a. The case file consisting of geometrical details and discretisation is imported.
    b. The prePDF file (containing the properties of the biomass slurry) is imported.
    c. The solver is selected
    d. The Turbulence model is selected
    e. Combustion model is selected
    f. Radiation model is selected
    g. Discrete phase model is selected to trace the trajectories of the particles
    h. The location and the velocities of the biomass slurry injections is defined.
    i. The properties required but not defined earlier in pre PDF file are defined
    j. Boundary conditions are incorporated
    k. Initialization of the flow field is done
    l. The file is saved and the iterations are started for solutions
4. Post processing of the results.

   The details of the above steps are given in subsequent chapters.

3.3.3 Experimental investigations

Experimental investigations of the biomass slurry were carried out in the modified furnace. Fuel slurries of various compositions were sprayed into the furnace and combustion of the slurry produces heat, temperatures at the various sections of the furnace are measured.

The results of the present investigations are discussed under four parts

1. Preparing the Biomass slurry samples and selecting the optimum compositions has been carried out in chapter.4
2. Experimental investigation of combustion of biomass slurry fuels in furnaces.

3. The application of the slurry fuel as a potential fuel in oil fired foundry furnace, oil fired steam generators and diesel engines are discussed.

Combustion of the biomass slurry, with the inlet of the slurry at room temperature and preheated to a temperature of 328K is carried out in the furnace. The temperature distribution at various sections of the furnace and emission analysis for various blends is determined.

3.4 Melting of aluminum using the slurry fired fuel in the furnace

Different slurries were used for melting a given quantity of aluminum. The performance of the furnace was compared with the furnace fired with LDO.

3.5 Conversion of furnace into a boiler

With a view of power generation with slurry fuel, the furnace was modified into a once through boiler for generating the steam; its performance was measured and compared with that of the furnace fired with LDO alone.

3.6 Performance testing of bullet 4-s diesel engine using biomass slurry

Slurries were prepared by mixing pulverized coconut shell with diesel and used as the fuel for running a Bullet Diesel engine. Load tests were carried out, various engine performance characteristics were drawn, and the results were compared with the characteristics obtained when the engine was run on diesel alone.

From the studies conducted, the main conclusions drawn were:

- Simple correlations to find the properties of the slurry were developed
- CFD simulations of the combustion process in the furnace were carried out using the commercial software Fluent. The Temperature distribution and emission analysis was done
- As the CSP percentage increases in the slurry the CO emission percentage reduction was determined from both CFD and Experimental analysis
- Correlation equation was developed to find the maximum temperature during the combustion of biomass slurry.
- The biomass slurry was used for melting of aluminum and it was observed that the cost of slurry fuel was less than that of LDO
- It was demonstrated experimentally that the biomass slurry can be used to generate steam
- Diesel slurries with coconut shell powder were prepared and tested in Diesel engines without any hardware modifications

The contributions to the knowledge from these studies are

- CFD analysis of combustion of biomass based slurry fuels in melting furnaces were carried out
- Experimental verification of combustion of biomass based slurry fuels in furnaces was done
- Establishing biomass based slurry fuel for commercial application

CHAPTER-4

PREPARATION OF SLURRIES

The method of preparing the slurries from the constituents is briefly described in this chapter, for evaluating the performance of the biomass slurry fuels, it is essential to know the various properties of the slurries.

4.1 Preparation of slurries and their properties

The properties of the slurry like calorific value, viscosity, specific heat, density and Thermal conductivity are determined. Correlations of the properties in terms of the constituents of the slurries are developed; even for CFD analysis of combustion of the biomass slurry, the above-mentioned properties are required.

Coconut shell powder is pulverised from matured coconut shells. The pulverization of coconut shell powder is not an organised industry in India. The product finds extensive use in plywood and laminated board industry as a phenolic extruder and as filler in synthetic resin glues, mosquito coils and agarbathis. Coconut shell powder is preferred to other alternate materials available in the market such as bark powder, furfural and peanut shell powder because of its uniformity in quality and chemical composition, better properties in respect of water absorption and resistance to fungal attack

Coconut shells free from contamination of coir pith, etc., are broken into small pieces and fed into a pulveriser. The powder from the pulveriser is fed into a cyclone and the parallel product is collected in bag filters. The shell powder is then fed into a vibrating sieving machine and packed according to size requirements for various end uses. The rejects from the sieving machine can be recycled in the pulveriser for size reduction. The main requirements for consistent good quality of coconut shell powder are proper selection of shell of proper stage of maturity and efficient machinery.

Dried pulverized coconut shell, was purchased from the CSP pulverization Industry. The particle distribution after sieve analysis of the powder is given in Table 4.1. Table 4.1 gives the sieve analysis for 50gm of Coconut shell powder and the grain size distribution is shown in Figure 4.1 based on the sieve analysis from Table 4.1 (given in Appendix-I)

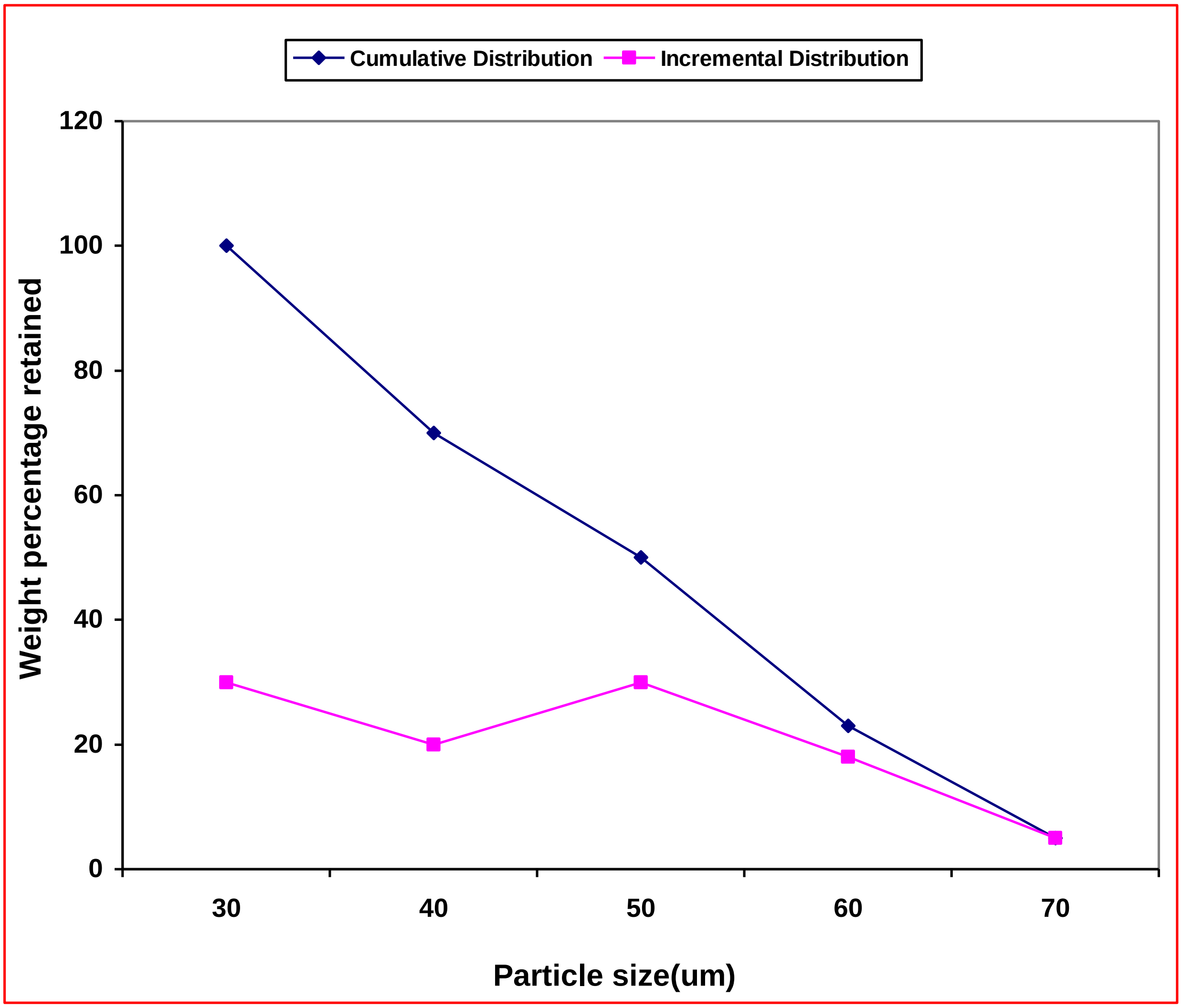


Figure 4. 2 Particle size Distribution of Pulverised coconut shell

Figure 4.1 shows the typical particle size distribution for the sample in the form of cumulative weight and incremental weight curves. The average particle size is (100-10) = 45 microns.

4.2 Proximate analysis of the pulverised coconut shell powder

Proximate analysis gives the amount of moisture, volatile matter, fixed carbon, and ash content of the pulverized coconut shell. The analysis was carried out according to IS: 1350 given for coal [79]; Table 4.2, gives the properties of the shell powder

Table 4.2 Properties of coconut shell powder

Sl. No.	Characteristics	
1	Volatile Matters [Wt. %]	78.30
2	Fixed Carbon [Wt. %]	13.42
3	Ash [Wt. %]	03.02
4	Moisture [Wt. %]	05.26
5	Gross Calorific Value [kJ/kg]	19107
6	Gross Density [g/cm^3]	0.40

4.3 Details of the carrier liquid-LDO

Light Diesel Oil [LDO] used in the preparation of the slurries were procured from Indian Oil Corporation outlet and their physico-chemical properties are listed in Table 4.3

4.4 Preparations of the slurries

Required quantity of the pulverized coconut shell was weighed and measured to an accuracy of 0.1mg using an Electronic (Digital) weighing machine. Different samples of the coconut shell powder, oil with water were prepared in a domestic mixer. During experimentation, the mixture was continuously stirred using a stirrer to prevent the settling of the solid particles.

Table 4.3 Physico-chemical properties of light diesel oil (LDO)

Sl. No.	Characteristics	LDO
1	Acidity (inorganic).	Nil
2	Ash (% Wt. max.)	0.02
3	Gross Calorific Value(kJ/kg)	41800
4	Net calorific value(kJ/kg)	39800
5	Flash Point (Pensky Martens min. ^{0}C)	66
6	Kinematic Viscosity (centistokes at 38^0 C, max)	2.5-15.7
7	Sediment (% Wt. max.)	0.10
8	Sulphur (total, % by Wt. max.)	1.8
9	Water Content (% by Volume, max.)	0.25

4.5 Viscosity of fuel slurry

Brook-Field Viscometer was used to measure the viscosity of different biomass slurries. The viscosity of the slurry samples at different temperature and spindle speeds were determined. In this system, a spindle connected to the motor drives a vertical spindle with a disk, paddle or cylinder that is submerged in the slurry fuel. The drive is connected to a calibrated spring. Both the spindle and the motor should rotate at a constant speed, but the spindle lags by certain amount due to the resistance offered by the rotation of the slurry fuel. This resistance offered for rotation is proportional to the viscosity. The instrument is calibrated and to a accuracy of ± 0.2kg/ms and the viscosity of different slurry fuels were measured. The viscosity values are tabulated in Table 4.4

4.6 Calorific value of the fuel

The calorific value of the biomass slurry is measured using Bomb calorimeter, a measured quantity of slurry fuel is taken in the bomb container and ignited and the heat that is developed is measured and noted for each composition. The instrument is calibrated. The accuracy of the bomb calorimeter with which the measurements can be carried out is $\underline{+}$100kj/kg. The calorific values for different slurries were measured and tabulated in Table 4.4. The properties of the various samples prepared and its viscosity and calorific values are given in Table 4.4

4.7 Density

The density of the biomass slurry is measured by weighing a known quantity of slurry fuel in a measuring beaker. The difference in weight with the slurry fuel, to empty beaker is found. The weight of the slurry fuel divided by the volume of the beaker for a particular height of the slurry in the beaker gives the density of the biomass slurry for a particular composition.

4.8 Specific heat [80]

For Biomass slurry based on the ultimate analysis for a blend of B10 $C_{0.29}H_{0.69}O_{0.04}N_{0.0009}$

Molecular Weight = (0.29) (12) + (0.69) (1) + (0.04) (16) + (0.0009) (14) = 4.83

Specific Heat

$C_p = 1.8(0.29) + 2.3\,(0.69) + 4\,(0.04) + 6.2\,(0.0009) = 2.28$ kcal/kg atom ^{0} C

$$C_p = \frac{2.28(4.186)}{4.83} = 1976\text{J/ kg K}$$

$$\boxed{C_p = 1976\text{J/ kgK}}$$

4.9 Thermal conductivity of biomass slurry [81]:-

a. $K = \rho\,[\;0.1159 + 0.00233\,M\;] + 0.013075$ Btu/hr ft^0 f

Where ρ = gms/c.c

M = average moisture content

For M < 40 %

$$K = 0.875\,[\;0.1159 + 0.00233(7.23)\;] + 0.013075$$

$$K = 1.1208 \text{ Btu /hr ft F}$$

$$= \frac{1.1208\ (252)(4.186)(3.28)(1.8)}{3600}$$

$$\boxed{\therefore \boldsymbol{K = 0.23W/m\text{-}k}}$$

Table 4.4 Different blends of the biomass slurry

Sl. No.	LDO	CSP	H_2O	Calorific value (kJ/kg)	Viscosity kg/m-s
1	90	10	-	39557	0.96
2	80	20	-	37255	1.42
3	70	30	-	35041	1.88
4	60	40	-	32768	2.34
5	50	50	-	30495	2.80
6	48	50	2	31930	2.73
7	46	50	4	31093	2.67
8	44	50	6	30256	2.60
9	42	50	8	29419	2.54
10	100	-	-	39800	0.5
11	-	100	-	19458	-
12	**85**	**5**	**10**	**39000**	0.52
13	**80**	**10**	**10**	**38300**	0.60
14	**75**	**15**	**10**	**37500**	0.86
15	**70**	**20**	**10**	**36900**	0.96
16	**65**	**25**	**10**	**36200**	1.32
17	**60**	**30**	**10**	**35700**	1.68
18	70	15	15	24775	0.71
19	70	10	20	23732	0.32
20	65	15	20	23650	0.55
21	70	05	25	24700	0.10
22	65	10	25	23558	0.16
23	60	15	25	21068	0.39

Previously coconut shell powder slurries were prepared [71] and the combustion analysis was carried out for samples up to 8% of water. Since from Table 4.4 it is observed that by increasing the percentage of water, the viscosity decreases, it is observed that samples 12 to 17 would be more suitable and these samples were considered for further combustion analysis

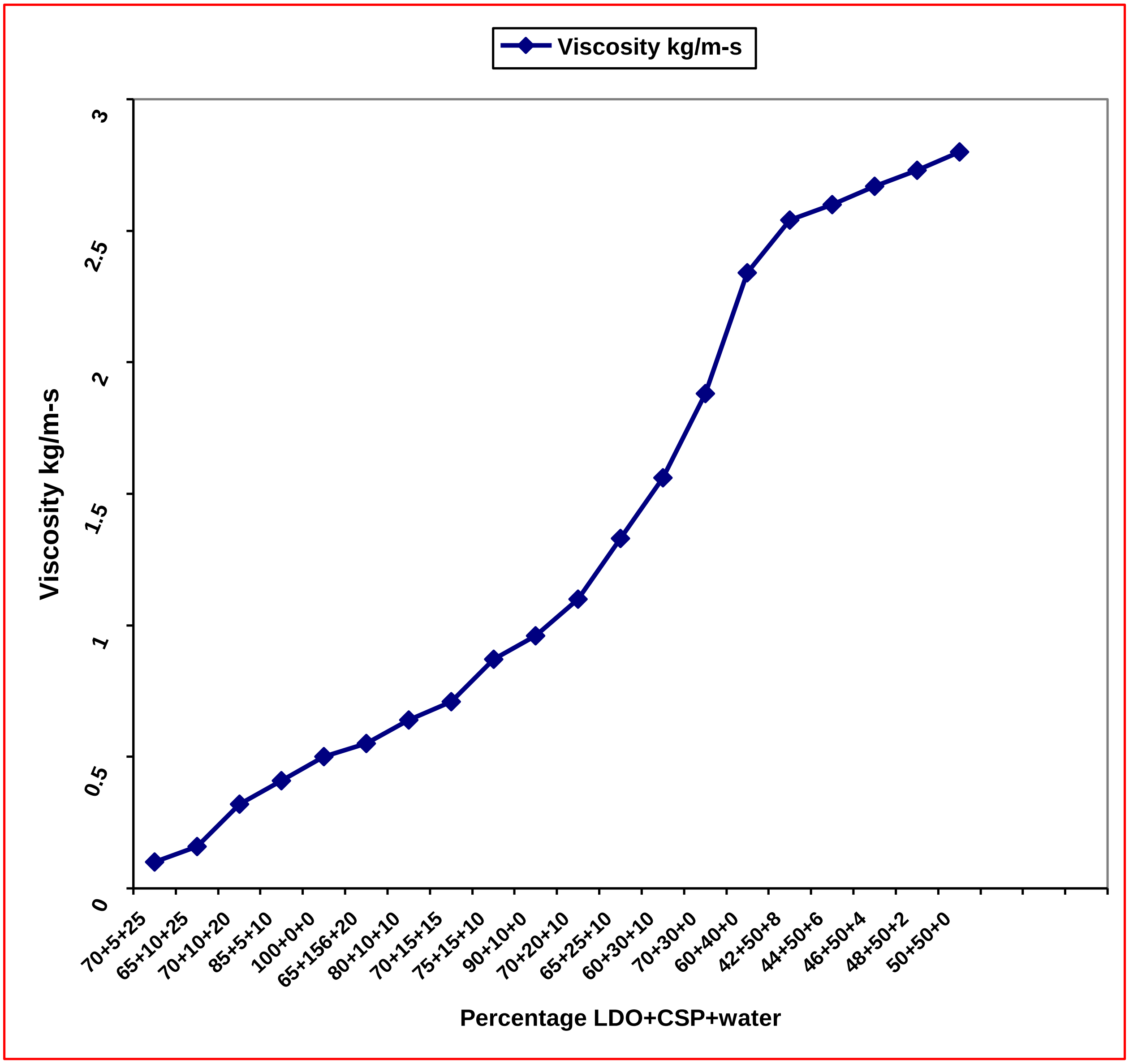


Figure 4.2 Viscosity v/s Blend

Based on the above Calorific value and Viscosity properties with respect to different blends, the optimum blend proportions with optimum calorific values and viscosities were selected for combustion analysis. The compositions with different blends are designated as follows for the further work.

TABLE 4.5 Blending ratios of light diesel oil, coconut shell powder and water

From the above analysis, the optimum blend is selected and it is designated as follows along with its properties.

Blends	Composition in terms of LDO+CSP+WATER	Viscosity kg/m-s	Measured Calorific Value kJ/kg
B0	100+0+0	0.50	39800
B5	85+5+10	0.52	39000
B10	80+10+10	0.60	38300
B15	75+15+10	0.86	37500
B20	70+20+10	0.96	36900
B25	65+25+10	1.32	36200
B30	60+30+10	1.68	35700

(* Blends in percentage of weight)

The various other properties that are required for further combustion analysis are determined as shown in Table 4.6

TABLE 4.6 Properties of biomass slurry

Blends	Fixed Carbon kg atom	Density (g/cm^3)	Viscosity kg/m-s	Specific heat kJ/kg K	Thermal conductivity, W/m-K	Measured Calorific Value kJ/kg
B0	7.00	0.400	0.50	2052	0.115	39800
B5	6.15	0.438	0.52	2000	0.123	39000
B10	5.98	0.875	0.60	1999	0.230	38300
B15	5.82	1.322	0.86	1955	0.330	37500
B20	5.65	1.750	0.96	1934	0.430	36900
B25	5.49	2.190	1.32	1901	0.530	36200
B30	5.32	2.231	1.68	1811	0.540	35700

(* Blends in percentage of weight)

It can be seen from Figure 6 and Figure 7 that with the increase in coconut shell powder up to 30%, there is a drop in the calorific value. The carbon percentage, after 40% it was not possible to increase the CSP composition as the slurry turned into a paste and it was highly viscous and with the increase in the percentage of water, the calorific value was very less as shown in Table 4.4

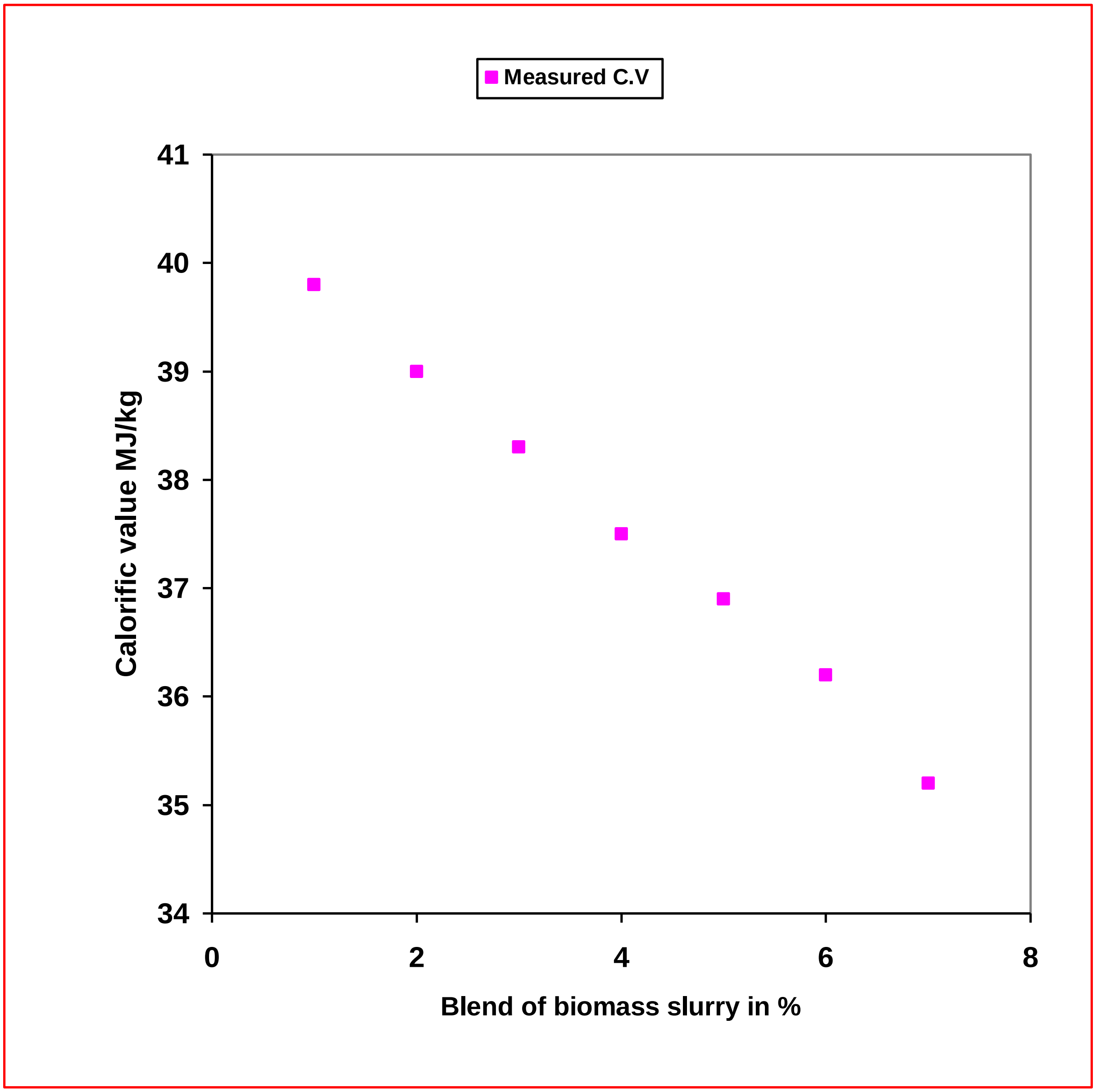


Figure 4. 3 Effect of blend on calorific Value

Figure 4.3 shows that as the percentage of biomass in slurry increases, there is almost linear drop in the calorific value of the fuel. Based on a particular application a suitable blend of the slurry can be selected as fuel.

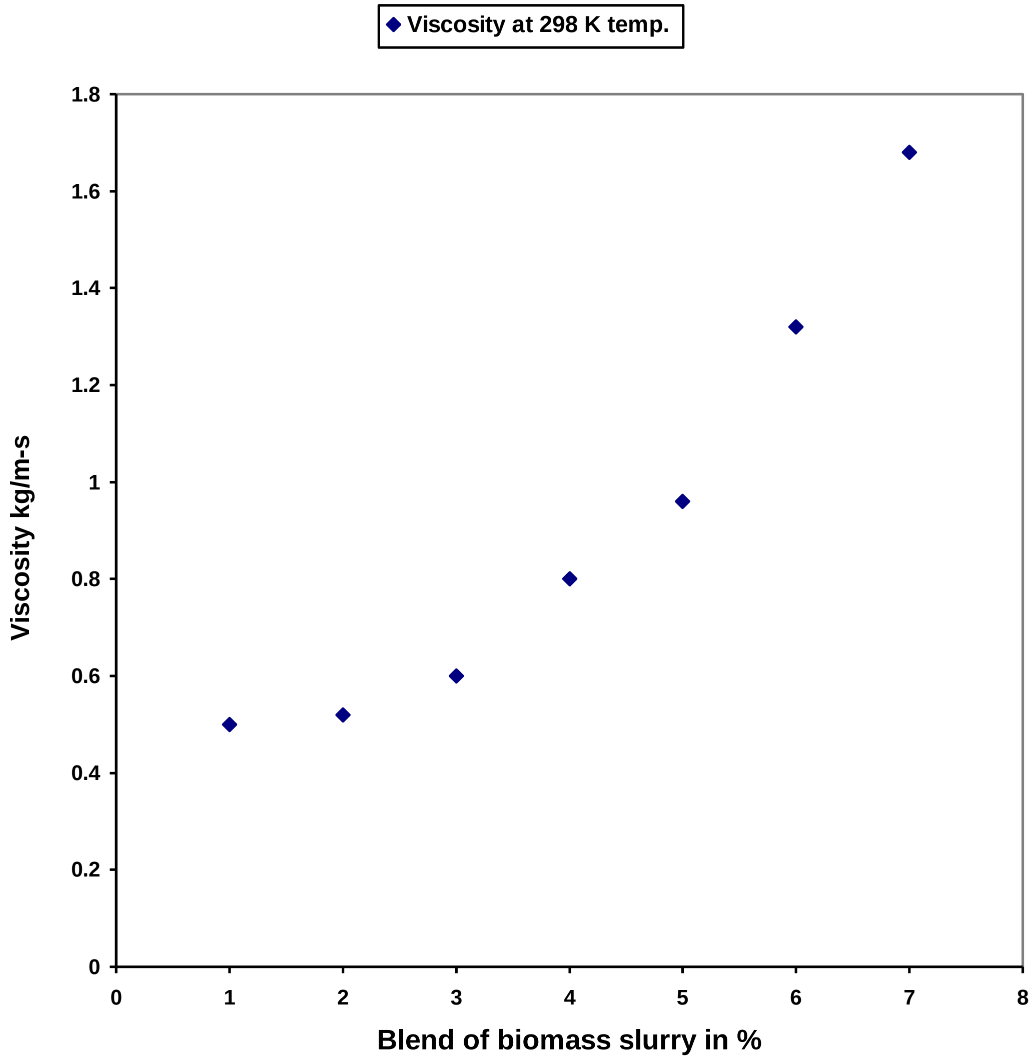


Figure 4.4 Effect of blend on Viscosity

Figure 4.4 shows the variation of viscosity v/s blend. The viscosity increases with the increase in CSP blend; from Figure 4.4 it is clear that the viscosity increases with the percentage increase in the CSP in the slurry.

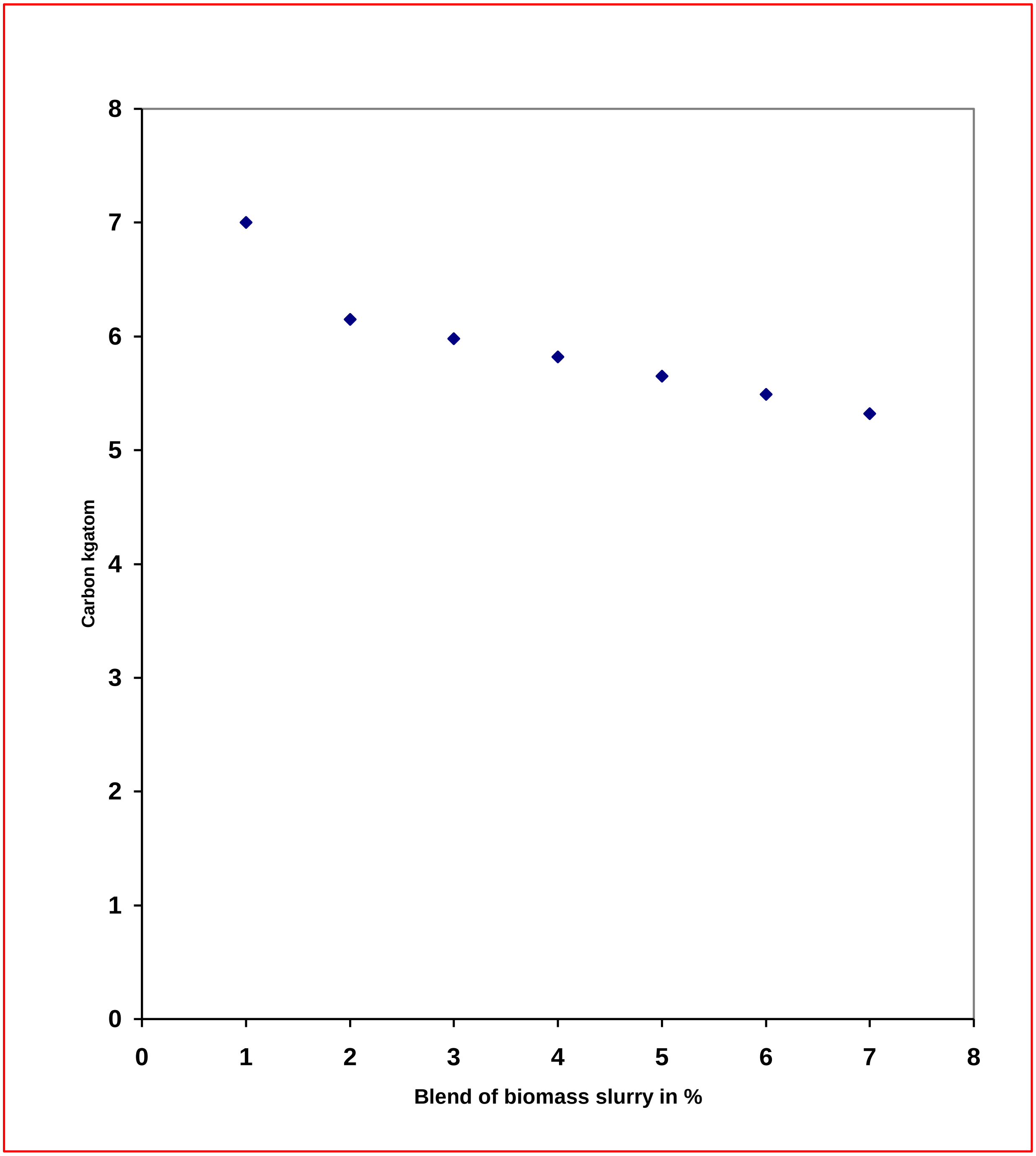


Figure 4.5 Effect of blend on carbon content

Figure 4.5 shows that with the increase in the percentage of CSP, the fixed carbon decreases linearly.

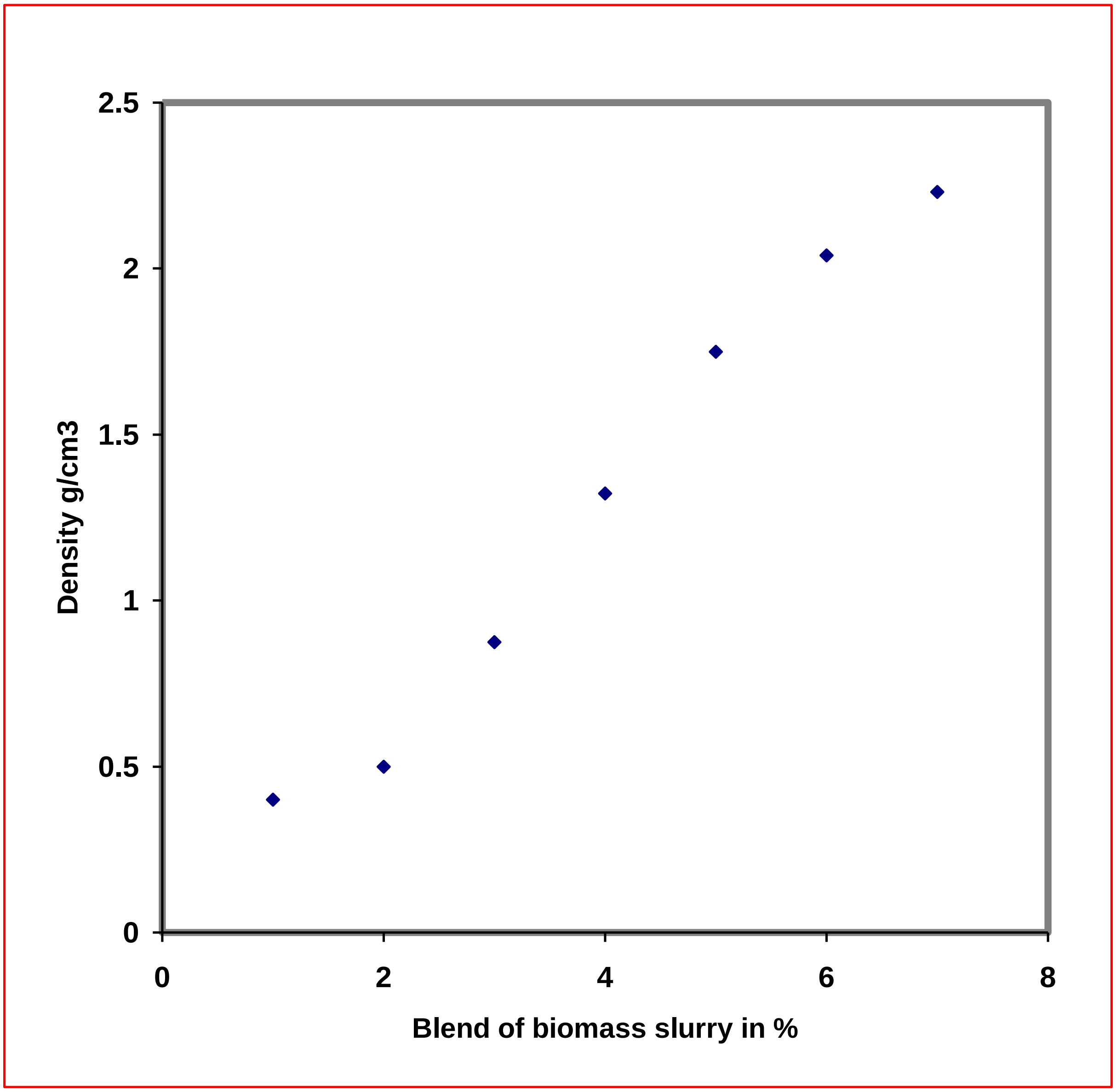


Figure 4.6 Effect of blend on Density

Figure 4.6 shows the variation of density with the increase in the percentage of the CSP in the slurry for a given percentage of water in the slurry. It can be seen that with the increase in percentage of CSP the density of the biomass slurry also increases, which in turn proportionally increases the viscosity as shown in Figure 4.7

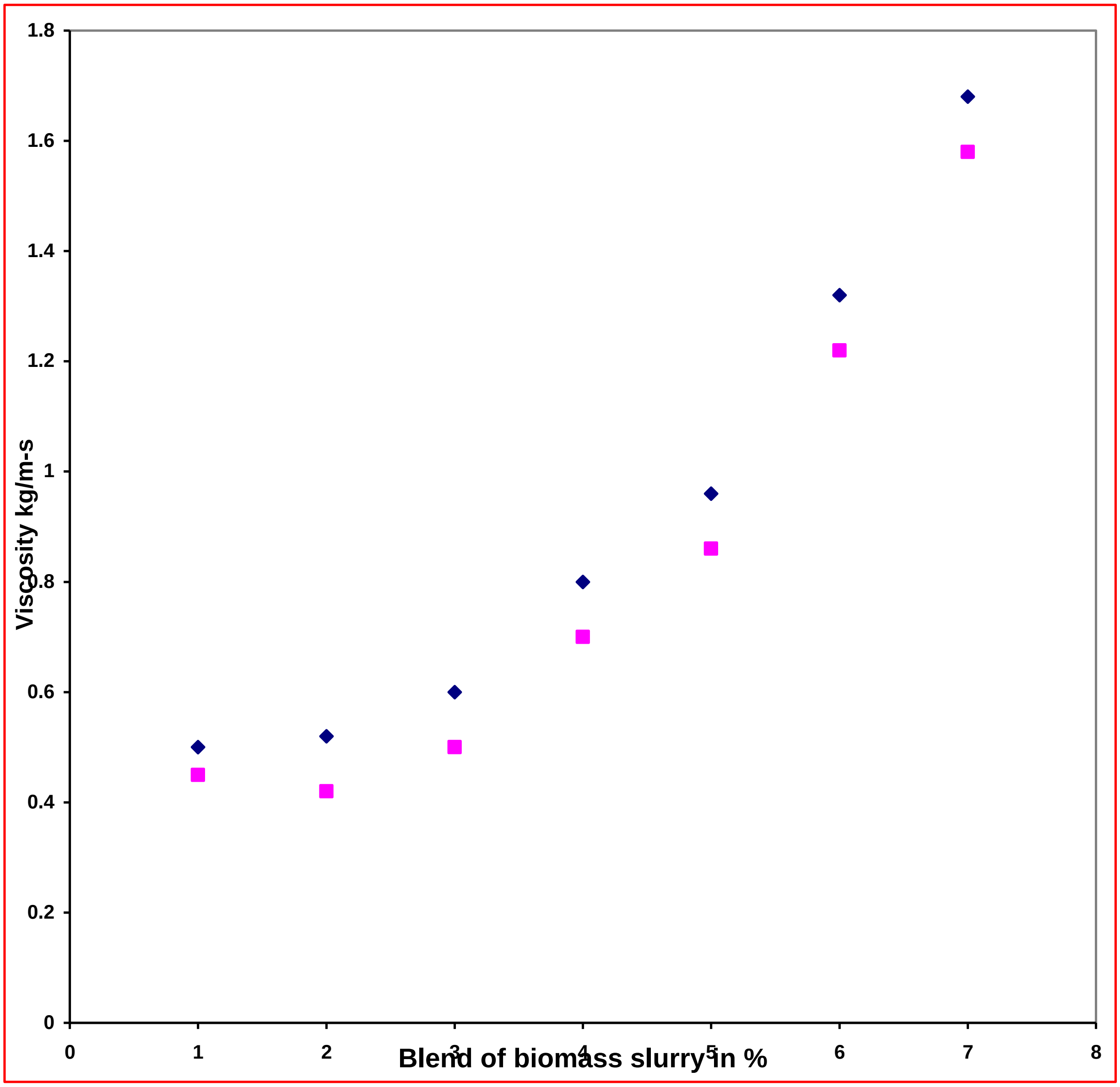


Figure 4. 7 Effect of Temperature on Viscosity

Figure 4.6 shows that the variation of viscosity of the slurry as a function of percentage of CSP for given percentage of water at temperatures of 298K and 328K. It can be observed from the Figure 4.7 that the viscosity of the biomass slurry increases with the percentage of coconut shell powder and the viscosity can be reduced to certain extent by preheating the slurry as shown in Figure 4.7 for a temperature of 328K.

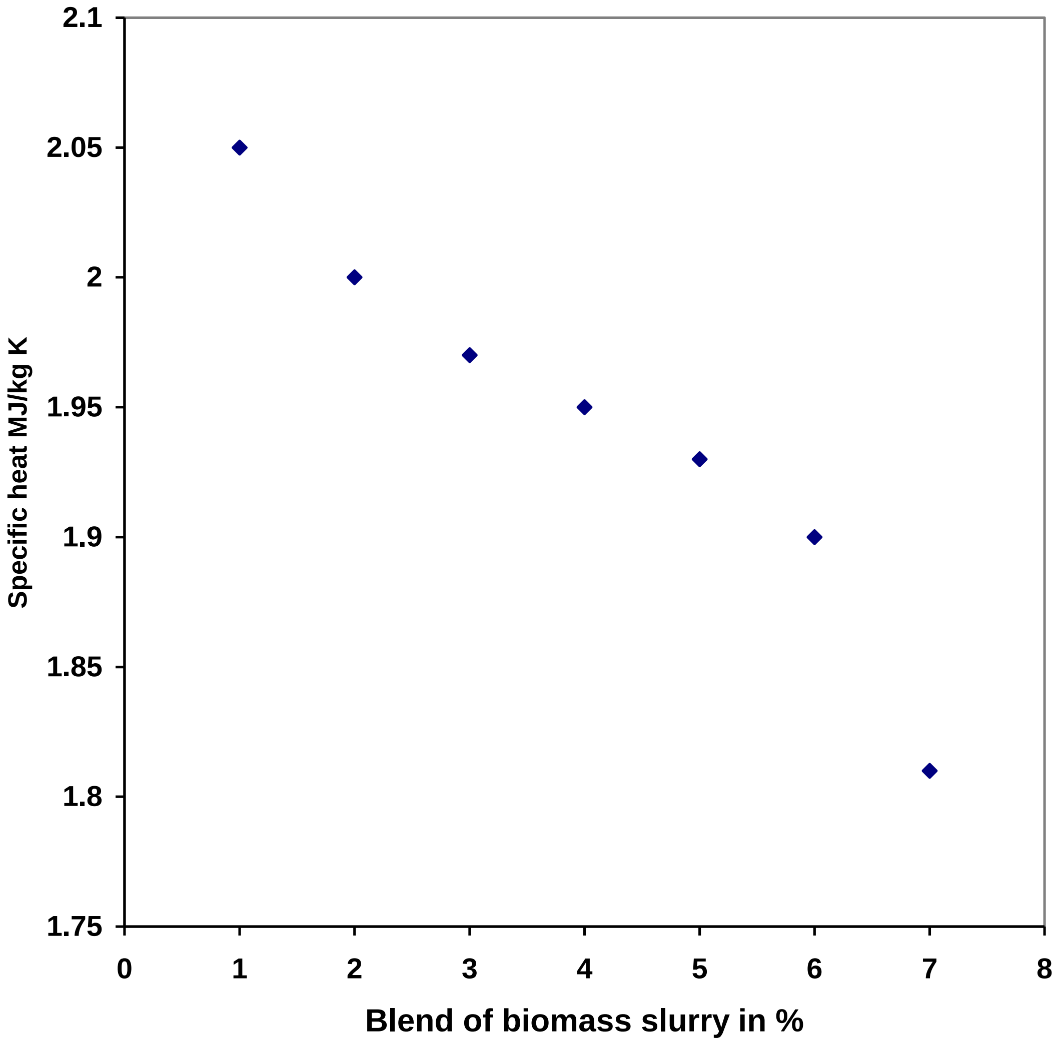


Figure 4.8 Effect of blend on Specific heat

Figure 4.7 shows the variation of specific heat of the slurry as a function of percentage of CSP for a given percentage of water. Figure 4.8 shows that the specific heat decreases with the increase in biomass percentage. The decrease is almost linear with the CSP percentage.

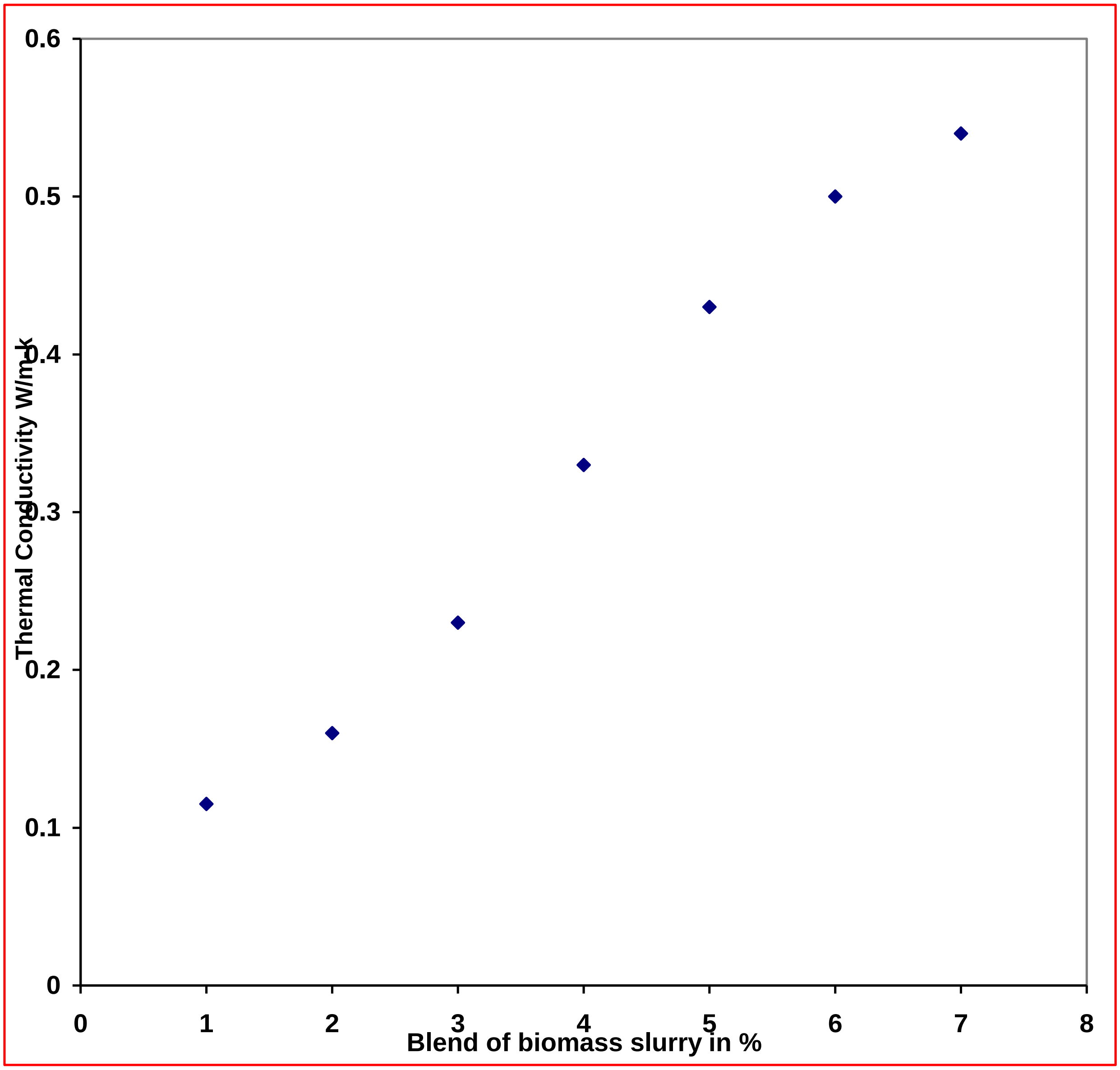


Figure 4. 9 Effect of blend on Thermal Conductivity

Figure 4.8 shows the variation of Thermal conductivity with the percentage of CSP for a fixed percentage of water in the slurry. It can be observed that the thermal conductivity of the slurry increases as the percentage of CSP increases.

4.10 Correlation equations for various properties of Biomass slurry

It can be observed from the above analysis that to determine the properties of coconut shell powder slurry fuels, we need to know the ultimate analysis of each constituent and based on those values, the ultimate analysis of the biomass slurry should be calculated. This is a very lengthy process. Therefore, to make the process simpler, Statistical-Multiple Linear Regression was applied and the correlation coefficients were calculated for all the properties of the Biomass slurry compositions. The viscosity, temperature and coal concentration were correlated by [82].

$$Y= 97.24 \times 10^{2} X_1^{-2.0103} X_2^{2.6073}$$

Where X_1 temperature deg. Cel. and X_2 ash wt. percentages in coal. Y is viscosity in centipoise. Based on the same principle the various properties of the coconut shell powder based slurry properties were calculated as follows [82a].

The various properties were correlated directly in terms of the independent variables LDO, CSP and Water. The correlation coefficients and the coefficient of variance were found to be good.

The regression equations can be made use of to calculate the above-mentioned properties of the biomass slurry for various compositions.

The calorific value of the biomass slurry can be determined from the correlation

Calorific value = 410.781(LDO) + 199.6 (CSP) + 358.6(water) kJ/kg—(1)

The correlation coefficient for this correlation is 0.9256 and the coefficient of variance is 0.9142

The Density of the biomass slurry can be determined from the correlation

Density = 0.004(LDO) +0.08(CSP) + (-0.023) (H_2O) gm/cm^3---- (2)

The correlation coefficient for this correlation is 0.979 and the coefficient of variance is 0.9685

The viscosity of the biomass slurry can be determined from the correlation

Viscosity =0.005(LDO) +0.051(CSP) + (-0.027)(H_2O) kg/m-s----(3)

The correlation coefficient for this correlation is 0.9596 and the coefficient of variance is 0.9394

The carbon content of the biomass slurry can be determined from the correlation

Carbon =0.07(LDO)+0.037(CSP)+0.001(H2O) **Kg-atom----(4)**

The correlation coefficient for this correlation is 1 and the coefficient of variance is 1

The specific heat of the biomass slurry can be determined from the correlation

Specific heat =20.6(LDO) +14.406(CSP) +20.14(H_2O) kJ/kg-K---- (5)

The correlation coefficient for this correlation is 0.9797 and the coefficient of variance is 0.9695

The Thermal conductivity of the biomass slurry can be determined from the correlation

Thermal conductivity = {0.001(LDO) + 0.019(CSP) + (-0.005)(H_2O) }W/m-K -(6)

The correlation coefficient for this correlation is 0.9787and the coefficient of variance is 0.968

The range of applicability of the above correlation is LDO from 60 to 85%, CSP from 5 to 30% and water from 2 to 10%.

The above equations helps in determining the different properties of coconut shell powder, LDO and water based slurry fuels for any composition. It reduces the work and time involved in determining the properties by various experimentations and laborious calculations.

4.11 Combustion of the above slurries in oil fired Furnace.

Table 4.7 Experimental values

Blends	Consumption time of the fuel/liter in min	Temperature K	Combustion Efficiency %
B0 (LDO)	18	1210	98.00
B5	13	1030	85.13
B10	11	1008	82.76
B15	11	0950	78.00
B20	10	0848	70.00
B25	08	0700	57.50
B30	06	0620	51.00

Table 4.7 shows the consumption time, maximum temperature and the combustion efficiency in the furnace for various slurries. It can be observed from the table that the consumption time and the temperature inside the furnace was not comparable to that of LDO (B0), the reason may be due to the slurry being a combination of solid and liquid particles, the combustion may not be complete. That is unburnt fuel may be present in the exhaust, the reason was not very clear. So, to study a detailed combustion analysis of the biomass slurry, CFD tool was used. A CFD model of the furnace was generated using preprocessor software- Gambit and the combustion analysis was carried out using Fluent-software. When the biomass combustion analysis was carried out, the velocity of the air was kept more than 68.0m/s, otherwise blocking of the nozzle with solid particles used to occur. The necessary changes from the CFD analysis were incorporated in the Experimental setup and the results were compared.

CHAPTER.5

APPLICATION OF COMPUTATIONAL FLUID DYNAMICS (CFD) TO THE COMBUSTION OF BIOMASS SLURRY

Computational Fluid dynamics (CFD) deals with the dynamic behavior of fluids and its mathematical interpretation. Fluid dynamics is based on the equations of continuity, momentum and energy equations, which represent the conservation of mass, momentum and energy. The commercially available computational fluid dynamics software-Fluent 6.0 is used to study the combustion of biomass slurry in cold flow condition, slurry inlet at room temperature and slurry heated at inlet to 328K. From the CFD analysis, the temperature distribution at various locations of the furnace is determined. The CFD analysis also predicts the emissions from the furnace to the atmosphere.

5.1 Objective of combustion modeling

Computational fluid dynamics is playing important role in simulating the combustion of biomass slurry in the combustor. The objectives of combustion modeling are

1. Simulate combustion processes
2. Help in interpretation and understanding observed combustion phenomenon.
3. Has a Substitute for difficult or expensive experiments
4. Guide the design of combustion experiments
5. Help to establish the influence of individual parameters in combustion processes, by conducting parametric studies.

5.2 Steps involved in the application of CFD tool to the combustion of biomass slurry

The following steps are involved in the application of the CFD tool-Fluent 6.0 to the combustion process of biomass slurry in the Furnace.

1. Geometrical modeling and discretisation of the combustion zone in the furnace is carried out using Gambit.

2. The biomass slurry fuel properties cannot be directly input to the fluent, thus a prePDF (probability density function) file is created, which can be fed to the fluent for studying the combustion of the biomass slurry. The calculations were carried out in two steps
    a. Adiabatic calculations
    b. Non adiabatic calculations
3. Next step is the input to the Fluent, which consists of [83]
    c. The case file consisting of Geometrical details and discretisation is imported.
    d. The prePDF file (containing the properties of the biomass slurry) is imported.
    e. The solver is selected
    f. The Turbulence model is selected
    g. Combustion model is selected
    h. Radiation model is selected
    i. Discrete phase model is selected to trace the trajectories of the particles
    j. The location and the velocities of the biomass slurry injections were defined.
    k. The properties required but not defined earlier in pre PDF file are defined
    l. Boundary conditions are incorporated
    m. Initialization of the flow field
    n. The file is saved and the iterations are started for solutions
4. Post processing of the results [84].

5.3 Geometrical modeling and discretisation of the combustion zone using gambit

The combustion chamber is a cylindrical furnace. The dimensions of the combustion chamber and the coordinate system used are shown in the Figure 5.1.

Dimensions of the furnace considered for modeling
Height of the furnace: 0.61m
Outer Diameter of the furnace: 0.93m
Inner Diameter of the furnace: 0.57m

Model-I

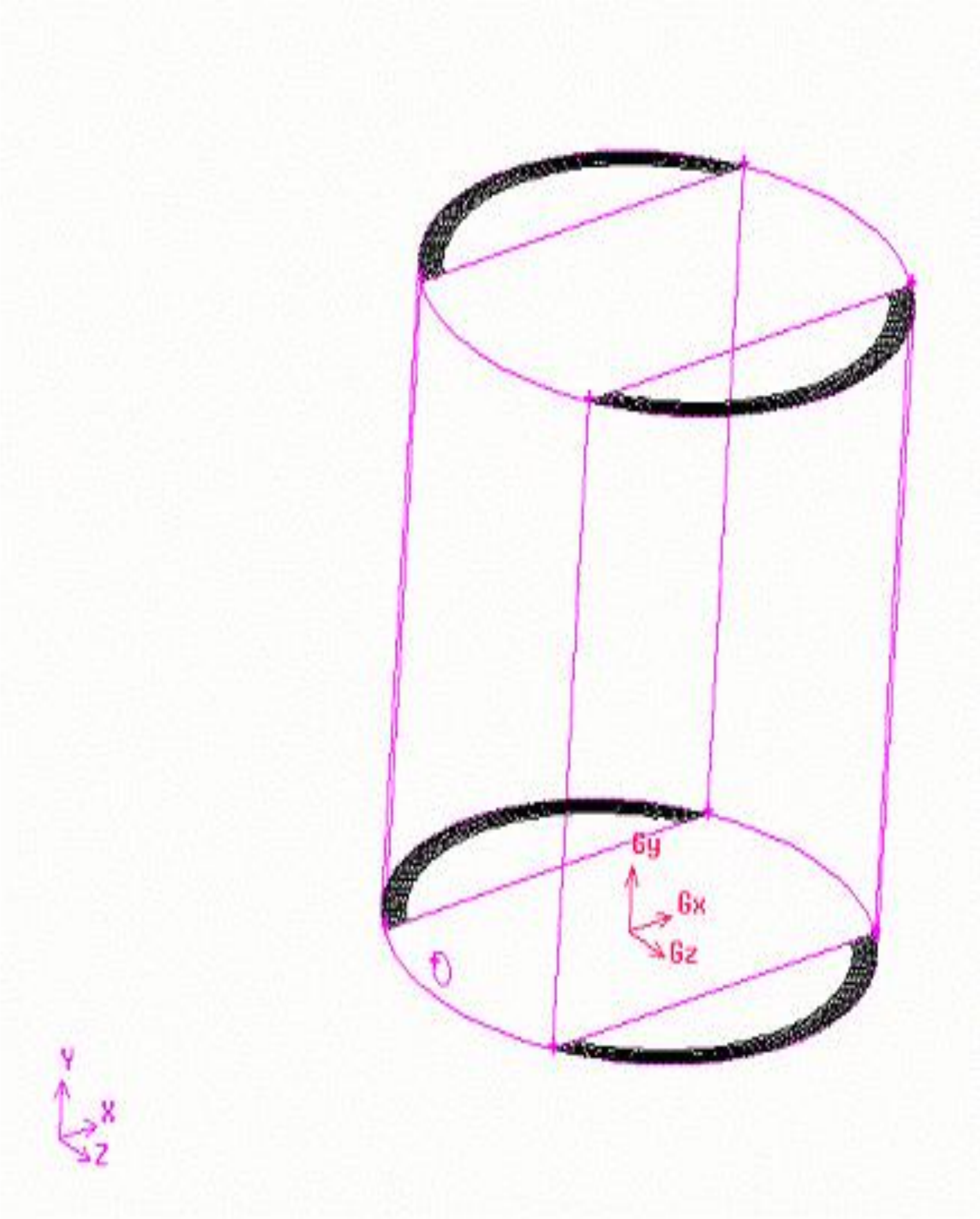


Figure 5. 2 - 3D biomass slurry Furnace Mesh outline Display

Model-II

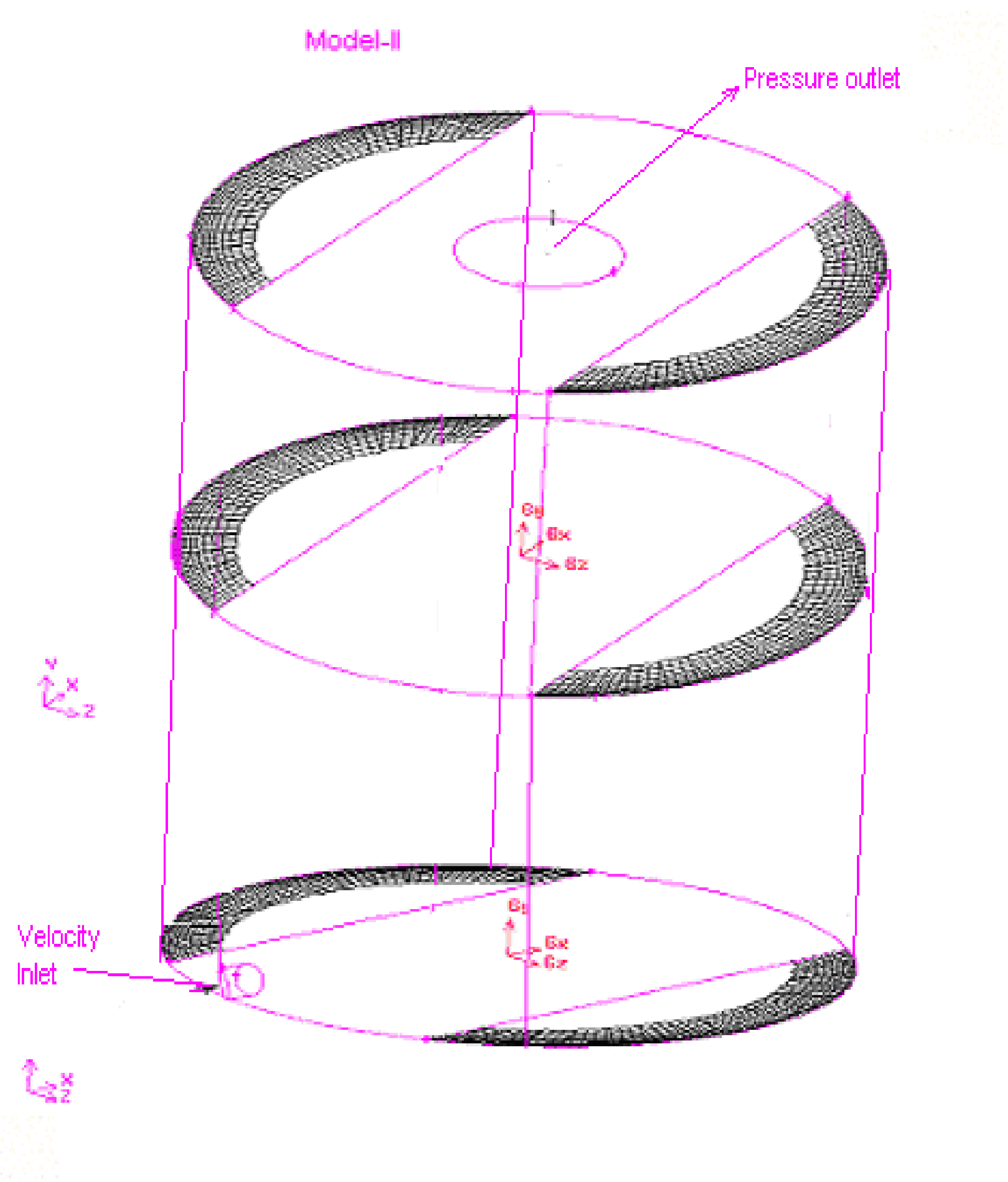


Figure5. 2 Furnace with top partially open (opening diameter of 150cm at the center)

Figure 5.2 shows the furnace with the top partially open (opening diameter of 150cm at the center). Initially the boundary layer of the furnace is created according to the given dimension, with the top partially opened. The meshing is done initially for the vertical cylinder, then the top portion of the geometry and the nozzle position is meshed.

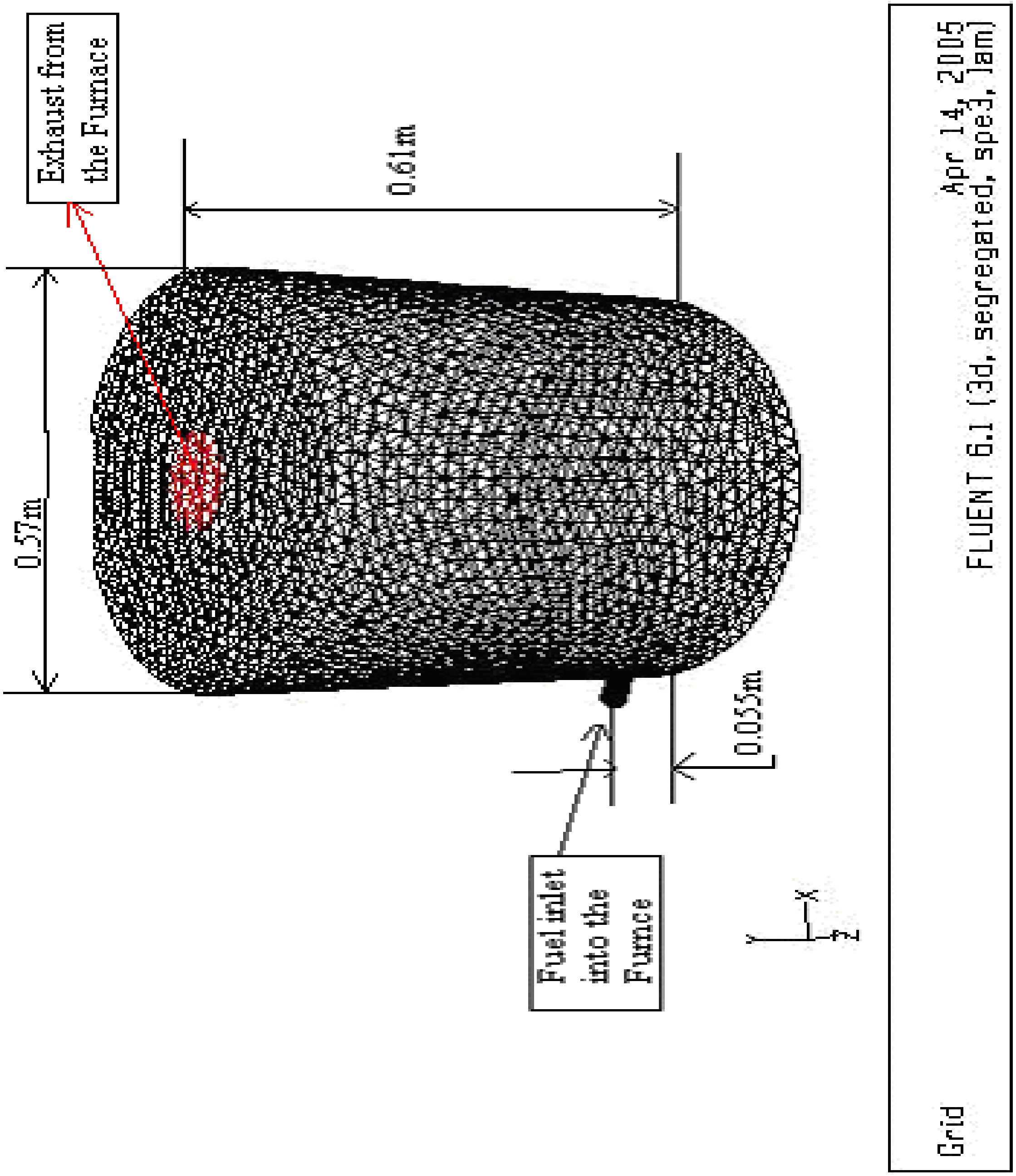


Figure 5.3 Computational grid of the furnace with top partially open.

Total number of tetrahedral elements: 117892 Size= 4

Figure 5.3 shows the grid generation of the furnace with top partially open, the grid size was varied from 6 to 3 and it was found that the most optimal grid size was 4, where in the combustion temperature for a size of 3 was same, but the time taken for the iterations was more.

5.4 Creation of the prepdf file to account for the properties of the biomass slurry

The non-premixed combustion model is selected, since there is no reaction takes place before entering the furnace. When the non-premixed combustion model is used, a PDF (probability density function) file will be created. The PDF file contains information that relates species concentrations and temperatures to the mixture fraction values. These values are used by the Fluent to obtain the scalars during the solution procedure. The thermo chemistry calculations are preprocessed in prePDF and tabulated for lookup in Fluent. Interaction of turbulence and chemistry is accounted for with a probability density function.

The system considered is non-adiabatic system, since there is heat transfer from the walls, slurry particles and the exhaust gases. Since non-adiabatic calculations are more time consuming than those of adiabatic systems, the adiabatic calculations are first considered.

Adiabatic Calculations

The pre PDF setup was started by considering the results of adiabatic systems, which will determine the appropriate system parameters that will make the non-adiabatic calculations more efficient. This process of beginning with an adiabatic system calculations is followed in all PDF calculations that ultimately require a non-adiabatic model. The figure 5.5 shows the time average mean temperature variation with respect to the mean mixture fraction for the adiabatic system. Figure 5.4 shows the Instantaneous Species Mole Fractions Derived from Equilibrium chemistry Calculation.

In non-premixed combustion, for chemistry models, the equilibrium chemistry was selected, since it is more accurate and Fluent, by default, prefers equilibrium chemistry. The beta function PDF model is selected as it is more accurate than delta PDF, since more mathematical calculations are involved in beta PDF, which closely represents experimentally observed PDFs.

In the empirically defined streams, fuel stream is selected which allows to define the composition in terms of atom fractions of C, H, O and N, along with there heating values and specific heat of the fuel. This is a useful option when the ultimate analysis and heating value of the fuel are known.

The chemical species in the fuel system is defined based on the equilibrium system, which consists of 11 species i.e. C, H, O, N, O_2, N_2, CO, CO_2, H_2, H_2O and C(S). C, H, O and N are defined because the fuel stream will be defined in terms of these atom fractions.

The fuel considered is known from the proximate analysis along with the ultimate analysis, to define the fuel composition in **prePDF.** The proximate analysis data is converted to dry ash free (DAF) basis and from these data the ultimate analysis of the fuel is known and the ultimate analysis of different slurry fuels is given in the Table 5.1

Once the mole fractions of the fuel is defined in terms of C, H, O and N (the density of the solid carbon is 1300 kg/m^3), prePDF computes the mixture density for the fuel by using this data.

Next, the system pressure and inlet stream temperatures are required for the equilibrium chemistry calculation. The fuel stream inlet temperature for biomass slurry combustion should be the temperature at the onset of devolatilisation. The oxidizer inlet temperature should correspond to the air inlet temperature. For the biomass slurry fuel the devolatilisation temperature is set to 600K and the oxidizer temperature to 600K. The system pressure is one atmosphere.

Table5.1 Ultimate analysis of Biomass slurry for different blends

Element	At. Wt.		B0			B5	
		Wt.	kg Atom	Mole Fraction	Wt.	kg Atom	Mole Fraction
C	12	84.1	7.00	0.306	73.71	6.15	0.29
H	1	15.9	15.9	0.690	14.93	14.93	0.69
O	16	-	-	-	11.03	0.6893	0.032
N	14	-	-	-	0.12	0.0086	0.0004
			22.90			21.85	

	B10			B15	
Wt.	kg Atom	Mole fraction	Wt.	kg Atom	Mole fraction
71.72	5.98	0.29	69.8	5.82	0.28
14.44	14.44	0.69	14.0	14.0	0.67
13.16	0.83	0.04	15.3	0.96	0.047
0.24	0.018	8.5e-04	0.36	0.026	1.2e-03
	21.23			20.8	

	B20			B25			B30	
Wt.	kg Atom	Mole fraction	Wt.	kg Atom	Mole fraction	Wt.	kg Atom	Mole fraction
67.75	5.65	0.28	65.77	5.49	0.28	63.73	5.32	0.28
13.75	13.75	0.67	12.99	12.99	0.66	12.5	12.5	0.65
17.42	1.09	0.054	19.50	1.22	0.062	22.7	1.42	0.074
0.48	0.035	0.0018	0.60	0.043	0.002	0.72	0.052	2.7e-03
	20.52			19.74			19.28	

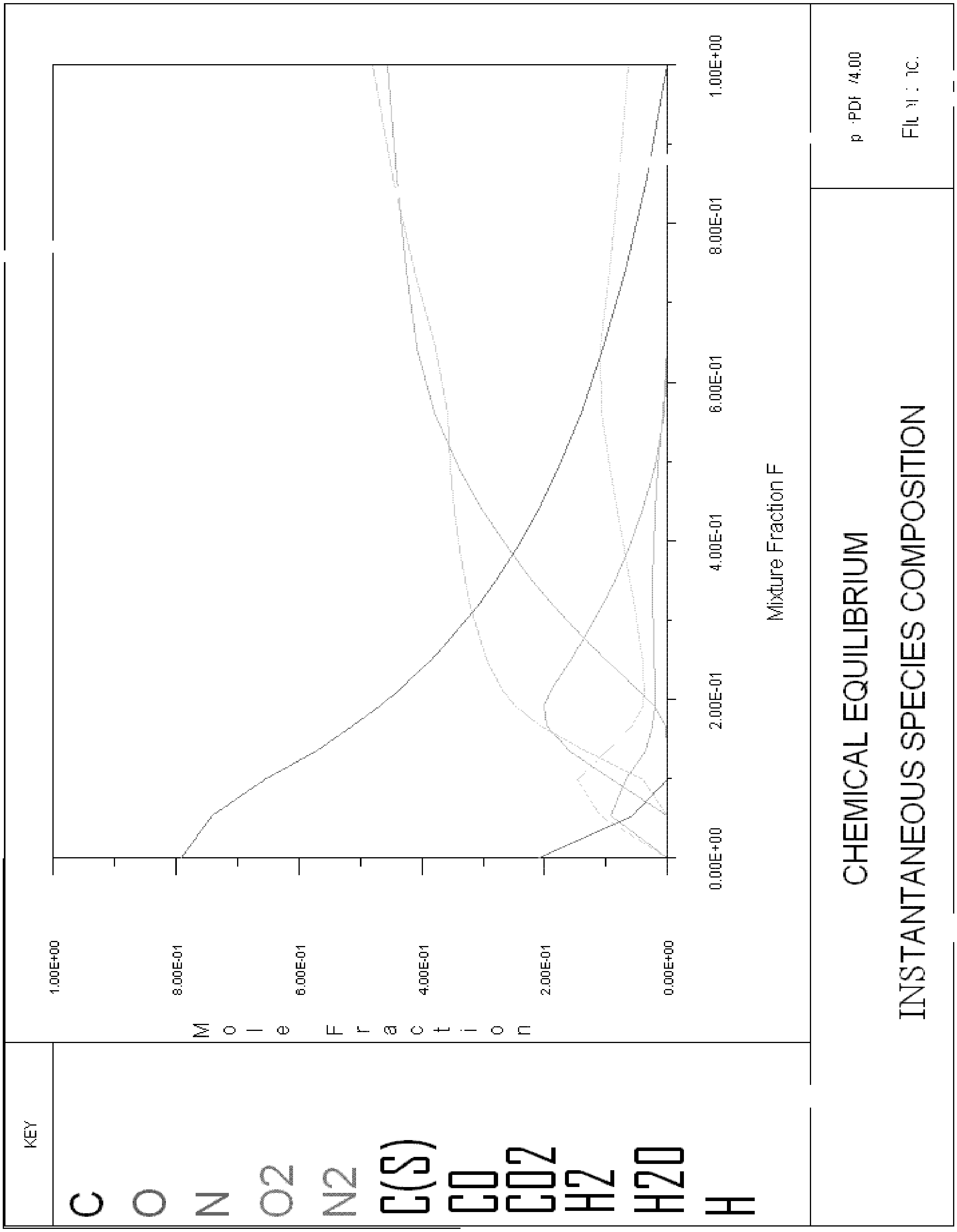


Figure 5.4 Instantaneous Species Mole Fractions Derived from Equilibrium chemistry Calculation

Equilibrium Assumption: The equilibrium model assumes that the chemistry is rapid enough for chemical equilibrium to always exist at the molecular level. An algorithm based on the minimization of Gibbs free energy is used to compute species mole fractions. Figure 5.6 shows the resulting mole fractions for a reacting system that includes 11 species in the combustion of biomass slurry with air. The equilibrium model is powerful since it can predict the formation of intermediate species and it does not require knowledge of detailed chemical kinetic rate data. Instead of defining a specific multi-step reaction mechanism, simply define the important chemical species that will be present in the system. **FLUENT** then predicts the mole fraction of each species based on chemical equilibrium.

5.5 Non-adiabatic Calculations

Creating a non-adiabatic PDF system requires that the system is redefined as non adiabatic and setting the peak system temperature 100K more than the adiabatic temperature. In the operating conditions, the minimum temperature should be less than the minimum system temperature i.e. below the temperature at which the volatiles begin to evolve from the slurry fuel. From this, the non-adiabatic calculations are predicted as follows.

```
              INITIALISING ENTHALPY AT TEMPERATURE LIMITS
                ........NON-ADIABATIC CALCULATION.....................

     POINTS   TO-GO H-POINT    EQUILIBRIUM       BETA-PDF
3949   209   16   T(K) = 1490.   F-MEAN = 0.86        F-VAR = .005
3950   208   16   T(K) = 1487.   F-MEAN = 0.86        F-VAR = .012
3951   207   16   T(K) = 1488.   F-MEAN = 0.86        F-VAR = .019
3952   206   16   T(K) = 1491.   F-MEAN = 0.86        F-VAR = .027
3953   205   16   T(K) = 1497.   F-MEAN = 0.86        F-VAR = .036
3954   204   16   T(K) = 1506.   F-MEAN = 0.86        F-VAR = .047
3955   203   16   T(K) = 1514.   F-MEAN = 0.86        F-VAR = .060
3956   202   16   T(K) = 1515.   F-MEAN = 0.86        F-VAR = .076
3957   201   16   T(K) = 1495.   F-MEAN = 0.86        F-VAR = .096
3958   200   16   T(K) = 1443.   F-MEAN = 0.86        F-VAR = .120
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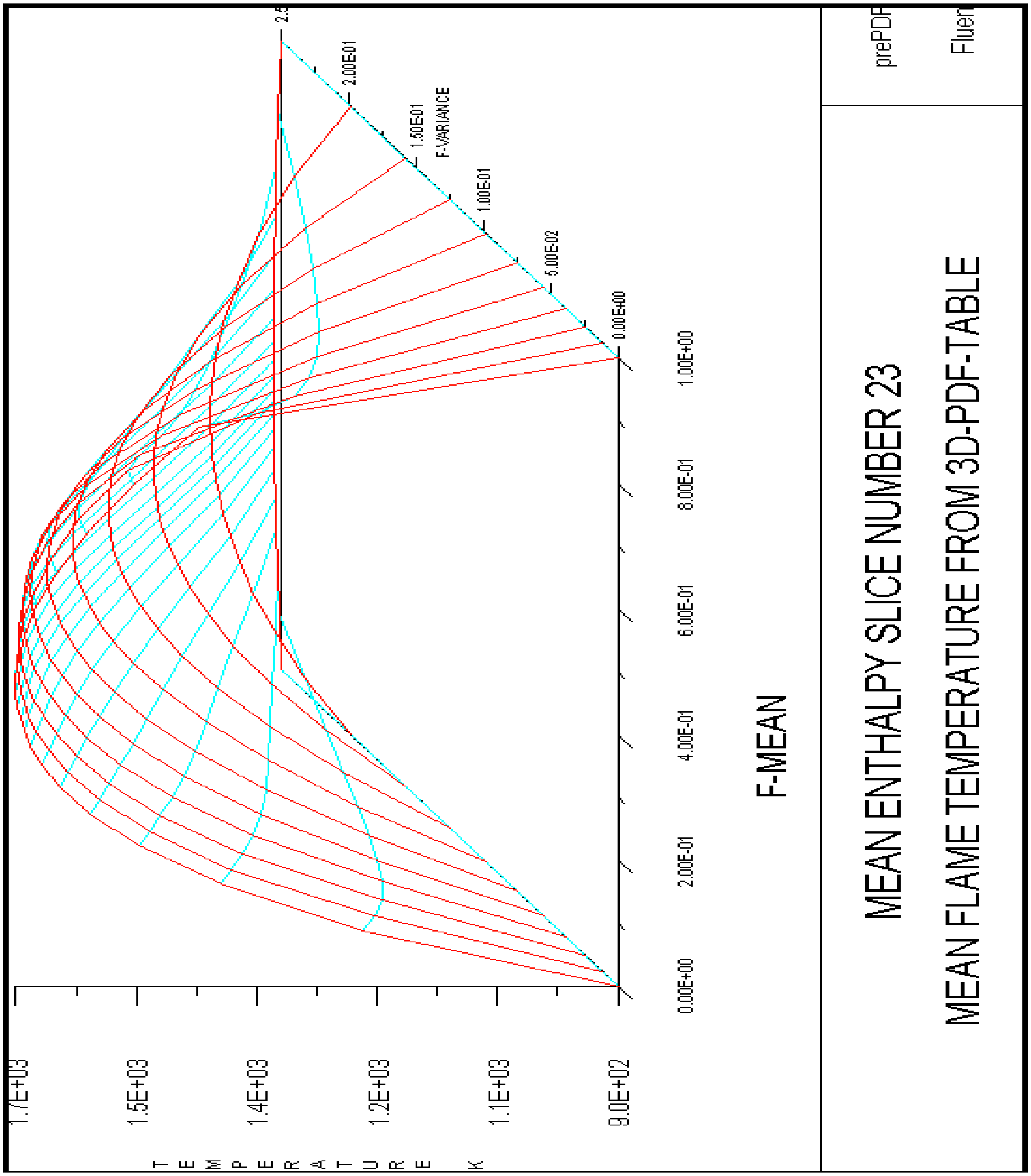

Figure 5.5 pre PDF Adiabatic Temperature

Figure 5.5 shows the Temperature generated by prePDF for a simple hydrocarbon system. (Single-Mixture-Fraction, Adiabatic system)

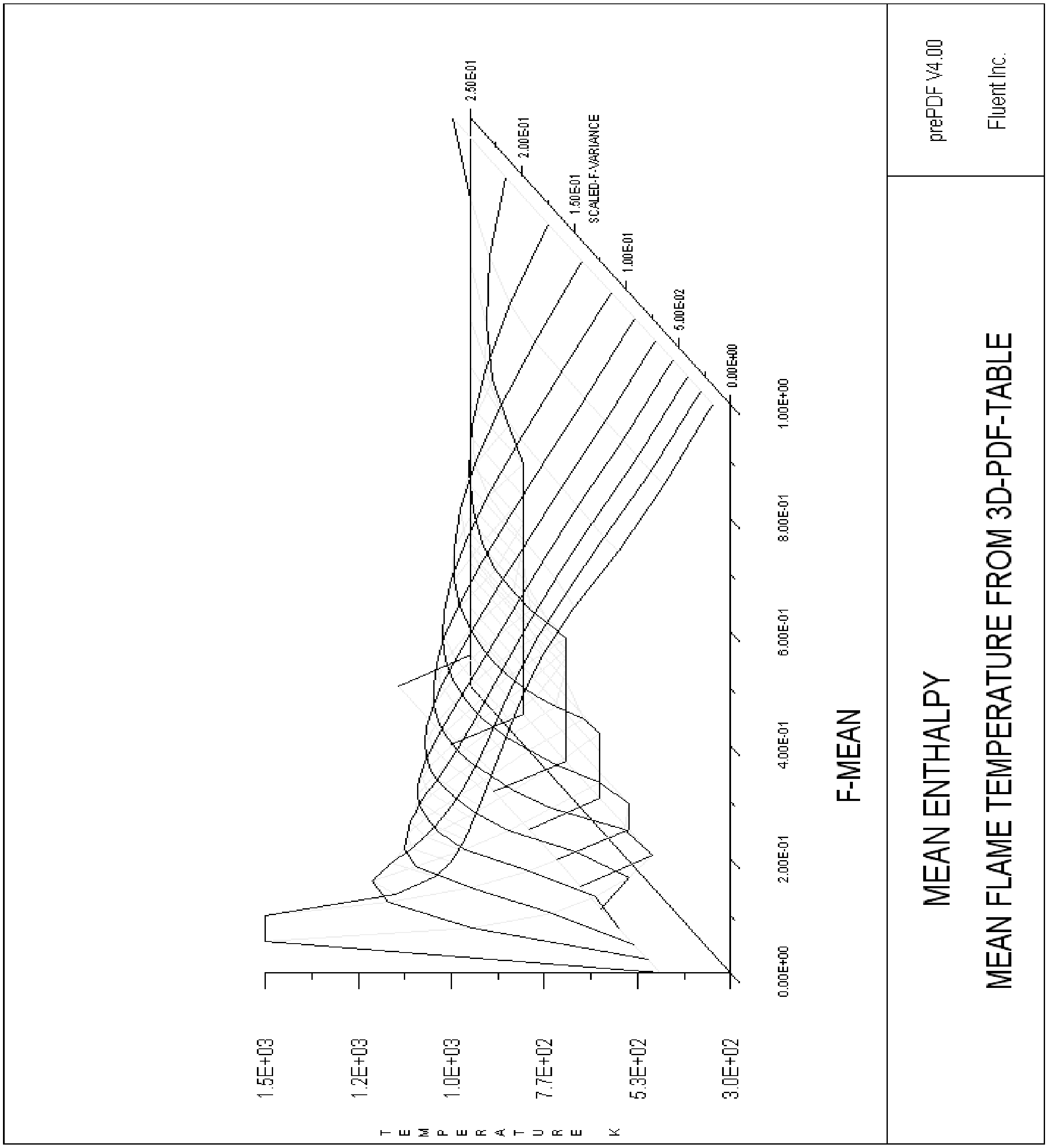

Figure 5.6 pre PDF Non-Adiabatic Temperature corresponding to adiabatic enthalpy

Figure 5.6 shows the 3-Dimensional Single Mixture Fuel Fraction Non Adiabatic system

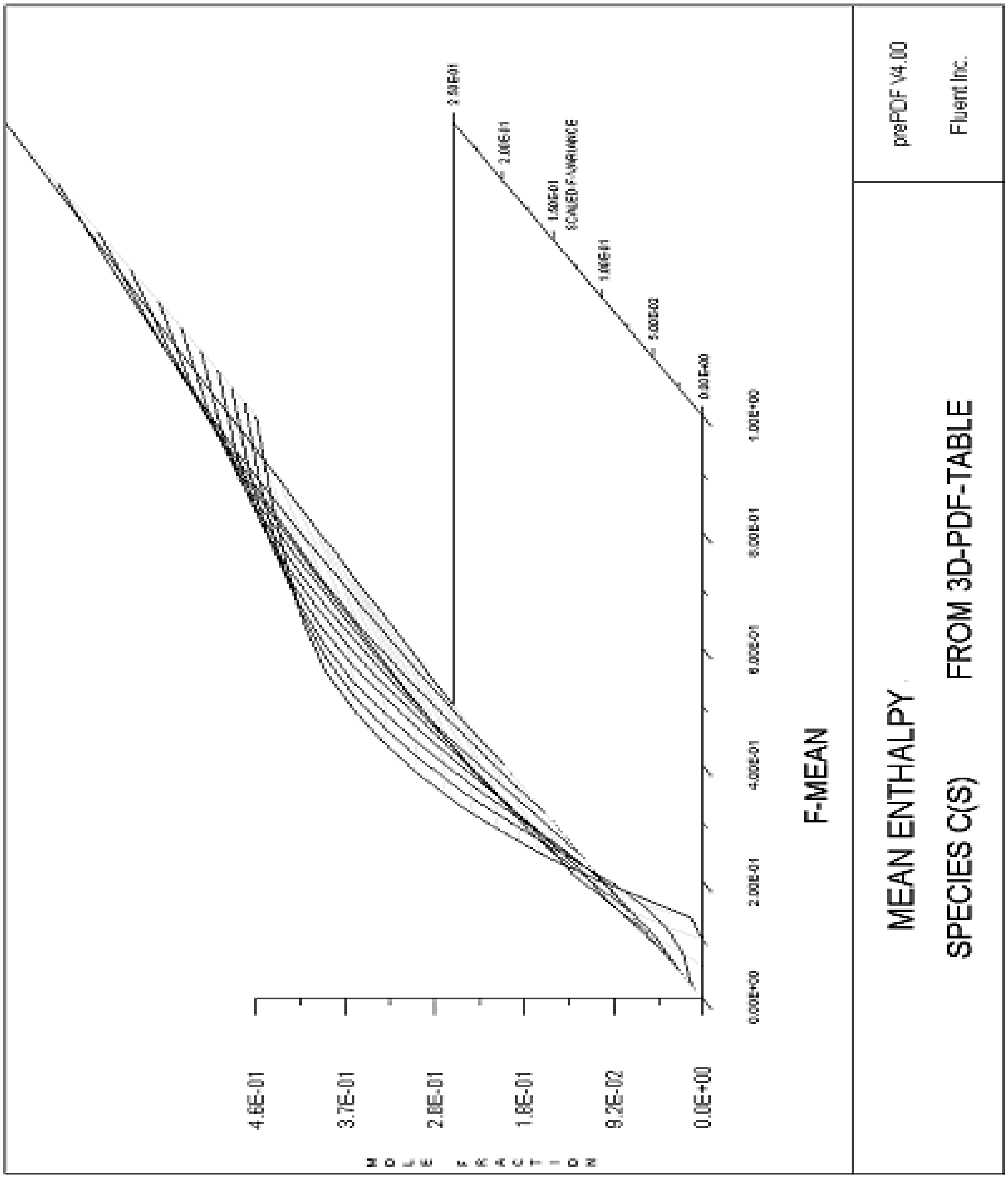

Figure 5.7 Time-Averaged C(S) Mole Fractions. Non-Adiabatic prePDF calculation

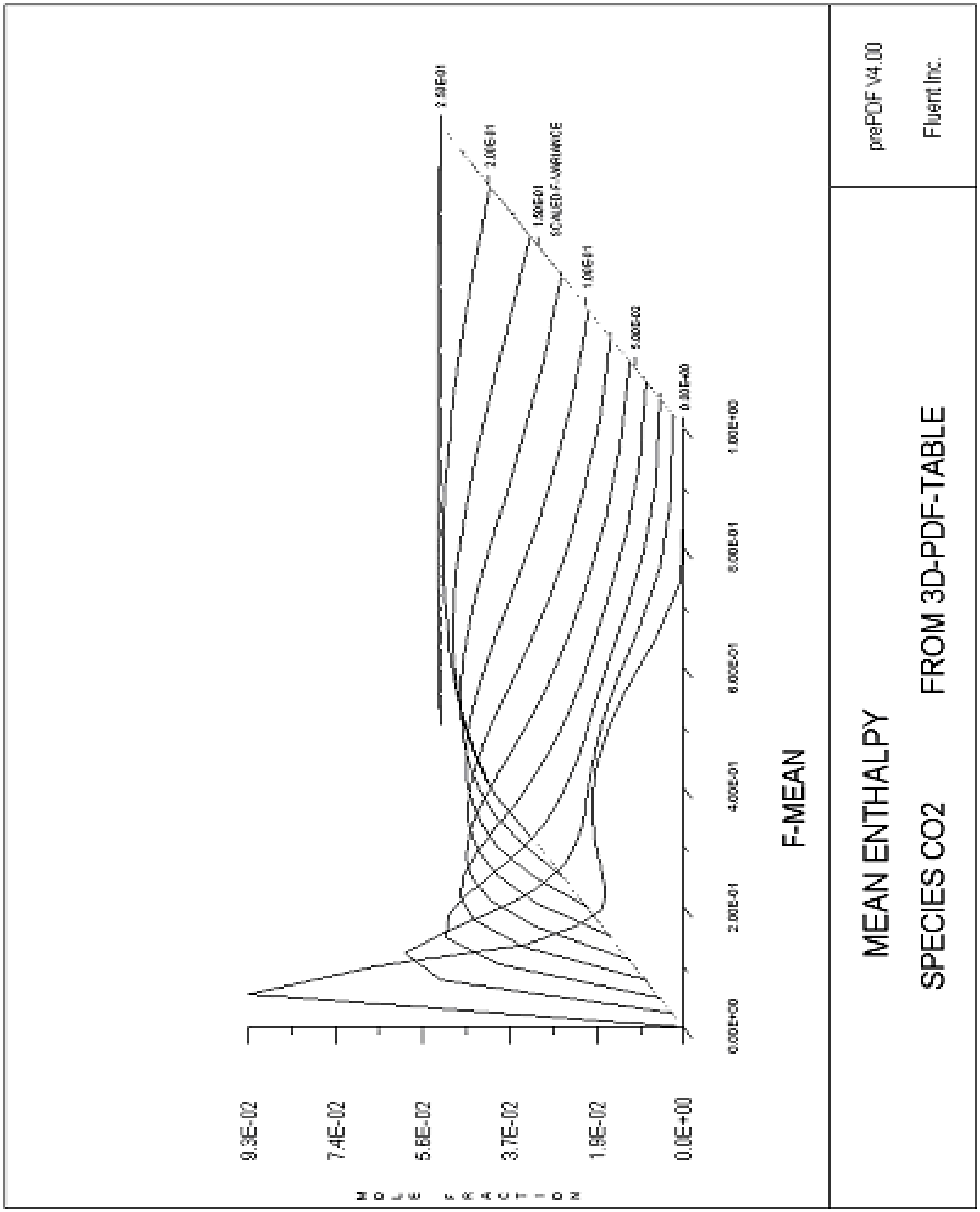

Figure5.8 Time-averaged CO_2 Mole Fractions. Non-Adiabatic prePDF calculation

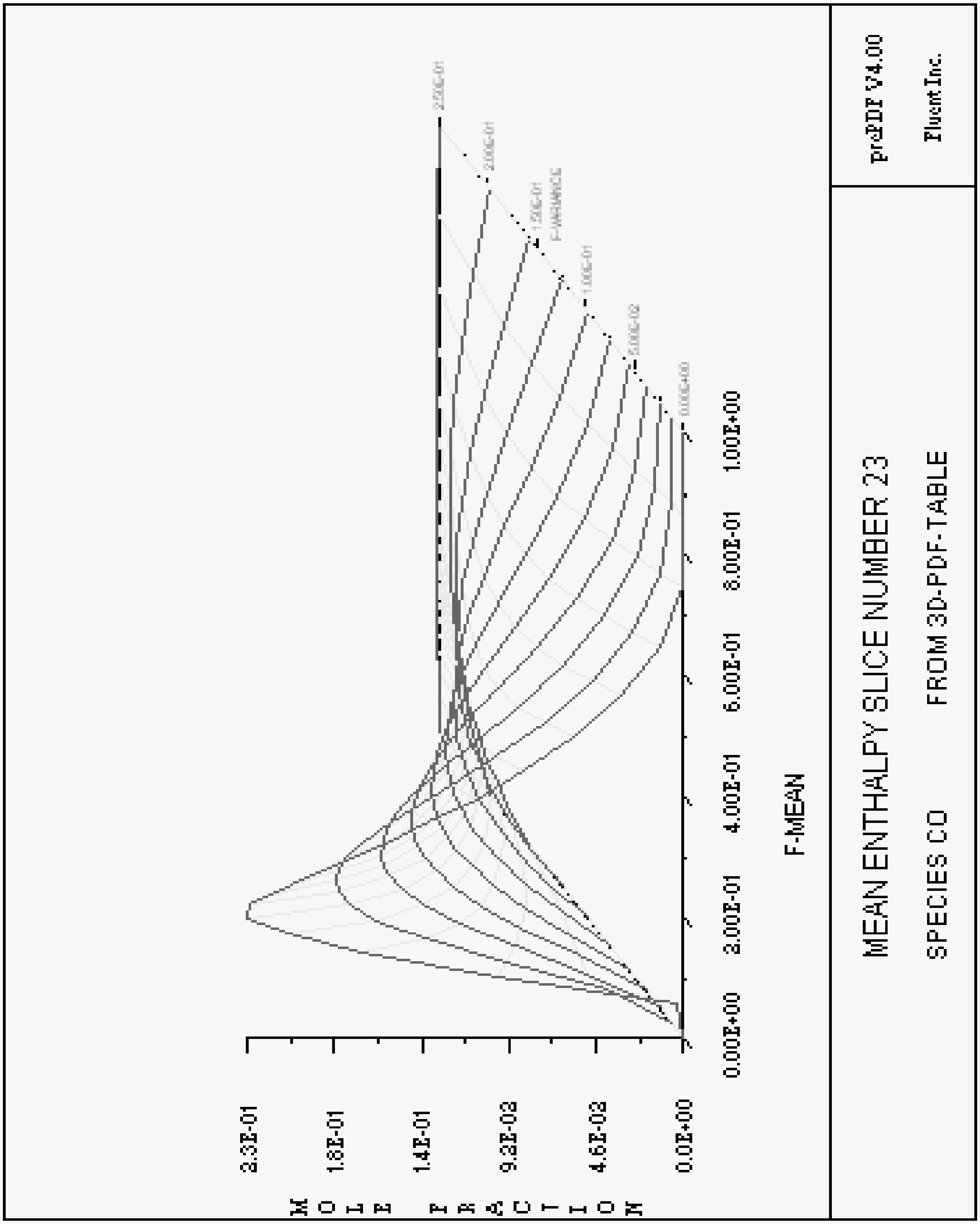

Figure 5.9 Time-averaged CO Mole Fractions. Non-Adiabatic prePDF calculation

Figure 5.6 shows the non-adiabatic temperature. Figure 5.7 shows the Time-Averaged C(S) Mole Fractions for Non-Adiabatic prePDF calculation. Figure5.8 shows the Time-averaged CO_2 Mole Fractions for Non-Adiabatic prePDF calculation. Figure5.9 shows the Time-averaged CO Mole Fractions for Non-Adiabatic prePDF calculation. The enthalpy field is initialized and the enthalpy grid adjusted to account for inlet conditions and solution parameters. Time-averaged values of temperature, composition, and density at the discrete mixture-fraction/mixture-fraction-variance/enthalpy points (21 points, as defined in the **Solution Parameters** panel) are then calculated. The result will be a set of tables containing time-averaged values of species mole fractions, density, and temperature at each discrete value of these three parameters.

With these results, the PDF file is saved and used in the fluent to study the combustion characteristics of biomass slurry fuels.

5.6 INPUT TO FLUENT SOFTWARE

a. Geometrical details and discretisation is imported.

The grid file is imported from the Gambit software. Initially based on the geometry of the Combustion chamber and the boundary conditions the geometry is created and fine meshing is done for more accurate results using Gambit software. This file is imported from PDF file, when the combustion is carried out using Fluent soft ware. After importing the file, the grid check is carried out. The grid check should not report any errors or negative volumes.

b. prePDF file (containing the properties of the biomass slurry) is imported.

Once the PDF file is read into the fluent software, the **PDF file written successfully** command, should be observed, which implies that there was no error in importing the PDF file. The PDF file contains information that relates species concentrations and temperatures to the mixture fraction values. These values are used by the Fluent to obtain the scalars during the solution procedure. The thermo chemistry calculations are preprocessed in prePDF and tabulated for lookup in Fluent. Interaction of turbulence and chemistry is accounted for with a probability density function.

c. The solver

The non-premixed combustion analysis of the biomass fuel is carried out using **segregated** solver. The option of **implicit, 3D, steady state, absolute velocity formulation** and **Cell based gradient** were selected. The solver helps in defining the kind of problem like segregated or coupled, wherein the non-premixed combustion comes only with segregated solver using implicit formulation. The problem should also be defined like 2D or 3D problem, so that the number of equations and iterations also will be defined. The flow is steady or unsteady also should be defined, as the present combustion is a continuous flow problem it is defined as a steady problem with absolute velocity and cell based gradient.

d. The Turbulence model

K-ε turbulence model was selected. Since the Reynolds number of the flow is 463125 based on the diameter of the furnace, the flow is turbulent and thereby **high Re number** K-**ε model** is selected from the turbulence menu.

e. Combustion model is selected

The species in the model is defined as non-premixed and immediately the different species that was defined in pre PDF will be highlighted along with there properties. Fluent will automatically activate solution of the energy equation when it reads the non-adiabatic PDF file.

f. Radiation model

The radiation model P-1 will be activated for the exchange of radiation between fuel and the particulates. Since the given problem accounts for radiation through the walls, thermocouple and exhaust gases, radiation is considered present and is activated.

g. Discrete phase model was selected to trace the trajectories of the particles

The flow of pulverized slurry particles was modeled using the discreet phase model. This model predicts the trajectories of the individual fuel streams, each representing a continuous stream of slurry. Heat, momentum and mass transfer between the slurry fuel and the gases was included by alternately computing the discreet phase trajectories and the gas phase continuum equations.

The number of continuous phase iterations per DPM iteration is set to 20 or more based on the particle size loading or larger grid size. The tracking parameter is set to around 10000 it was used to abort trajectories of particles in recirculation. The total mass flow rate of slurry fuel of 0.003kg/s was defined and the Rosin-Rammler size distribution is activated since the particle size keep varying as shown in the sieve analysis of coconut shell powder. The number of particle stream is set to 10 and the range of specified initial conditions to 09 discrete particle streams with varying injection group.

h. Biomass slurry injection

The material biomass was selected in the material dropdown list, which is not there in the fluent database, but it is created using the slurry properties with its appropriate properties. The oxidizing species oxygen was selected in the oxidizing species. The point properties that is the point of injection is calculated and the initial conditions are calculated. The furnace initial conditions were set as X- Position = -0.285m, Y-Position = 0.055m, Z – Position = -0.003m, inlet diameter = 0.01m, X-Velocity = 47.81m/s, Y-Velocity = 18.11 m/s, Z-Velocity = 47.81 m/s, Temperature = 1000K, Total flow rate = 0.002kg/s, Minimum diameter = 20e-6m, Maximum diameter = 70e-06m, Mean diameter = 45e-06m, with this properties the injection definitions are defined as in the fluent software.

Under the particle type option combusting is activated, which helps in slurry fuel devolatilisation and char burnout.

i. The properties required but not defined earlier in pre PDF file were defined

When we use the non-premixed combustion model, the material used for all fluid zones is automatically set to PDF-mixture. The constituent species of this mixture are the species that are defined in prePDF, we cannot change them in FLUENT. When the nonpremixed model is used, heat capacities, molecular weights, and enthalpies of formation for each species considered are extracted from the chemical database, so that we will not modify any properties for the constituent species in the PDF mixture. For the PDF mixture itself, the density is determined from the tables and the specific heat is determined via the mixing law, using specific heat values for the constituent species obtained from the chemical database.

The physical property inputs for a non-premixed combustion problem are therefore only the transport properties (viscosity, thermal conductivity, etc.) for the PDF mixture. To set these in the Materials panel, PDF mixture was selected as the Material Type, PDF-mixture (the default, and only choice) in the Mixture Materials list, and set the desired values for the transport properties.

All thermodynamic data including density, specific heat and formation enthalpies were extracted from the prePDF chemical database when the non-premixed combustion model is used. These properties were transferred to Fluent as the PDF-mixture material, for which only transport properties, such as viscosity and thermal conductivity are defined for various blends as given in the Table 5.2 (in the Appendix-I). In the absorption coefficient wsggm-cell-based were selected.

The following properties are set for the combustion particles like density, specific heat thermal conductivity, vaporization temperature, volatile component fraction; combustion fraction etc. in the devolatilisation model single Rate devolatilisation model is selected with pre exponential factor = 492000 and the activation energy = 7.4e07 as default values given by fluent [83]. In the combustion model kinetics/diffusion limited option is selected with mass diffusion limited rate constant = 5e-12, kinetics limited Rate pre-exponential factor = 0.002 and kinetics limited rate activation energy = 7.9e+07 which are the default values defined by Fluent for non-premixed mixture combustion [84].

j. Boundary conditions are incorporated

The boundary conditions are set with velocity inlet in terms of intensity and hydraulic diameter i.e. the inlet diameter into the combustion chamber and since the slurry comes from the discrete phase the mean mixture fraction and mixture fraction variance are set to zero.

The pressure outlet is set with gauge pressure of zero which implies that the system pressure at the exit to be the operating pressure.

The wall of the combustion chamber was treated as an isothermal boundary with a temperature of 1000K and material of the wall is mild steel.

k. Initialization of the flow field

In the solution parameters the under relaxation factors are set and initialization is done with the computation from the velocity inlet. With this input values initialization is done and the apply command is given by solving the monitors-residual.

With this data the file is stored in case file and the number of iterations will be specified in the iteration step. Once the iterations are completed the file is stored in the data file and the post processing results are tabulated, which are presented and discussed in the chapter on Results and discussions.

5.7 Post-processing results

The post processing option allows one to choose, the planes at which the desired property contours can be plotted. The output can be in terms of the temperatures and emissions. It is also possible to select an option to show the trajectories of the particles.

In the case of the cold flow analysis, the trajectories of the particles are traced to determine the residence time. In the case of the combustion of the biomass slurry, the temperature distribution at various locations in the furnace is determined in general and temperature contour plots at selected transverse planes are selected. The emissions from the furnace outlet are also obtained as output of the CFD analysis.

5.8 Results of CFD analysis

The results obtained from the CFD analysis for different compositions of the coconut shell based slurry fuel are presented (in terms of temperature distribution and emission from the furnace outlet) and discussed in Chapter.7

CHAPTER-6

EXPERIMENTAL INVESTIGATIONS

In the present investigation, coconut shell powder based fuel slurries prepared were burnt in the furnace, by changing the furnace setup according to the CFD analysis.

Furnace temperature distributions and emission from outlet of the furnace were measured in the experiments. Effect of coconut shell powder concentration on Temperature distribution in the furnace and the emission from the furnace outlet are studied.

Melting of aluminum in the furnace and steam generation as a function of the composition of the slurry was studied. In addition, the performance of the diesel engine by using the slurry is also studied.

6.1 Experimental setup

The experimental setup consists of an oil-fired furnace with the burner or nozzle placed at the bottom periphery of the furnace. To this burner a blower is connected, which supplies both primary and secondary air for combustion. The fuel supply line was connected to the burner through oil preheated.

The fuel supply system consists of two tanks. One is a LDO tank and the other is biomass slurry (LDO+CSP+WATER) tank. The slurry tank is fitted with a mechanical stirrer driven by an electric motor in order to avoid settling of the coconut shell powder. Compressed air connection was provided to the slurry to create pumping action if required. The slurry tank was made airtight for this purpose. The outlets of both the tanks were connected to a single supply line and by operating the valves, fuel supply to the burner can be had from any one of the tanks. The schematic diagram of the setup is shown in Figure 6.1 and Plate.3

6.2 Nozzle

Figure 6.2 shows the burner used in the experimental setup. It consists of a central hole, through which the liquid fuel or slurry flows. The rate of flow of the biomass slurry fuel can be controlled by operating the fuel valve, which is connected to the oil line coming from the oil pre-heater. Atomization rate can be controlled by operating the needle valve. There are two airports, one for the primary air supply and the other for secondary air supply. In the primary air supply, line a continuous helical path was provided to create swirling of air. The swirling helps better mixing of air with fuel. At the exit of the burner, a nozzle is provided. The sudden expansion of air creates vacuum, which helps to draw the fuel from the fuel nozzle. Over the primary air passage, the secondary air passage was provided. The air enters tangentially to this passage. The quantity of air supply can be controlled by passing the gates provided in the main entrance of the burner.

6.3 Operating procedure of the furnace

The slurry was prepared by mixing a measured quantity of light diesel oil with measured quantity of coconut shell power and water. The slurry was poured into the slurry tank and closed. The stirrer was switched on to continuously stir the slurry. To start with, the valve connected to the oil tank was opened and the oil was made to flow through the oil pipe line. Blower was switched on and the furnace was fired by adjusting the velocity of air suitably, so that the flame does not come out of the furnace and a stable flame is achieved.

The Furnace was readjusted with the nozzle position with respect to the CFD results obtained and the experimentation was carried out, Light Diesel oil (LDO) was first burnt and then the biomass slurries were burnt, during combustion the Temperature distribution, consumption time of the fuel and emission analysis of the fuel was recorded

The slurry prepared by mixing CSP, LDO and water was burnt. The flames were photographed and shown in the Plate.3. The mixture was burnt without any difficulty. There was no need to add any stabilizing agent. The flame was found to be stable. By adding shell powder to LDO, oil can be replaced partly by shell powder as an energy source. Plate.5 shows the combustion of biomass slurry with LDO and water. Initially when lighting the furnace, the furnace was preheated for minimum of 30 minutes with LDO. Until the furnace reaches red-hot condition, Preheating was necessary as it was not possible to readily ignite the shell powder based water slurry, since it used to take long time. The preheating of the furnace helps in evaporating the water present in the slurry and also in the ignition of the shell powder.

The Furnace was run for nearly 9 hours continuously and during that period no blockage of the nozzle was encountered and the flame was very stable. While burning the various fuels, the temperatures of the flames were measured at different planes using Chromel-Alimuinum Thermocouple. The time taken for consumption of the fuel was recorded and the emission of the biomass slurry was recorded using gas analyzer.

The furnace was modeled with the nozzle placed at the bottom of the furnace as shown in the Figure 6.1. The inlet of fuel to the furnace is at the bottom and the fuel enters the furnace in a spray form. Biomass slurry enters the furnace at the bottom with an average mass flow rate depending on the composition of the fuel. The furnace temperature of 600k was maintained constantly before the slurry fuel is let in to the furnace. With CSP as the solid fuel, hardly any fly ash was found. However, by firing the Furnace for a long time, a few grams of fly ash was collected and proximate analysis of fly ash showed hardly any fixed carbon. This indicated that the combustion of the solid fuel was complete. Furnace was fired continuously 8-10 hours a day, for months together. The commercially available nozzle did not pose any problem with coconut shell powder oil mixture up to a blend of 30% after that the slurry became to a highly viscous (paste form) and blocking of the nozzle started taking place. Therefore, the CSP based slurries can be used in the existing oil fired foundary furnace without any hardware modifications

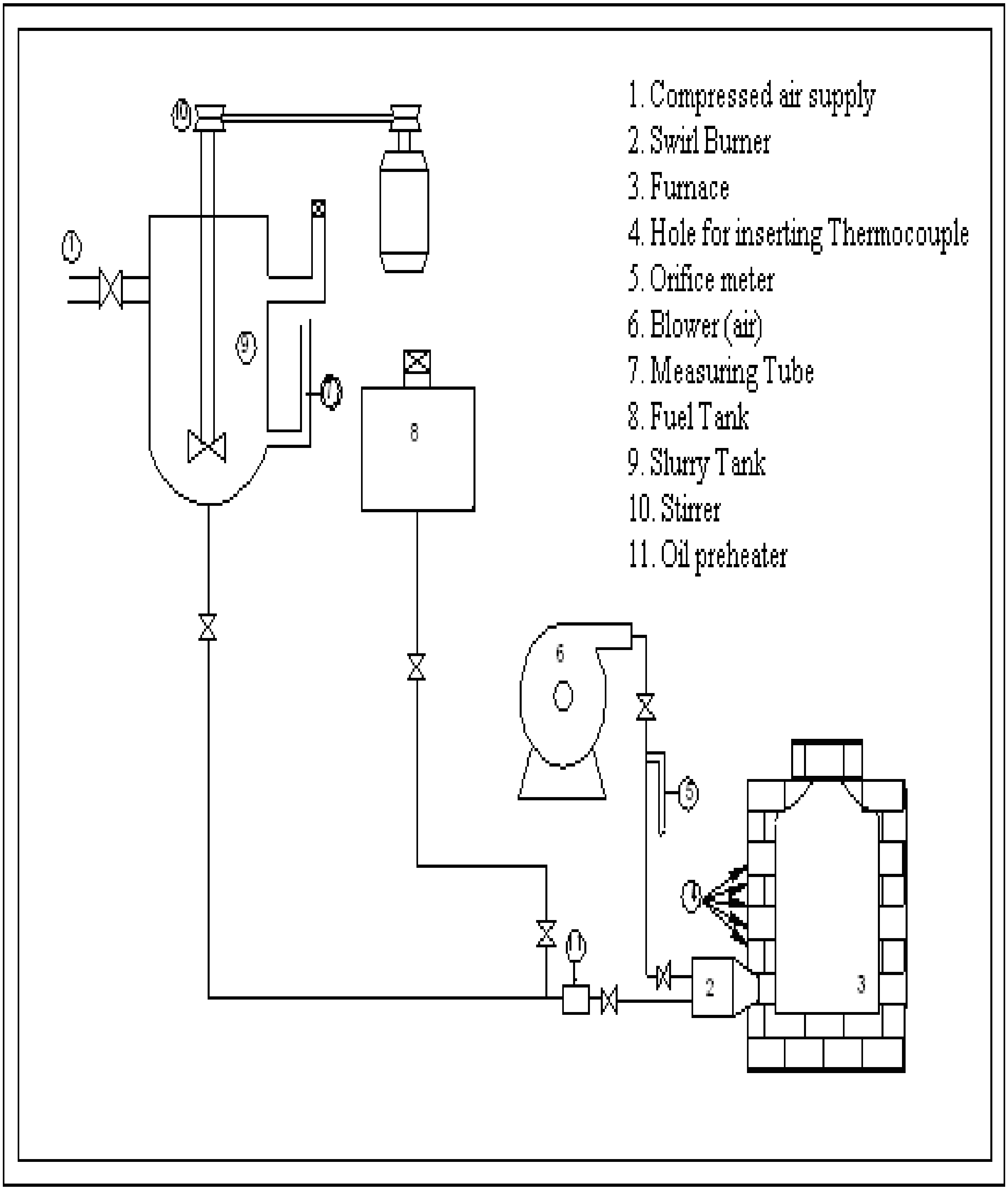

Figure 6.1 Experimental setup of the furnace

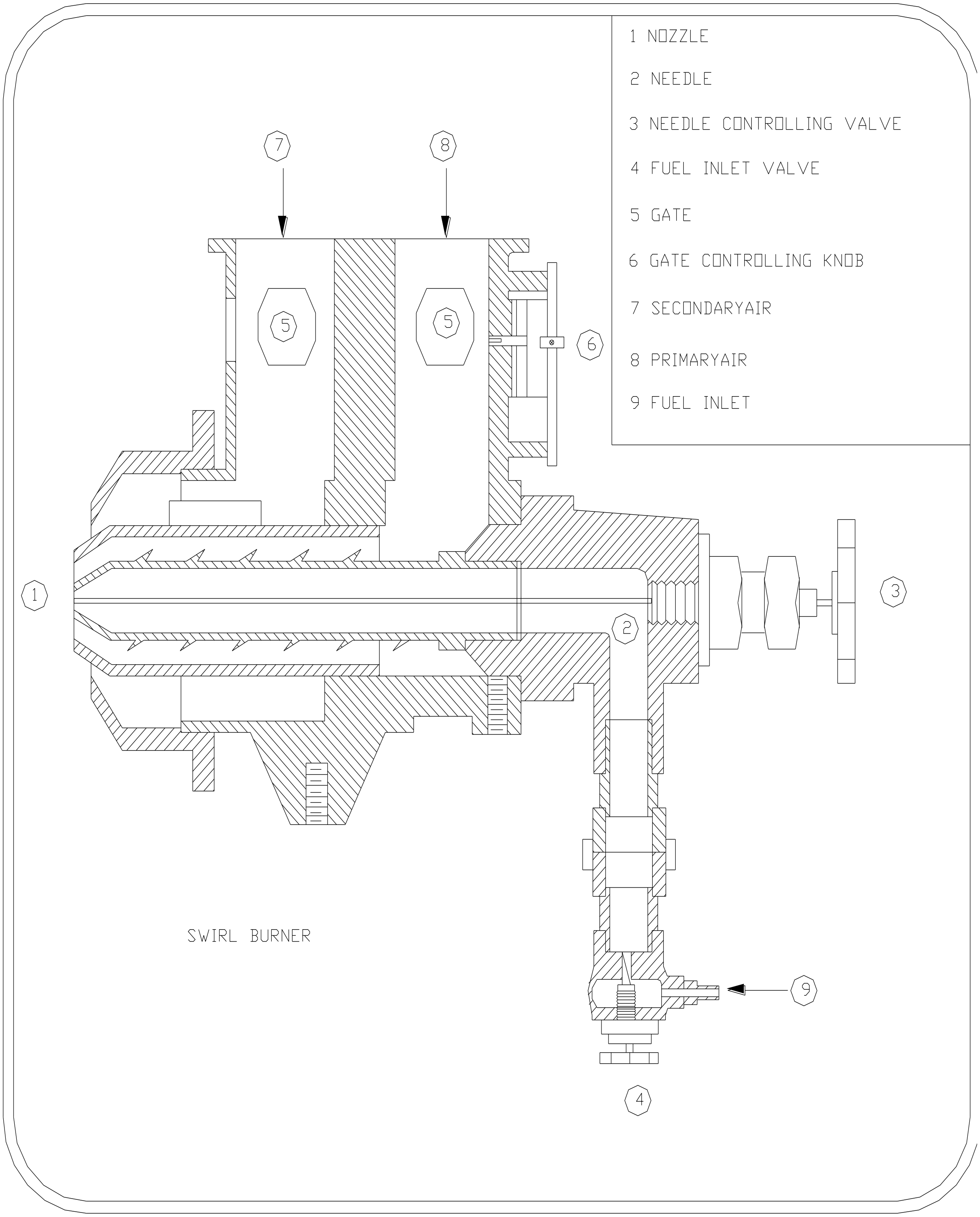

Figure 6.2 Nozzle cross sectional view

Table 6.1 Specifications of the furnace

FURNACE DETAILS	MEASUREMENTS
1. Diameter of the furnace	570mm
2. Height of the furnace	610mm
3. Refractory bricks used	Fire clay
4. Thickness of the bricks	200 mm(2layers)
5. Outer Casing material of the furnace	Mild steel
6. Materials that can be melted	Cu, Al, Gunmetal, Brass
7. Blower details	
a. Type of Blower	Centrifugal
b. Speed of blower	2880
c. Discharge of blower	1.8m^3/ minute
d. Pressure Developed	18 cms of water(gauge)
e. Motor	3 phase Induction Motor (1.5hp)
8. Slurry tank details	
a. Height of the tank	450mm
b. Diameter of the tank	251mm (cross section area = 49481mm^2)
9. Fuel tank details	
a. Dimensions of the tank	310x150x200mm
10. Stirrer Assembly Details	
a. Motor	Single Phase Induction Motor(0.75kw)
b. Speed	140rpm v-belt driven with a speed reduction of 3:1
c. Diameter of the stirrer shaft	30mm
d. No. of Blades	4

6.4 Measurement of flame temperatures of the slurry fired furnace

By maintaining steady flame inside the furnace, temperatures at different planes were measured using chromel- Aluminum Thermocouple, the thermocouple is of 120mm length it was inserted from the top of the furnace to whichever position or height desired and the temperature is measured. The thermocouple was placed in the desired position by making use of the stoppers that were fixed to the thermocouples handle. Three thermo couples were used to measure the temperatures in the furnace in a given plane (at 120^0 apart). The different slurries of the biomass slurry were prepared and the combustion temperatures were measured.

6.5 Measurement of the slurry flow rate

The flow of the biomass slurry was measured by using a measuring tank and a calibrated glass tube attached to the tank. A known quantity of biomass slurry fuel is measured and filled in the slurry tank. The slurry tank was fixed with a calibrated measuring tube, which can measure to an accuracy of 1cm. The time taken for the consumption for a particular level of flow was measured using a stopwatch. The ratio of volume to time for the consumption gives the flow rate of biomass slurry. The accuracy with which the volume can be measured is 4.95c.c and the time can be measured to a accuracy of 1 second.

6.6 Measurement of the airflow rate

The measurement of the airflow rate from the compressor to the nozzle was measured by a standard Orifice meter i.e. fixed in the flow pipe of the air compressor. The accuracy with which the airflow rate was measured is $1m^3/s$.

6.7 Measurement of CO at outlet of the furnace using chromatography

The percentage of CO emission from the combustion of slurry fuel was measured using a gas analyzer, which can sense only the CO emission from the exhaust gases. The analyzer was a high precision portable instrument. The accuracy of measurement of CO is 0.1%.

6.8 Melting of metals

The slurry-fired furnace was tested for melting aluminum using different compositions of fuel slurries. The various compositions of slurry fuels were prepared and the furnace was fired. The time taken for melting a fixed quantity of Aluminum (1 kg) was noted along with the emission. The melting abilities of these fuels were compared with that of LDO.

With LDO, the time taken was nearly 16 minutes, while with pulverized coconut shell powder and water it was nearly 18 minutes for 1 kg of aluminum using B15 blend, inclusive of the time taken to heat the crucibles. However, the flow conditions were varied to maintain stabalised flames of almost same height.

While melting aluminum a maximum temperature of 900K to 1000K, was sufficient to melt and pour the metal into the mould, the consumption time, cost of the fuel and the emission analysis of the fuel was discussed in Results and Discussion chapter and the setup is shown in Figure 6.3.

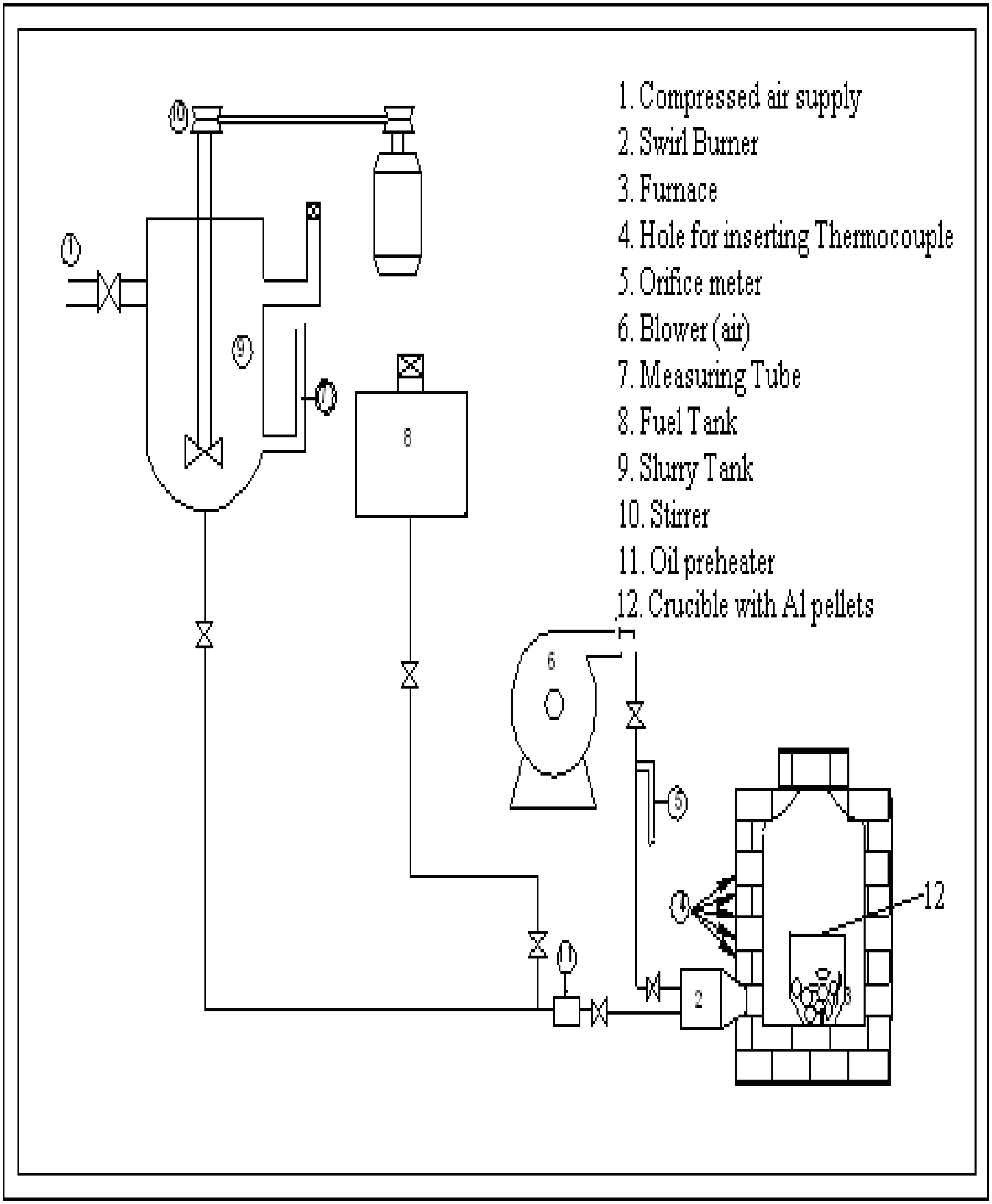

Figure 6.3 Experimental setup for Melting Al.

6.9 GENERATION OF STEAM

The slurry fuel was used to generate steam; the furnace was later converted into a boiler. The setup is shown in the Figure 6.7 and the copper coil details are given in Table 6.2. Water at room temperature was let through copper pipe and the steam generated is let into the steam chamber, before letting into the steam turbine. Once a pressure of 4kg/cm^2 is built up in the steam chamber, it was let into the steam turbine, so that a maximum speed of 3700rpm is reached by the turbine and 60W of power was generated out of this setup.

It was observed that up to a blend of 30% of coconut shell powder had no problem in generating the required quantity of steam for power generation. The copper coils beyond the furnace outlet were properly insulated, so that there were minimum losses of heat to the atmosphere. The turbine was located as near as possible to the furnace.

The pressure in the steam chamber was measured using a ISO standard specified pressure gauge and the pressure inside the steam chamber was maintained in the range of 4 to 5 kg/cm^2.

Table 6.2 Copper coil details for steam generation

Material of the coil	24-26% Cr, 19-22 Ni
Length of the coil	14m
Diameter of the Tube	16mm OD, 12mm ID
Diameter of the coil	200mm

The steam generating capacity and steam pressure were measured for different blends. The steam generation setup with the furnace is shown in Figure 6.4. The results are presented and discussed in Chapter 7.

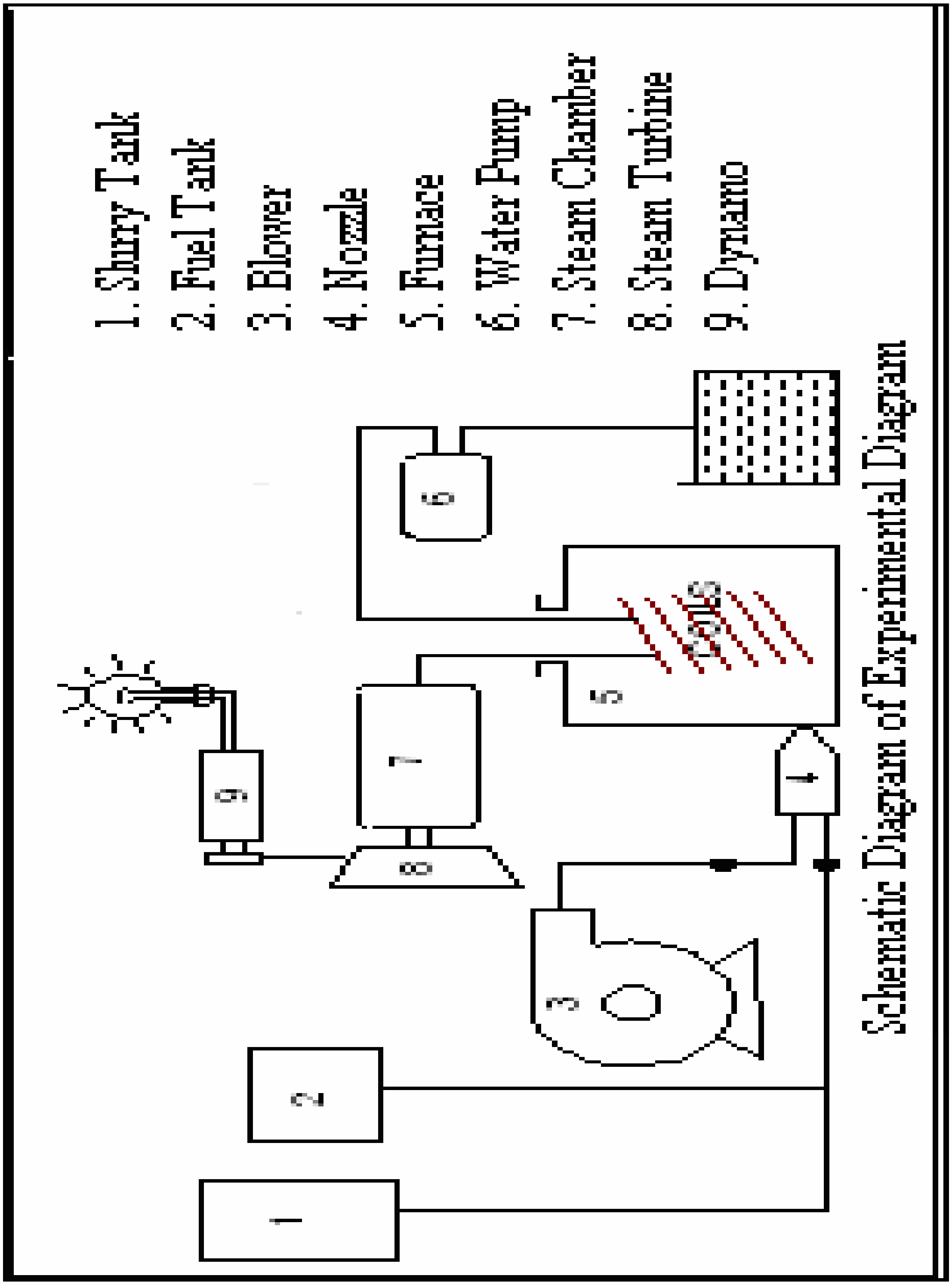

Figure 6.4 Experimental setup for Generating Steam.

6.10 Performance characteristics of diesel engine

The biomass slurry was prepared using commercially available diesel and the slurry fuel was tested to run the Bullet 350cc-5hp engine. The load tests were carried out. The experimental setup for conducting the load test is shown in Figure 6.8. It consists of a four-stroke air cooled single cylinder diesel engine, rope brake dynamometer for measuring torque, fuel and slurry tanks, which supply fuel to the engine by gravity, a measuring burette to measure fuel consumption rate. The volume flow rate of air entering into the engine is measured using orifice meter.

Initially when the engine is started Diesel oil is used and once the engine attains the normal running condition, the diesel oil fuel supply is stopped and biomass slurry fuel is let in. Once the engine is running on biomass slurry, loads were added in steps and the performance of the engine is evaluated with that of the diesel oil.

After each load was added, the engine is allowed to attain steady speed, when the speed is constant, the time taken for the engine to consume 20c.c of fuel sample is recorded. The procedure was repeated for various loads and constant speed.

The various parameters like specific fuel consumption indicated thermal efficiency, brake thermal efficiency and mechanical efficiencies of the fuel on the engine are evaluated by varying the load on the engine. The tests were conducted on standard conditions.

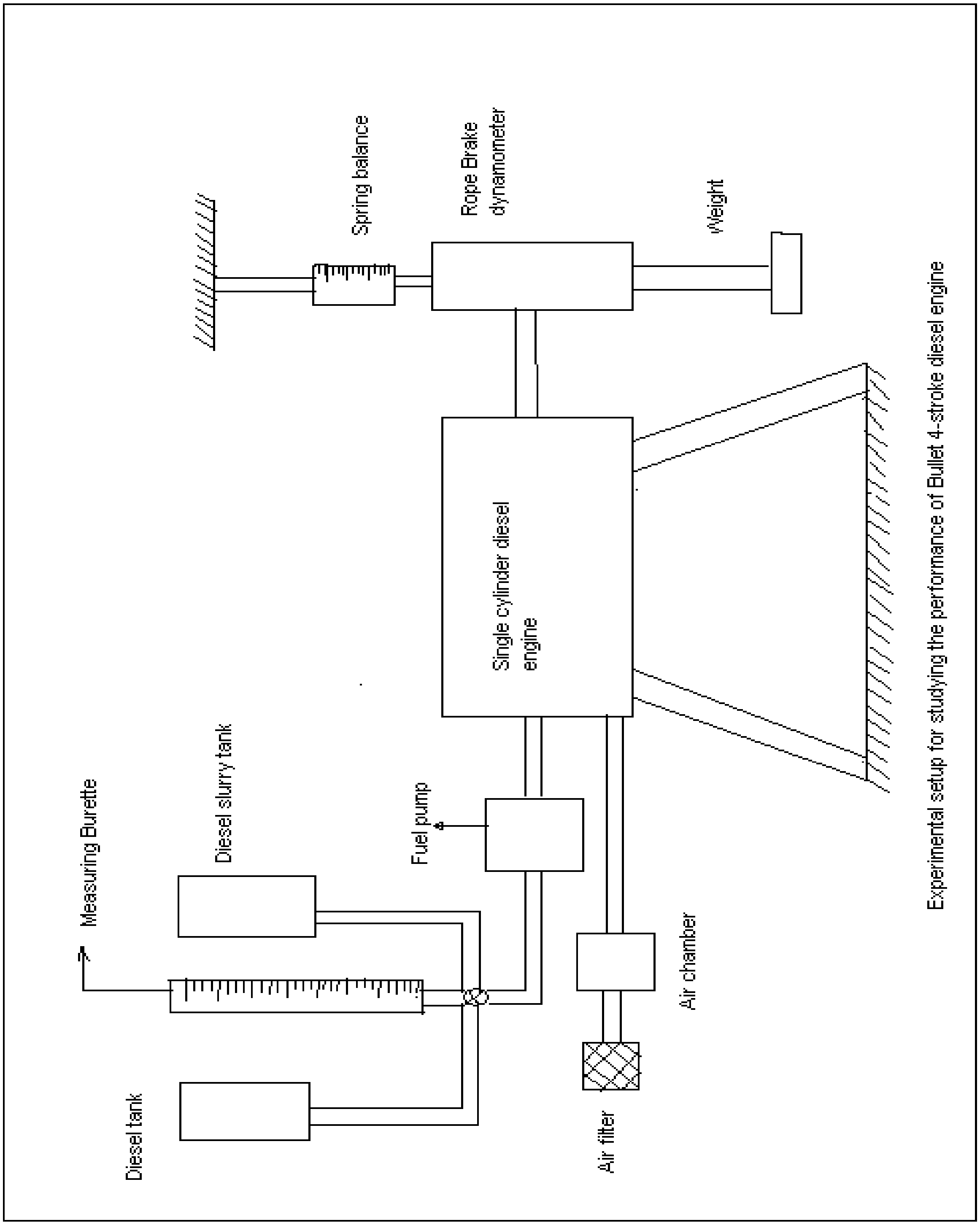

Figure 6.4a Experimental setup for Diesel engine.

Table 6.3 DETAILS OF THE DIESEL ENGINE

Description	Vertical air cooled, Compression Ignition, Direct injection, four stroke cycle, Diesel engine
Bore	78mm
Stroke	68mm
Displacement	325 cm^3
Compression Ratio	18:1
Fuel tank capacity	4.5 liters
Oil sump capacity	1.0 liter
Lubrication oil consumption	0.012kg/hr
Dry weight	38 kgs
Rated power	5.0 hp
Specific fuel consumption	205 gms/bhp/hr
Brake drum Radius	870mm
Full Load calculations	13.26 kgs

The engine torque is measured using rope brake dynamometer. The oil consumption in a specified time was measured using a measuring burette. The speed was kept constant through out the testing to ensure constant speed and varying load basis of testing the fuel. The speed was measured using a standard tachometer. The Results are presented and discussed in Chapter.7

6.11 Uncertainty analysis:

An experimental investigation is not completed without estimation of the uncertainties associated with measured quantities and the final calculated values. The technique used to calculate the uncertainty values follows that of Kline and McClintock [85]. The accuracy of the Orifice meter, Gas chromatograph, Weighing machine, Thermocouple, Tachometer, Bomb calorimeter and Brook viscometer are $1 m^3/s$, 0.1%, 0.1mg, 1K, 1rpm, 100kj/kg and 1kg-m/s respectively.

The uncertainty associated with the calibration of the calorific value is discussed below: Uncertainty associated with the measurement of output of calorific value is estimated at 0.7%. Uncertainty associated by the use of correlation for the estimation of calorific value and the temperature depends on the uncertainties associated with the correlation itself and the measuring distance of the location of the thermocouple and the temperature measurement. The possible errors associated with the measurement of the temperature are mainly due to the error in measuring thermocouple output. The digital meter has got an accuracy of 1K. The error in reading this output is due to the error in the digital meter. The deviation of the digital meter is ±0.8 percent. Therefore, the maximum error in reading the maximum output of 1400K is estimated to be with in

$$\pm 1400 \text{ x } (0.8/100) \pm 1 = 12.2\text{K}.$$

Based on these, the uncertainty associated in the calculation of the maximum enthalpy is 0.02%. Combining all the uncertainties associated with the measurement of the calorific value was estimated, following the procedure of Kline and McClintock.

CHAPTER-7

RESULTS AND DISCUSSIONS

7.1 INTRODUCTION

The results of the present investigations are discussed under four parts

1. Preparing the Biomass slurry samples and selecting the optimum compositions has been carried out in chapter.4.
2. CFD analysis was carried out in two parts.
    a. Cold Flow analysis of biomass slurry
    b. Combustion analysis of Biomass slurry
3. Experimental investigation of Combustion of Biomass Slurry fuels in Furnaces.
4. The application of the fuel slurry as a potential fuel in oil fired foundry furnace, oil fired steam generators and diesel engines are discussed.
    a. Temperature distribution inside the furnace during the combustion of different compositions of slurries has been measured. The flames have been photographed for different conditions.
    b. The furnace was tested for melting Aluminum with different blends of biomass slurry.
    c. By introducing a copper coiled tube of suitable length, it was tested for steam generation and running of a steam turbine.
    d. The Emission and Cost estimation of the Biomass slurry fuel over LDO is compared.
    e. By blending CSP with Diesel, the slurry is tested on a Diesel engine

7.2 CFD Analysis

7.2.1Cold flow analysis

The cold flow analysis of combustor is the initial and most essential setup in under standing the fuel flow structure inside the combustion chamber. Air/ water is used as the working gas for simulation of the cold flows within the combustor.

The flow structure within the combustion chamber helps in optimisation of the combustion geometry and for verification of numerical models, because it is not possible to predict the combustion flow with out preliminary evaluation of physical models.

In Trial-I the nozzle was placed exactly at 90^0 as shown in figure 5.9 and the flow analysis was carried out, it was observed that the fuel path was making a direct impact on the opposite side of the furnace and was escaping out of the furnace. so the nozzle inlet position was varied to different angles as given in Table 7.1 and the flow analysis was studied.

7.2.2 Results of Cold Flow Analysis of Biomass Slurry

Trial-I (with respect to Table-5)

In this trial the nozzle was exactly at 90 deg. to the inlet position of the furnace [Model-I]

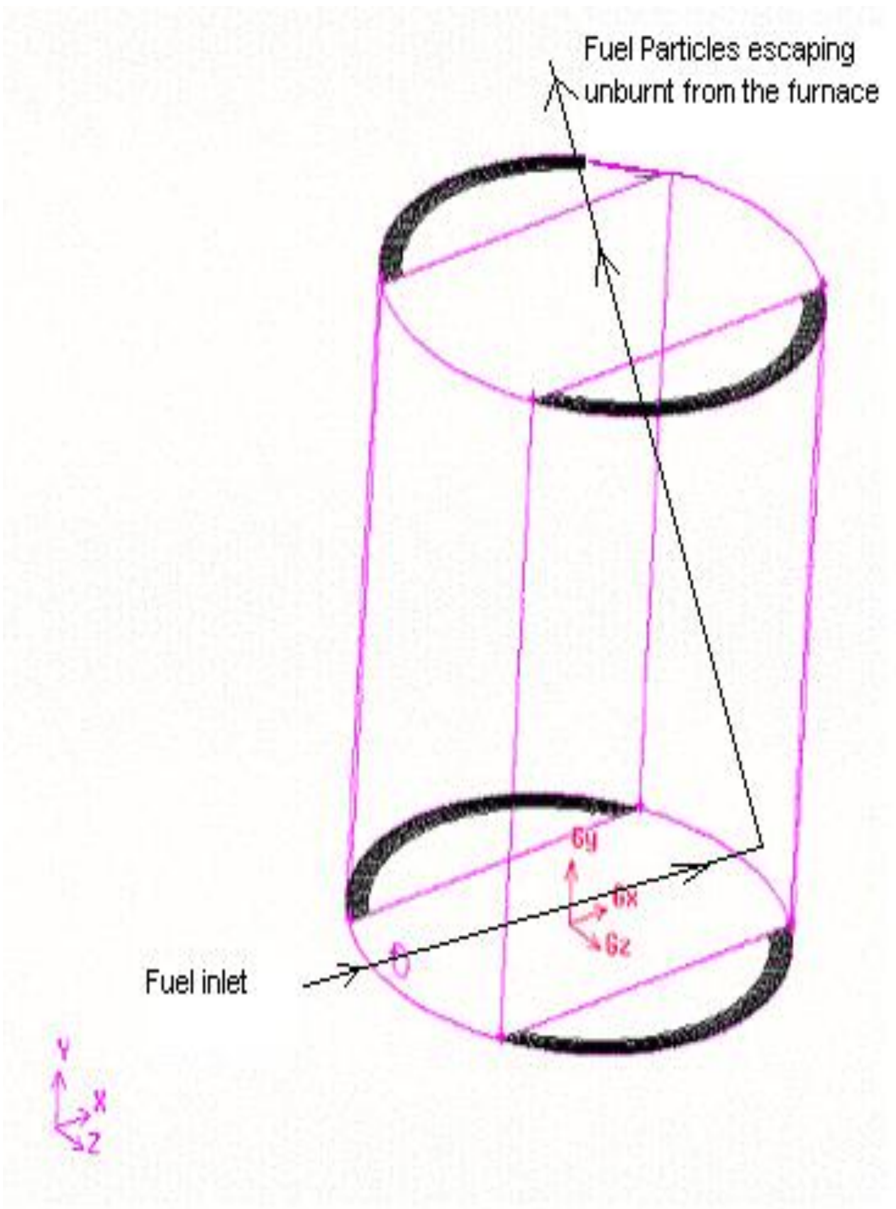

Figure7.1 Model-I

Trial-II (with respect to Table-5)

With the inlet angle of 85deg with respect to vertical y-axis [86]

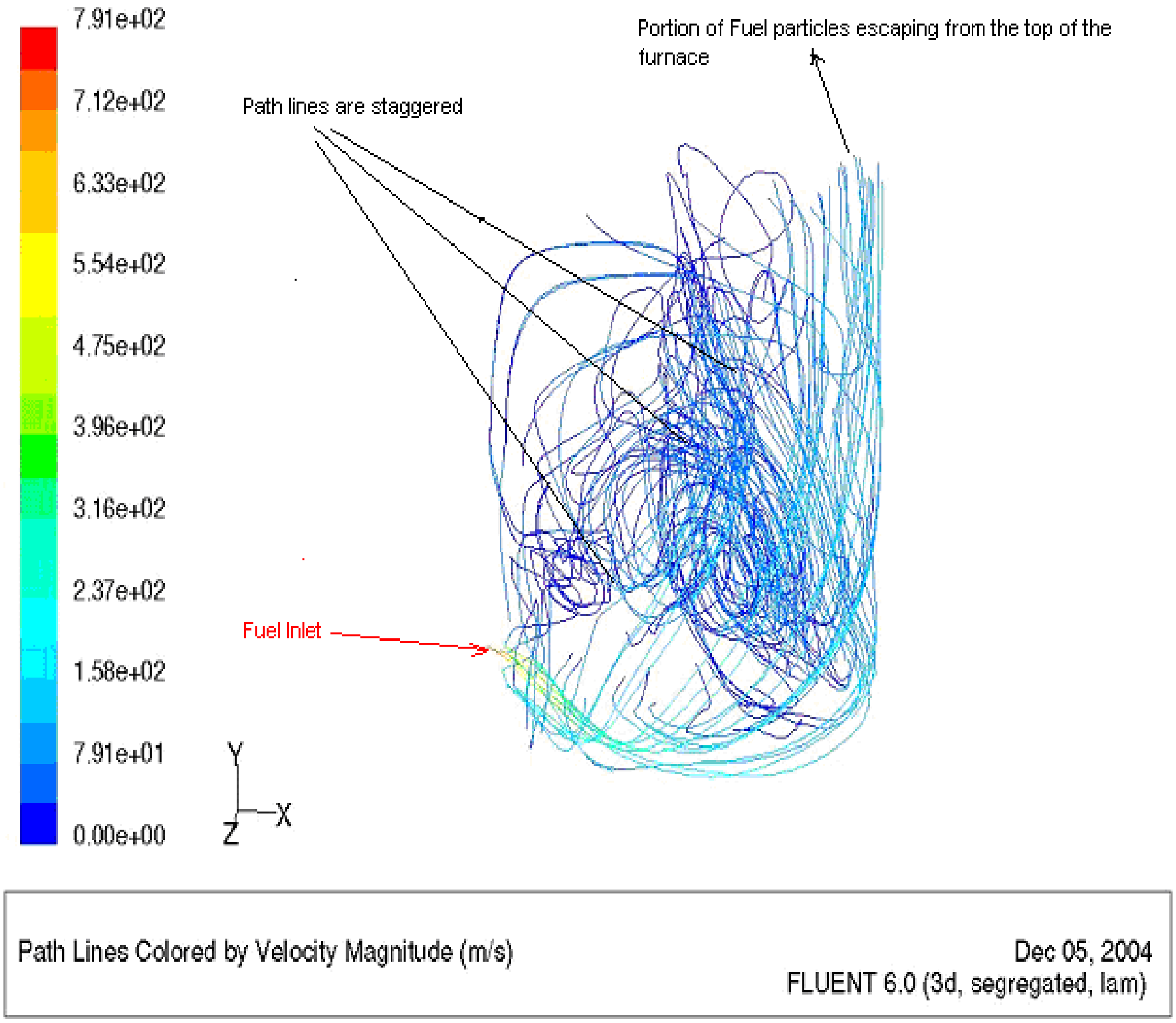

Figure 7.2 Trial-II path lines

Figure 7.2 shows the fuel trajectories for an inlet angle of 85deg. with respect to y-axis.

In Trial-II, it can be observed that a portion of the fluid particles are escaping of the furnace and the flow of the fuel particles are staggered due to incorrect position of the nozzle, fuel inlet into the furnace and during combustion, results in uneven temperature distribution inside the furnace.

Trial: III (with respect to Table-5)

With the inlet angle of 75deg with respect to the vertical axis

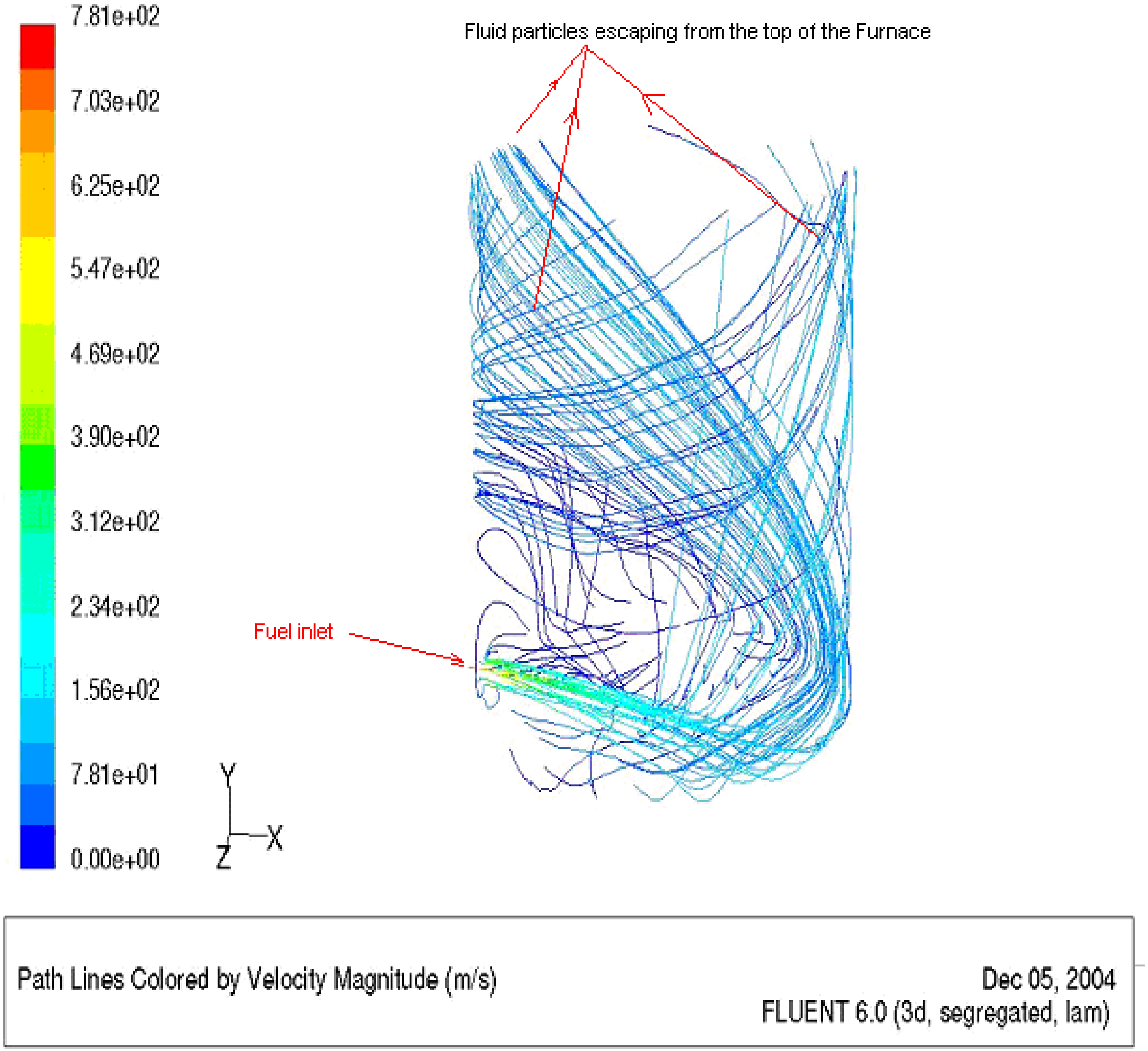

Figure 7.3 Trial-III path lines

It can be observed from Figure 7.2 and 7.3 that the fuel was escaping from the top of the furnace as in Model-I, so the furnace was remodeled with the top partially closed as shown in Model –II, i.e. Figure 7.4 and the cold flow analysis was carried out.

Model-II

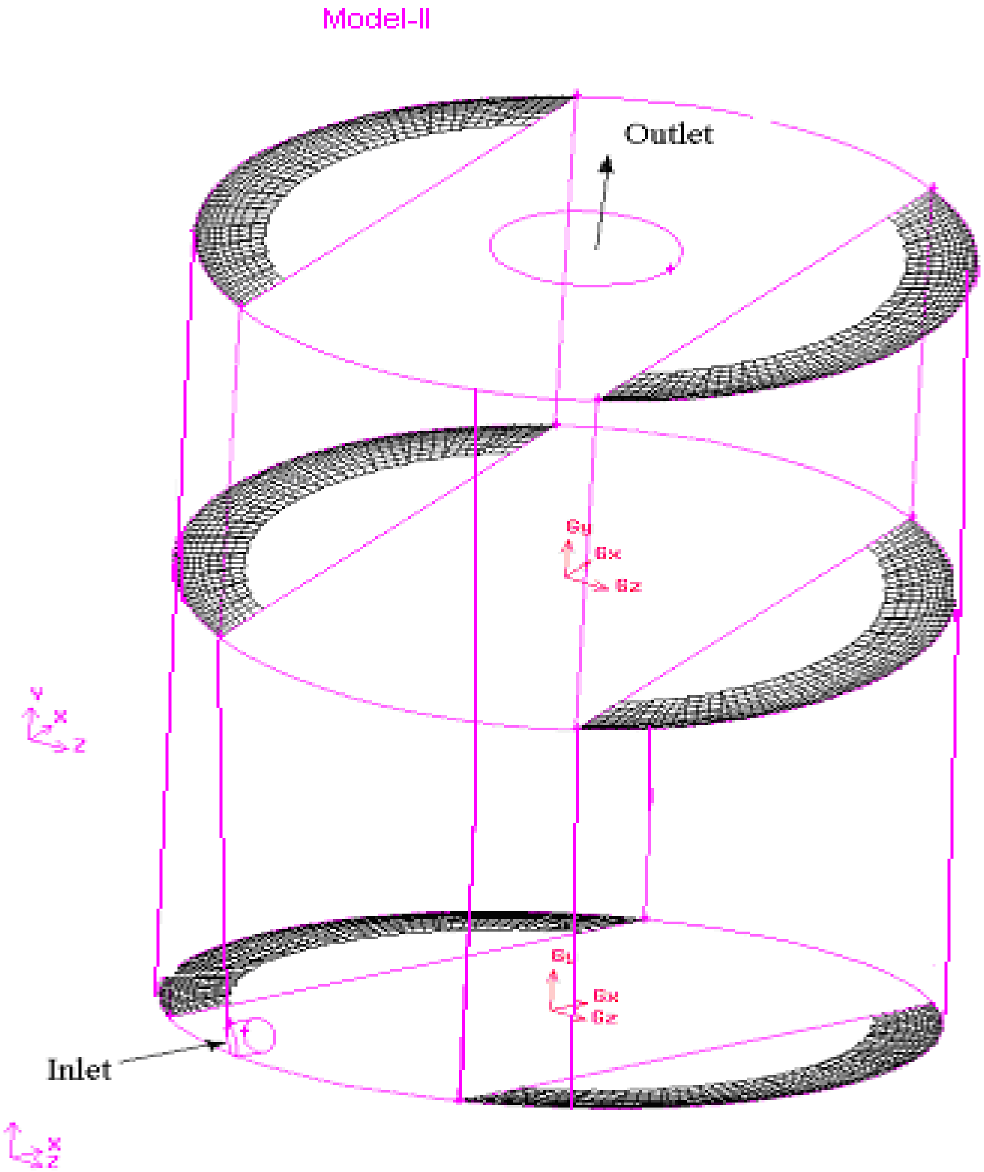

Figure 7.4 model II

With the above boundary conditions, the model was fine meshed and the cold flow analysis of the fluid was carried out for different inlet angles of the fuel.

Trial-VII (with respect to Table-4)

With the inlet angle of 40 deg. with respect to x- axis & 80 deg. to y-axis

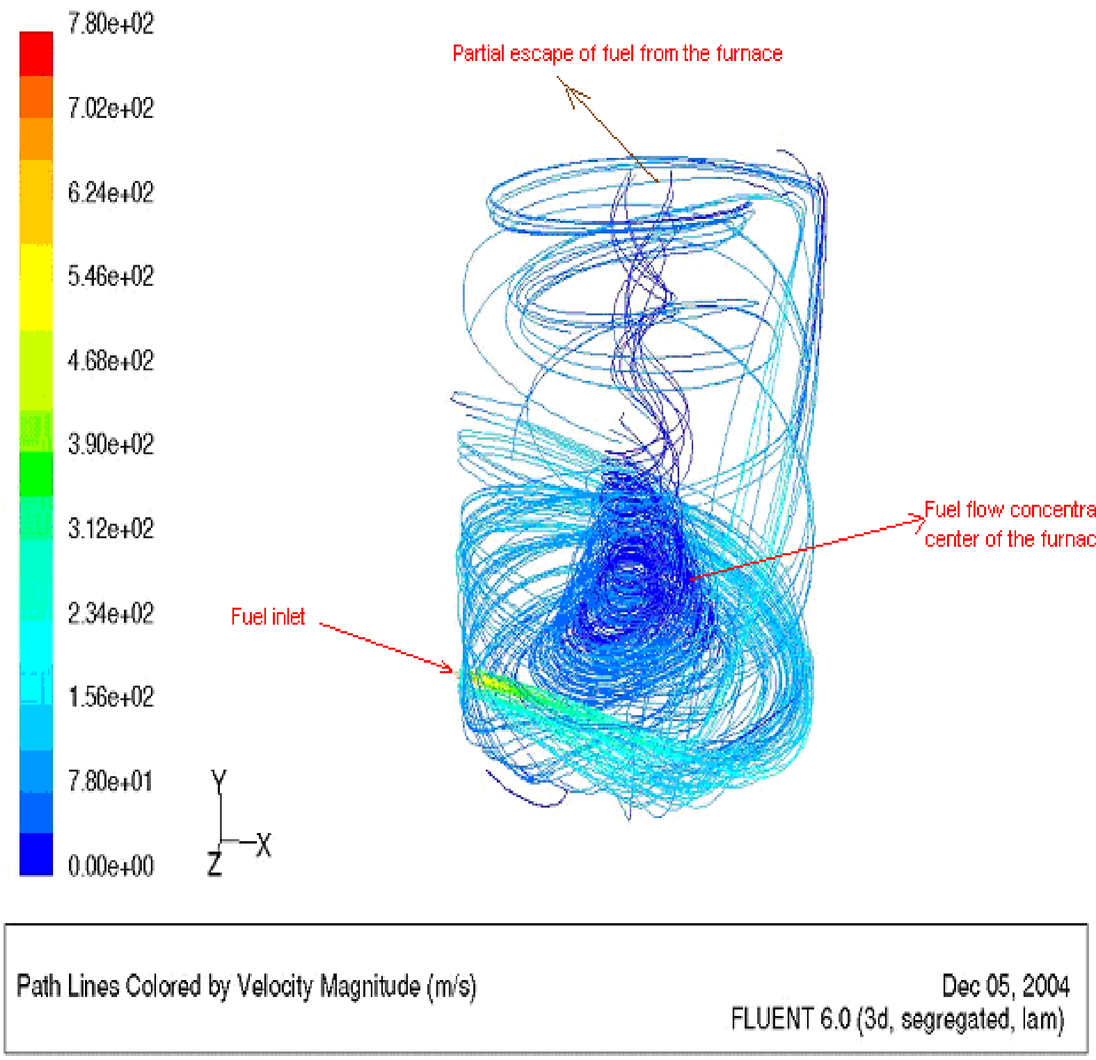

Figure 7.5 Trial –VII path lines

It can be observed from Figure 7.5 that only a small percentage of fuel was escaping from the top of the furnace compared to the Figures 7.2 and Figure 7.3 of Model-I, because of the small opening as in Model-II.

Trail- XI

With the inlet angle of 75 deg from positive y-axis, and an horizontal Inclination of 45 deg with respect to x and z axis 75 deg

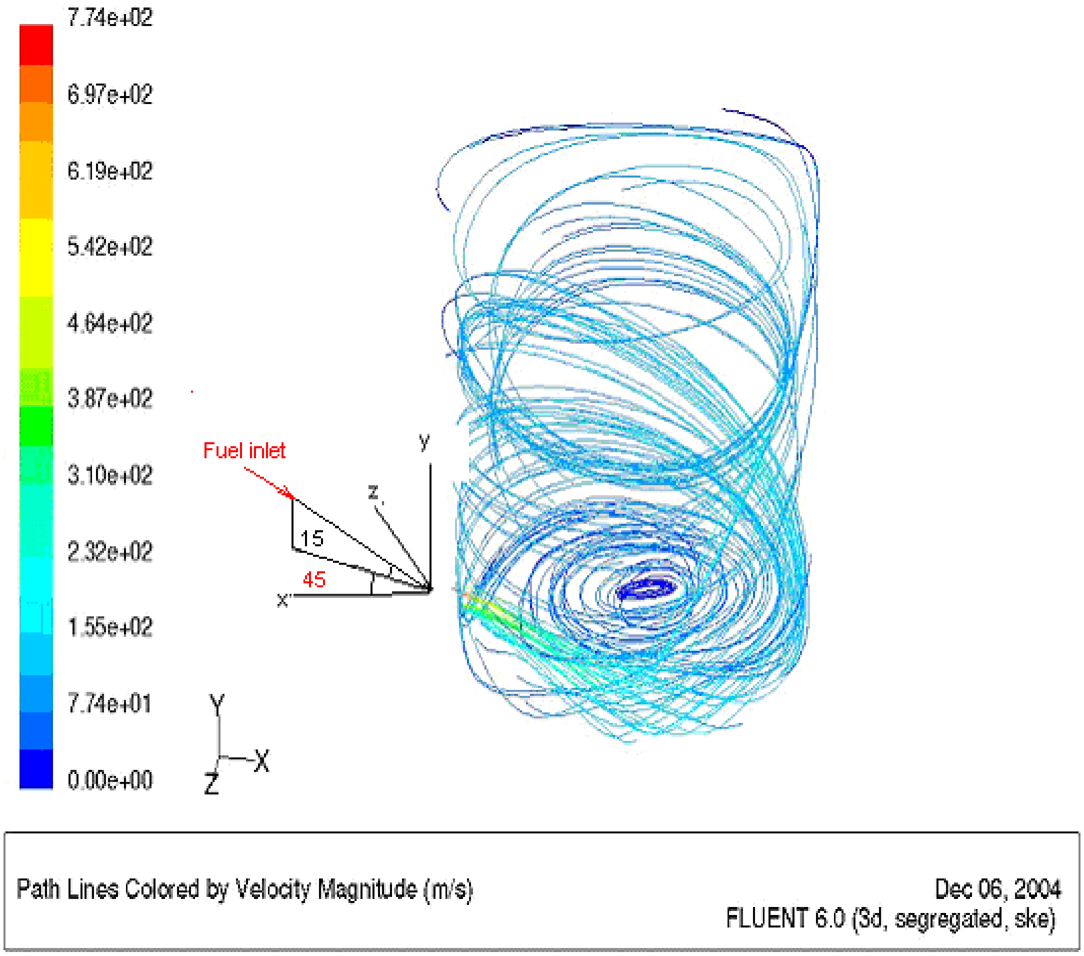

Figure 7.6 Trial XII path lines

Figure 7.6 shows the flow path of the fuel for the given inlet angle, it is observed from the flow path that there is hardly any fuel escaping from the furnace. From the above trials and Table 7.1 it can be observed that the residence time, helps in complete combustion of the slurry fuel and also when the flow is swirling as shown in Figure 7.6 the temperature distributions is also even.

From Trial-II

Residence time of the fuel in the furnace based on the above path lines from the injection point of the fuel is

$$= \frac{\text{Total length of the path line}}{\text{Velocity of the inlet fuel}}$$

$$= \frac{\Pi d\ (\text{number of rounds})}{700\text{m/s}}$$

$$= \frac{\Pi(0.35)(1.5)}{700} = \underline{0.002356\text{secs}}$$

From Trail-III

From Trail-III, it is clear that the fuel is concentrating in the center of the furnace and because of this concentration the combustion of the fuel will be concentrated in the center and the temperature distribution may not be even.

From Trail-XI

Residence time of the fuel in the furnace from Figure.5.15

$$= \frac{\text{Total length of the path line}}{\text{Velocity of the inlet fuel}}$$

$$= \frac{\Pi d\ (\text{number of rounds})}{700} = \frac{\Pi(0.35)(4)}{700\text{m/s}} = \underline{0.006283\text{secs}}$$

From Trail-XI it is clear that the flow is evenly distributed from the entry to the exit. The residence time of the fuel is also maximum compare to the other trails. Based on the above inlet angles, the flow analysis were conducted for nearly 22 inlet trails. Most of the flow analysis was staggered and it was not possible to calculate the residence time of the fuel and the most optimum i.e. the maximum residence time was selected as Trail-XI from Table 7.1 and as shown in Figure 7.6 and on this inlet angle the combustion analysis was carried out.

Table-7.1 Residence time of the fuel

Trial no.	Inlet angle	Residence time in secs
I	90 deg to y-axis	-
II	85 deg to y-axis	0.002356
III	80 deg to y-axis	0.002232
IV	75 deg to y-axis	0.002149
V	30 deg. w.r.t. x axis & 85 deg. to y-axis	0.003125
VI	35 deg. w.r.t. x axis & 80 deg. to y-axis	0.003985
VII	40 deg. w.r.t. x axis & 80 deg. to y-axis	0.004129
VIII	45 deg. w.r.t. x axis & 80 deg. to y-axis	0.005469
IX	50 deg. w.r.t. x axis & 80 deg. to y-axis	0.005362
X	55 deg. w.r.t. x axis & 80 deg. to y-axis	0.005268
XI	45 deg w.r.t. x axis & 75 deg to y-axis	0.006283
XII	45 deg. w.r.t. x axis & 70 deg. to y-axis	0.006012

As discussed in the CFD analysis after modeling the furnace, the fuel was let into the furnace at various angles to increase the residence time of the fuel. From the trails, it was observed that an inlet angle of 45 deg. to x-axis and 15 deg. to y-axis position of the nozzle gave the maximum residence time of the fuel inside the furnace [86].

7.2.3 Combustion analysis of Biomass slurry in Oil Fired Furnace using CFD

The biomass slurry which is a combination of light diesel oil (LDO), coconut shell powder (CSP) and water is combined for various proportions with the percentage of water kept constant and the combustion analysis of the slurry was carried out as follows. Initially only the LDO is let into the furnace at room temperature and the combustion analysis is carried out. With other blends, the inlet temperature of the slurry considered to be at room temperature or 328K [87].

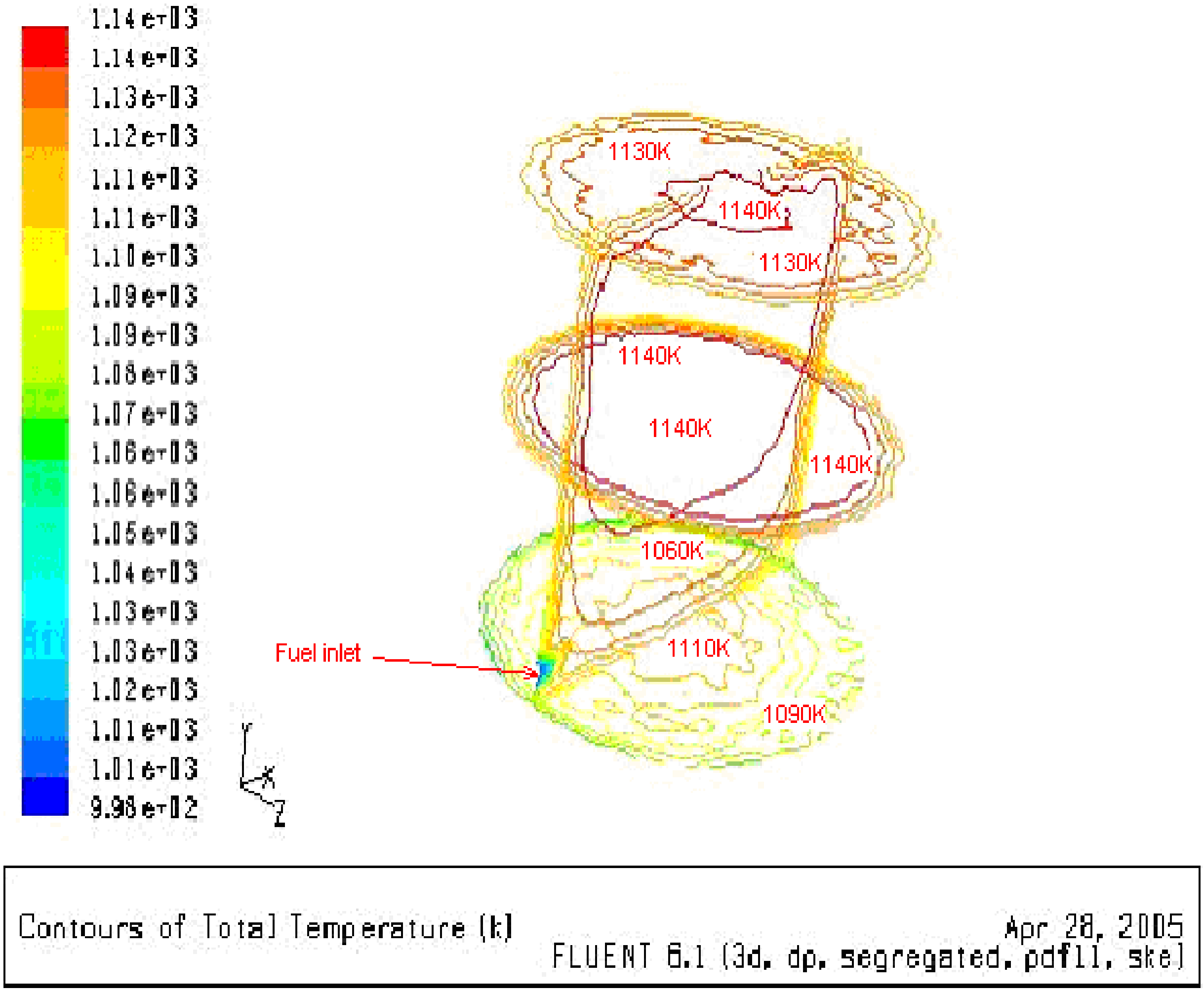

Figure 7.7 Temperature Distributions inside the Furnace for fuel inlet at 298K

Even though the results from the CFD analysis has been obtained for LDO and several blends, only the typical results for B10 alone is shown in Figures from figure 7.7 to Figure , however the maximum temperatures due to combustion and the emissions for other blends are tabulated in the Tables. Figure 7.7 shows the temperature distribution resulting from the combustion of the slurry B10 at three transfer planes bottom, middle and top. It can be observed from Figure 7.7 that the maximum temperature exists in the central plane and extends to the top. However, at the top there is a slight reduction in temperature towards the circumference. It can also be observed that at the bottom plane the core temperature is less than the maximum. There is a reduction in temperature marginally towards the circumference. The same observations can also be seen from the Figure 7.8.

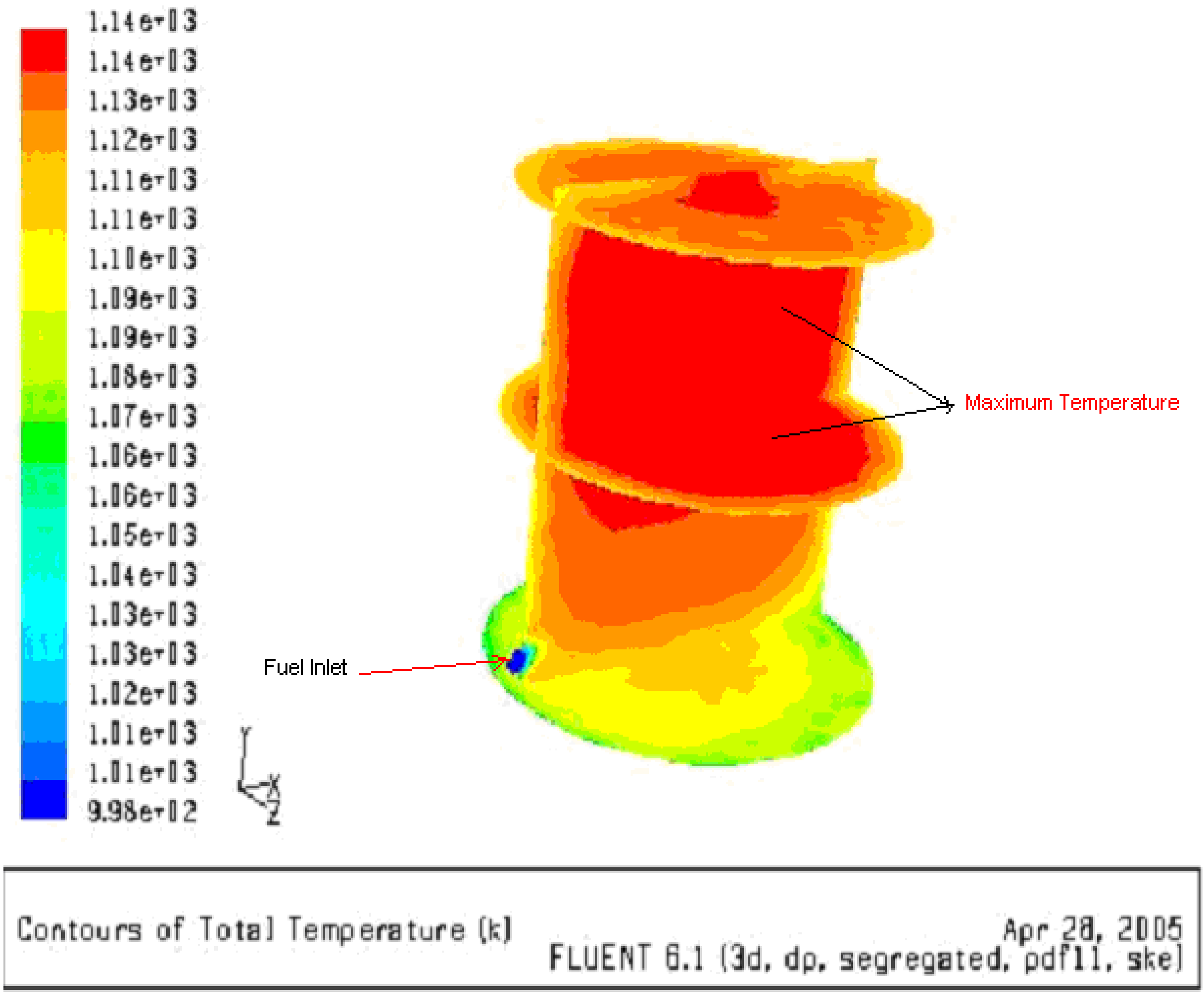

Figure 7.8 Temperature Distribution inside the Furnace for fuel inlet at 298K

It can be seen from Figure 7.8 that the maximum temperature occurs at the center plane of the furnace and it implies that initially liquid fuel combustion is taking place and in the later stage solid particles combustion is taking place and by the time fuel reaches the center height of the furnace the combustion is complete.

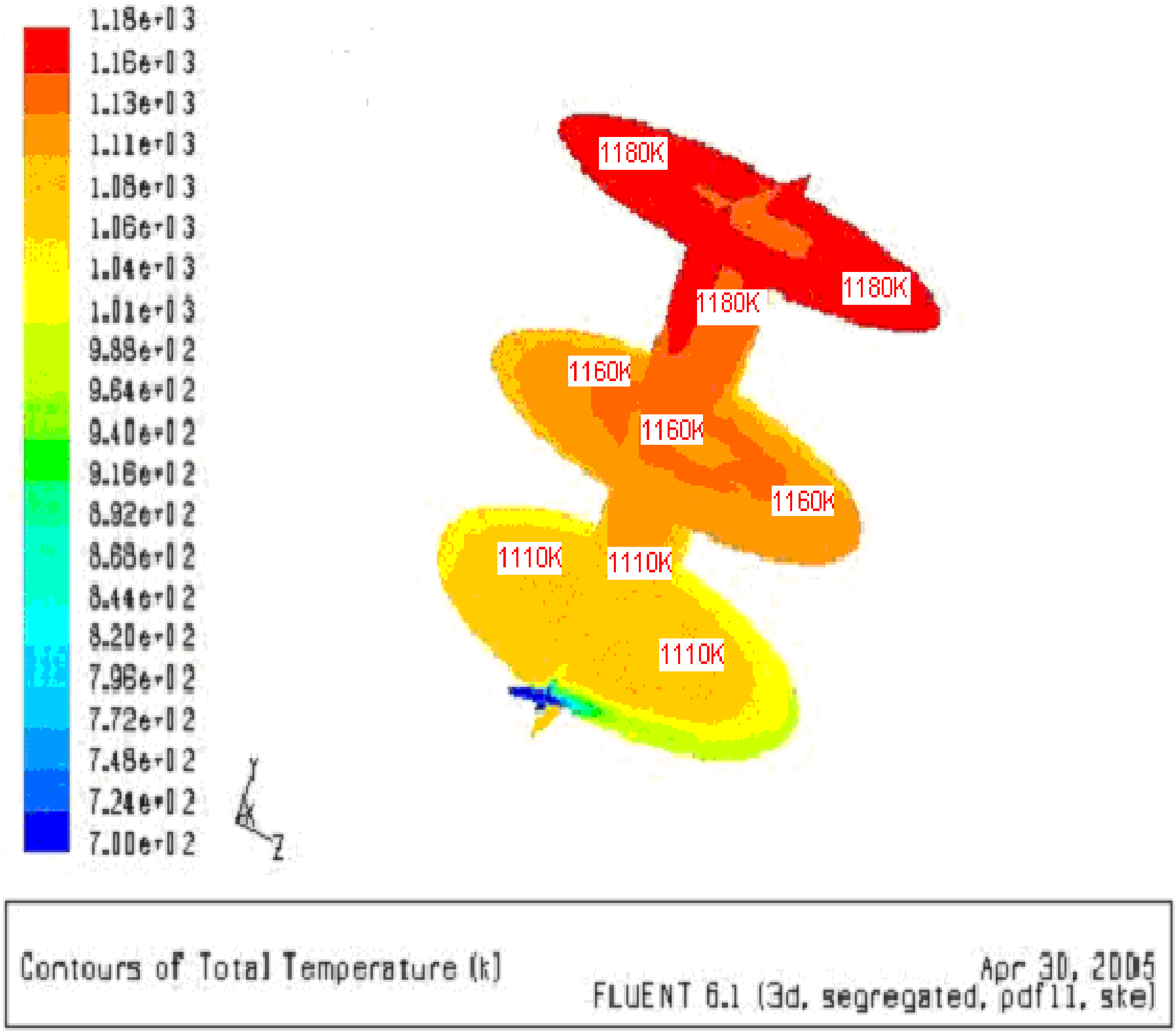

Figure7.9 Temperature Distribution inside the Furnace for fuel inlet at 328K

Figure 7.9 shows the temperature distribution resulting from the combustion of the slurry B10, (which is preheated before combustion to a temperature of 328K) at three transfer planes bottom, middle and top. It can be observed from Figure 7.9 that the maximum temperature exists in the central plane and extends to the top. However, at the top there is a slight reduction in temperature towards the circumference. It can also be observed that at the bottom plane the core temperature is less than the maximum. There is a reduction in temperature marginally towards the circumference.

Based on similar combustion analysis for different blends the temperature analysis for different blends is shown in Table 7.2

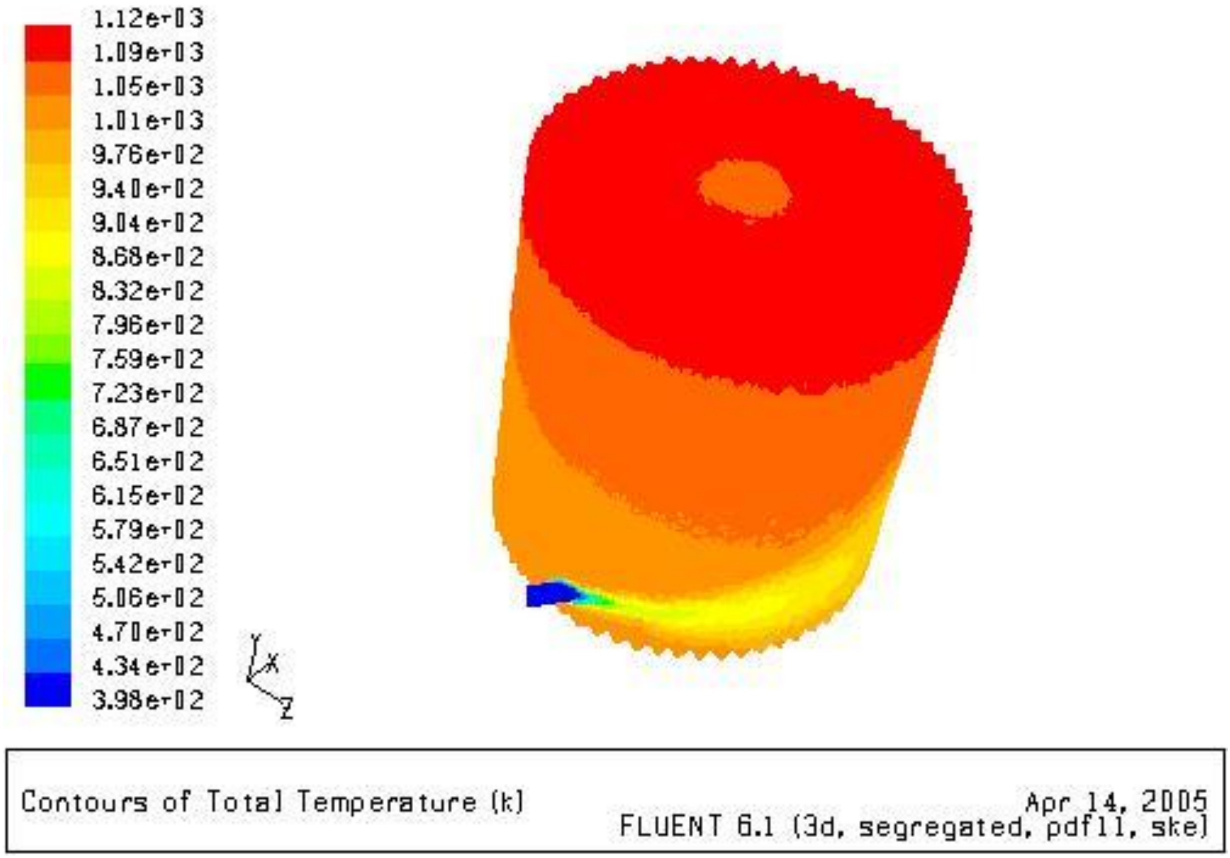

Figure7.9a Temperature Distribution inside the Furnace for fuel inlet at 298K for a blend of B15

Table 7.2 Maximum Temperatures in the furnace

Blends	**CFD results of Temperatures ^{0}K Fuel inlet at**	
	Room (298K)	**Elevated (328^{0}K)**
LDO	1300	1320
B05	1230	1280
B10	1140	1180
B15	1126	1170
B20	1110	1160
B25	0970	1040
B30	0825	0970

Based on the results from Table 7.2, it can be observed that by preheating the slurry fuel, the temperature in the furnace due to combustion increases marginally. As the composition of the coconut, shell powder increases the preheating increases the combustion temperature in the furnace. The effect of pre heating of the slurry increases as the percentage of coconut shell powder in the blend increases.

C. CFD- Emission Analysis for B10 blend slurry fuel

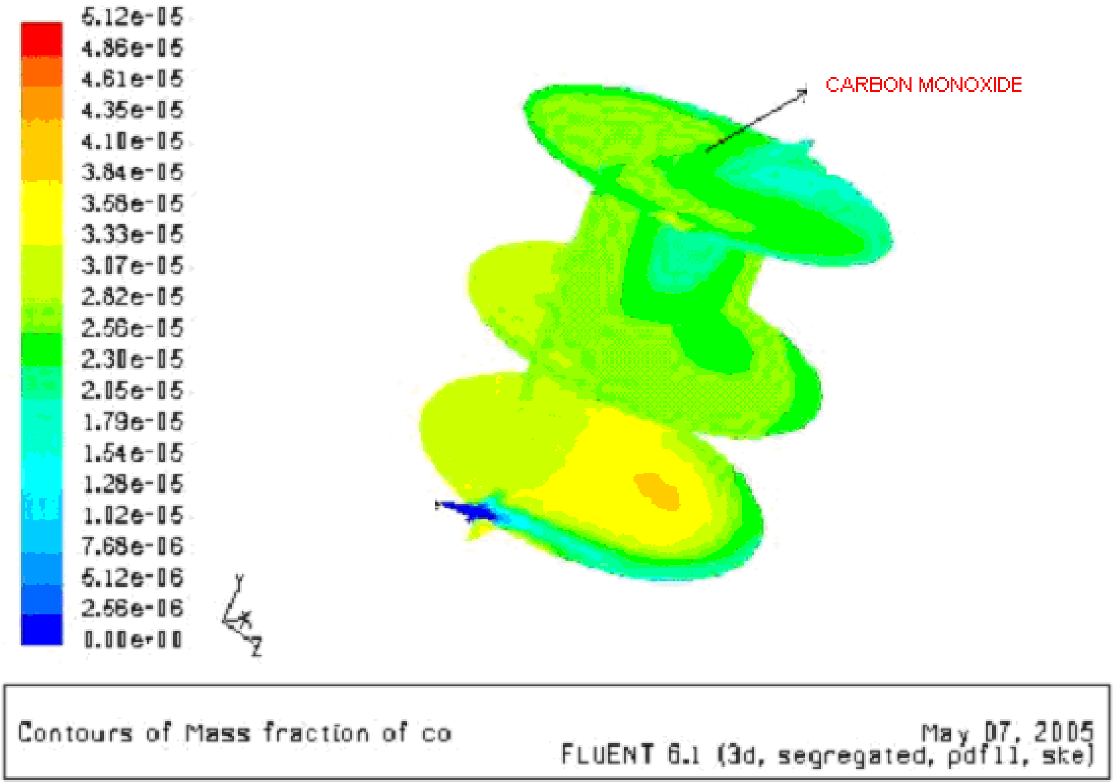

Figure 7.10 CO Emissions for B10 Biomass slurry fuel

Figure 7.10 shows the CO emissions by the combustion of biomass slurry and it was compared to be less than that of LDO as shown in Table-7.

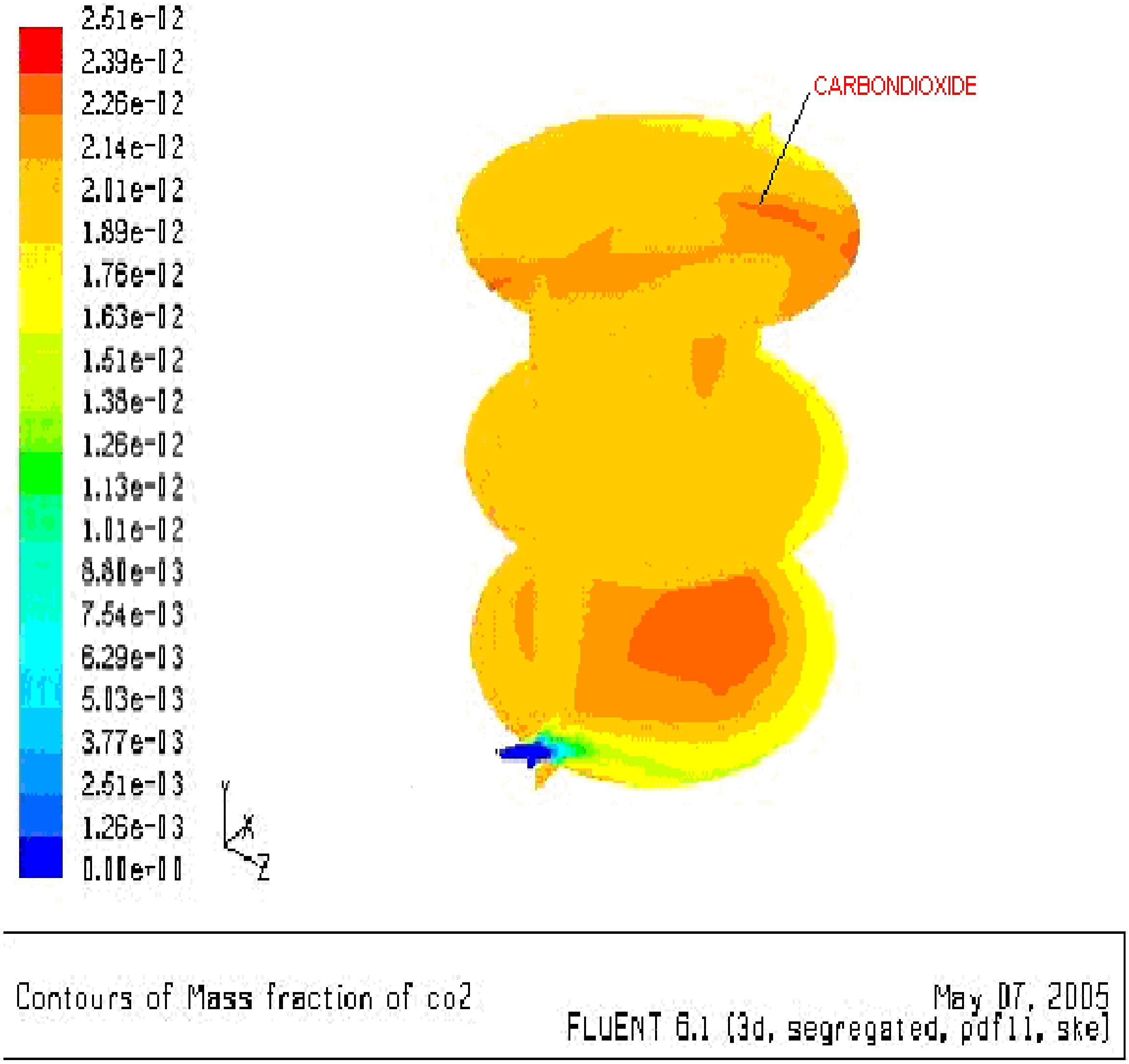

Figure 7.11 CO_2 Emissions for B10 Biomass slurry fuel

Figure 7.11 shows the emission of carbon dioxide by combustion of biomass slurry in the furnace. It is observed that the carbondioxide is more at the bottom compared to central and top planes. Only a small portion of the top plane shows the maximum carbon dioxide.

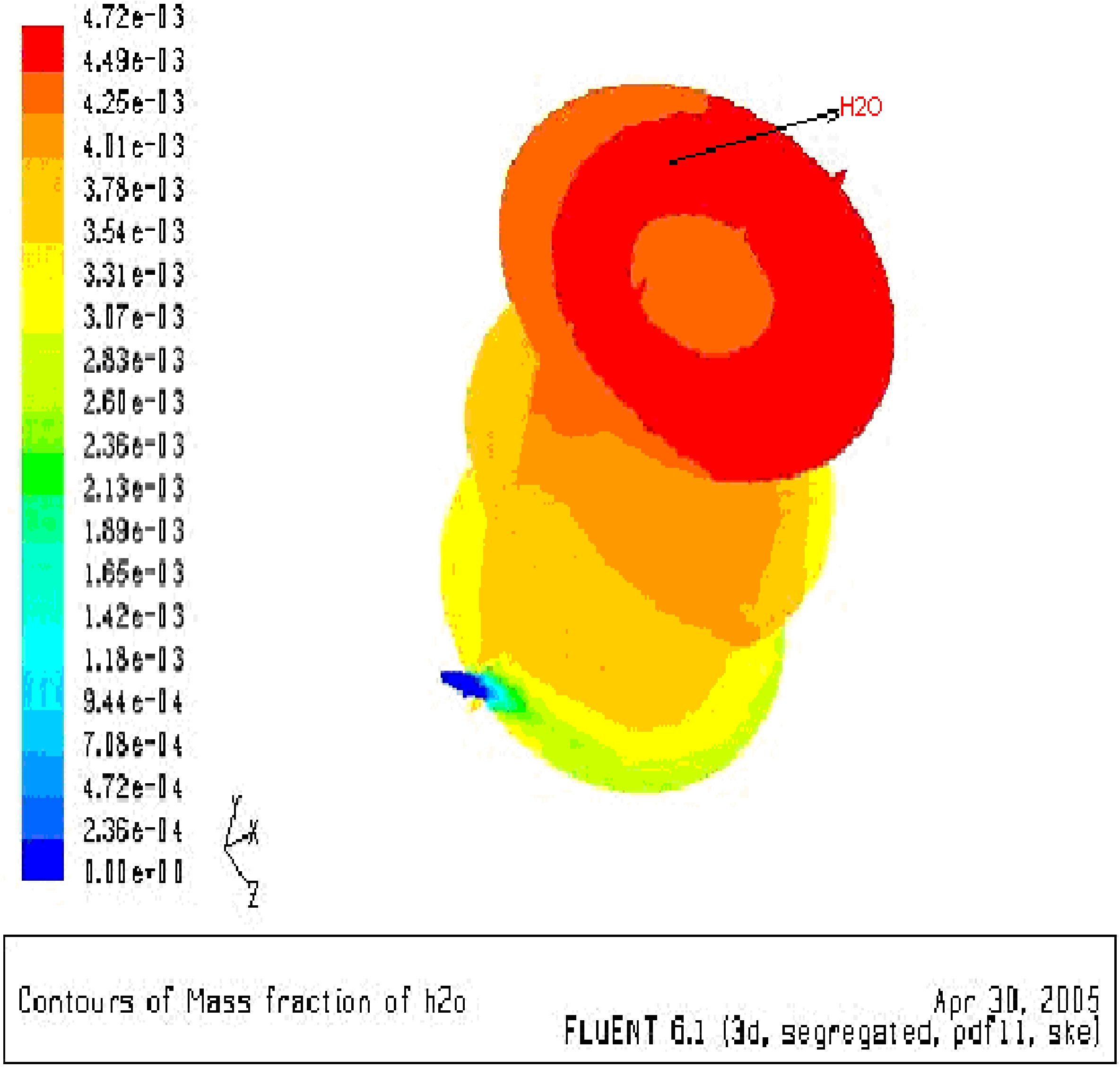

Figure 7.12 H_2O Emission for B10 Biomass slurry fuel

Figure 7.12 shows the water content by the combustion of biomass slurry in the furnace. It is observed that the percentage of water is maximum from central plane to the top plane.

Table-7.3 CFD- CO Emission Analysis

Blends	CO ANALYSIS % COMPUTED	
	ROOM	ELEVATED
LDO	4.4	4.0
B05	4.3	3.8
B10	4.1	3.5
B15	4.0	3.4
B20	4.0	3.3
B25	4.2	3.5
B30	4.3	3.7

It can be observed from Table-7.3 that the percentage of CO emission decreases as the percentage of coconut shell powder increase in the slurry upto a blend of 20 and then again increases, because of incomplete combustion of the slurry. Thus Biomass slurry is a better fuel compared to LDO in terms reductions of the emissions due to combustion.

Table-7.4 Exhaust gas analysis with respect to variation of % of air

%air	LDO					B5**					B10**				
	CO	CO_2	H_2O	O_2	N_2	CO	CO_2	H_2O	O_2	N_2	CO	CO_2	H_2O	O_2	N_2
10%	3.15	3.85	7.82	1.0	38.0	2.79	3.34	7.51	1.14	39.05	2.84	3.26	7.36	2.98	40.1
20%						2.77	3.36	7.52	1.80	42.67	2.81	3.28	7.34	3.00	42.3
30%						2.75	3.36	7.56	2.85	46.62	2.79	3.29	7.32	3.03	45.3
40%						2.74	3.37	7.58	3.01	49.18	2.78	3.30	7.30	3.12	47.5
50%						2.73	3.38	7.59	4.75	53.73	2.65	3.31	7.29	3.35	51.2

%air	B15**					B20**				
	CO	CO_2	H_2O	O_2	N_2	CO	CO_2	H_2O	O_2	N_2
10%	2.62	3.20	7.31	1.98	36.8	2.59	3.06	6.91	2.90	38.5
20%	2.61	3.24	7.29	1.99	37.0	2.57	3.08	6.93	2.92	39.2
30%	2.59	3.25	7.28	2.12	37.7	2.56	3.09	6.95	2.93	43.2
40%	2.58	3.26	7.25	2.16	38.5	2.55	3.10	6.98	3.40	45.7
50%	2.58	3.30	7.24	2.20	38.9	2.53	3.12	6.99	3.46	45.9

%air	B25**					B30**				
	CO	CO_2	H_2O	O_2	N_2	CO	CO_2	H_2O	O_2	N_2
10%	2.50	3.20	7.31	1.98	36.8	2.38	2.89	7.81	1.90	38.5
20%	2.49	3.22	7.29	1.99	37.0	2.37	2.91	7.80	1.92	39.2
30%	2.49	3.23	7.28	2.12	37.7	2.37	2.90	7.79	1.93	43.2
40%	2.48	3.24	7.25	2.16	38.5	2.38	2.91	7.78	2.40	45.7
50%	2.47	3.25	7.24	2.20	38.9	2.38	2.92	7.78	2.86	45.9

(* Blends in percentage of weight) (**Exhaust gas analysis in Kg moles)

For various compositions of the biomass slurry, the excess air percentage has been increased from 10 to 50%. It was observed that the emission of CO decreases with the increase in percentage of air where as the percentage of CO_2 increases with the excess air. However, both the values do change marginally with excess air. The increase of coconut shell powder percentage in the slurry, results in the reduction of percentage of both CO and CO_2.

7.3 EXPERIMENTAL RESULTS

Based on the CFD-cold flow analysis of biomass slurry the nozzle position of the furnace was changed in the Experimental setup and the combustion of the biomass slurry was carried out. The Consumption time, Temperature and CO emission are measured in the experiments. The results were compared with CFD analysis.

Table 7.5 Consumption time of fuel and Combustion efficiency of the Furnace before and after modification

Blends	Consumption time of the fuel/liter in min Experimental values		Combustion Efficiency % of the Slurry fuel w.r.t. LDO	
	Before Modification	After Modification	Before Modification	After Modification
B0 (LDO)	18	18	-	
B5	13	18	88.67	98
B10	11	19	82.76	91
B15	11	20	78.00	89
B20	10	20	70.00	84
B25	08	22	57.50	74
B30	06	23	51.00	73

Table 7.5 shows the consumption time of fuel and the combustion efficiency of the furnace for the various blends of the slurry before and after modification. It can be seen from Table-7.5 that the consumption time of the fuel is increased by changing the position of the nozzle according to the CFD analysis. This increase in time of consumption of given quantity of fuel is a reflection of the increase in residence time of the fuel in the furnace. Combustion efficiency of the furnace is also increased with the modification as expected for all the blends of the slurry.

The combustion efficiency of the furnace is based on the furnace temperatures obtained for various blends compared with LDO. The combustion efficiency of the furnace with biomass slurry fuel is calculated assuming the LDO combustion values as the Standard or Reference value.

$$\textbf{Combustion Efficiency} = \frac{\textbf{(Temperature of the Biomass slurry Blend)}}{\textbf{(Temperature of the LDO at the same combustion conditions)}} \times \textbf{100}$$

Table 7.6 Maximum Temperature in the furnace: comparison with CFD results

Blends	**Computed Temperatures K Fuel inlet**		**Measured Temperatures K Fuel inlet**	
	Room	**Elevated (328K)**	**Room**	**Elevated (328K)**
LDO	1300	1320	1210	1236
B05	1230	1280	1170	1220
B10	1140	1180	1088	1098
B15	1126	1170	1065	1075
B20	1110	1160	1020	1080
B25	0970	1040	0900	0970
B30	0825	0970	0801	0895

Table 7.6 shows the variation of furnace Temperatures for various blends obtained by both CFD analysis and Experiments. It is observed that the experimental values are less than that of CFD analysis, as expected, due to heat losses from the furnace walls, top of the furnace opening, thermocouple inserts in the furnace wall and through the thermocouple probes used.

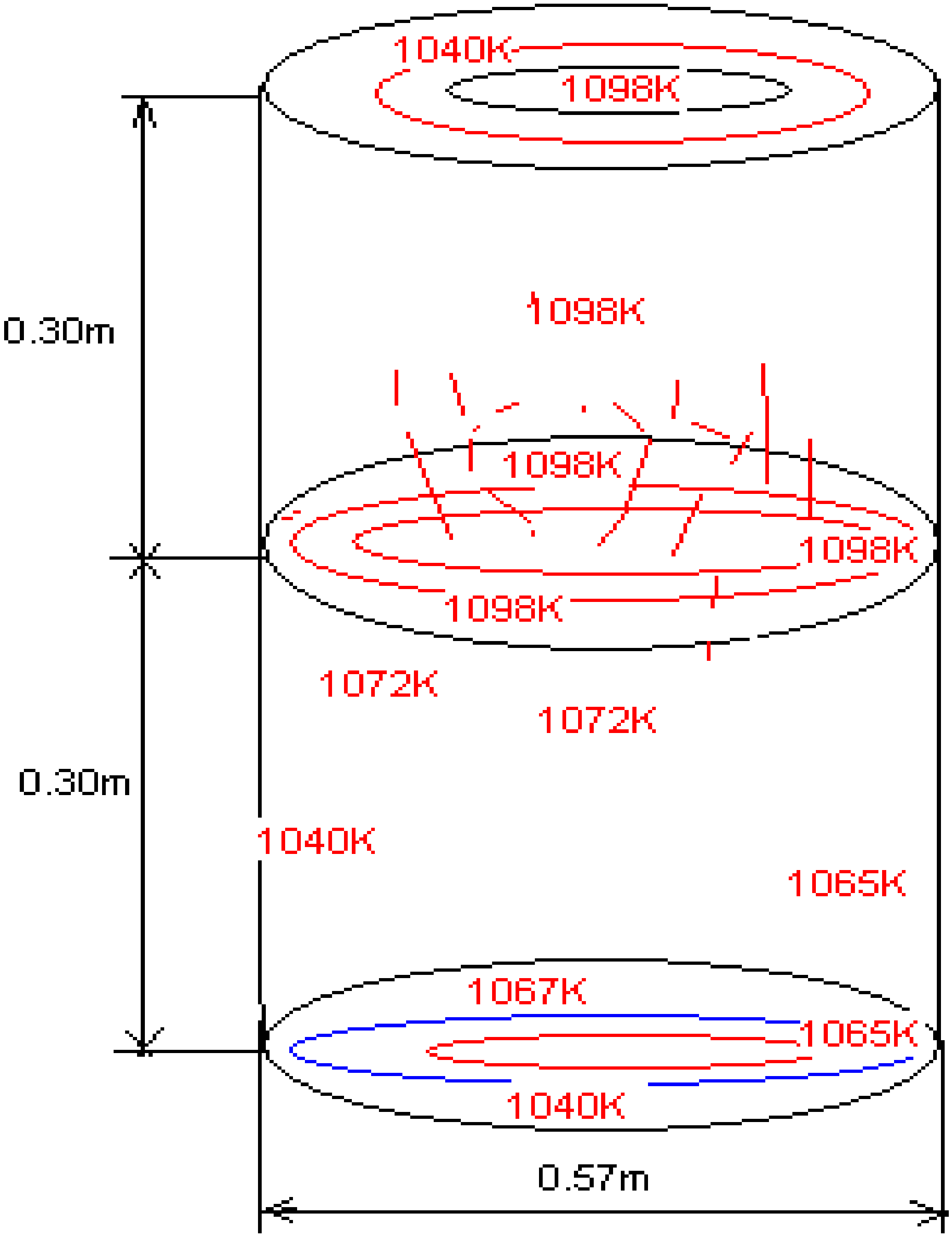

Figure 7.13 Experimental Temperature Distribution for Blend B10 at 328K inlet temperature.

Figure 7.13 shows the temperature distribution resulting from the combustion of the slurry B10 at three transfer planes bottom, middle and top. It can be observed from figure 7.13 that the maximum temperature exists in the central plane and extends to the top.

However, at the top there is a slight reduction in temperature towards the circumference. It can also be observed that at the bottom plane the core temperature is less than the maximum. There is a reduction in temperature marginally towards the circumference. Compare to the CFD results, the experimental values at several planes are marginally lower as expected. The trends observed in the CFD results are also observed in the experimental values. (Figure 7.9)

Figure 7.14 shows the experimental temperature distribution resulting from the combustion of the slurry B10 at three transfer planes bottom, middle and top. It can be observed from Figure 7.14 that the maximum temperature exists in the central plane and extends to the top. However, at the top there is a slight reduction in temperature towards the circumference. It can also be observed that at the bottom plane the core temperature is less than the maximum. There is a reduction in temperature marginally towards the circumference. Compare to the CFD results, the experimental values at several planes are marginally lower as expected. The trends observed in the CFD results are also observed in the experimental values. (Figure 7.9). Compared to the Figure 7.13 the temperatures in the Figure 7.14 are lower by about 10 K in view of the fuel inlet at room temperature.

Figure 7.15 shows the temperature distribution at three planes corresponding to the bottom, middle and top for the case of blend B15 for a slurry inlet temperature of 328k. it can be observed from Figure 7.14 that the same trends as observed in Figure 7.13 are also observed here although the temperature values are slightly lower than that in Figure 7.13 as expected. It is also interesting to note that the temperature in the furnace increases from the bottom to the central plane and remains almost at the same temperature up to the top of the furnace.

Figure 7.16 shows the temperature distribution at three planes corresponding to the bottom, middle and top for the case of blend B20 for a slurry inlet temperature of 298K (room temperature). It can be observed from Figure 7.16 that the same trends as observed in Figure 7.13 and Figure 7.15 are also observed here although the temperature values are slightly lower than that in Figure 7.13 and 7.15 as expected. It is also interesting to note that the temperature in the furnace increases from the bottom to the central plane and remains almost at the same temperature up to the top of the furnace.

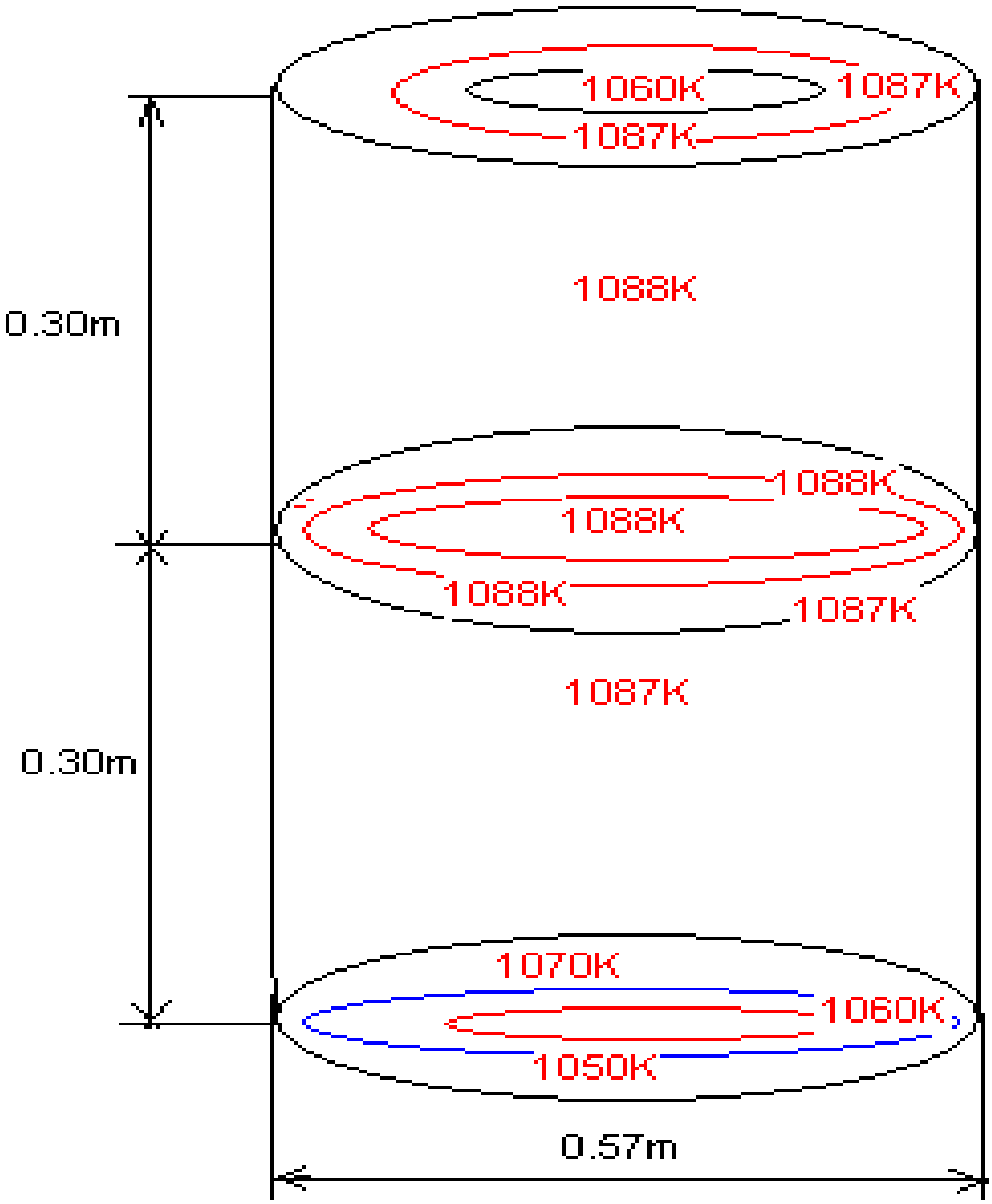

Figure 7.14 Experimental Temperature Distribution for Blend B10 (fuel inlet at Room temperature)

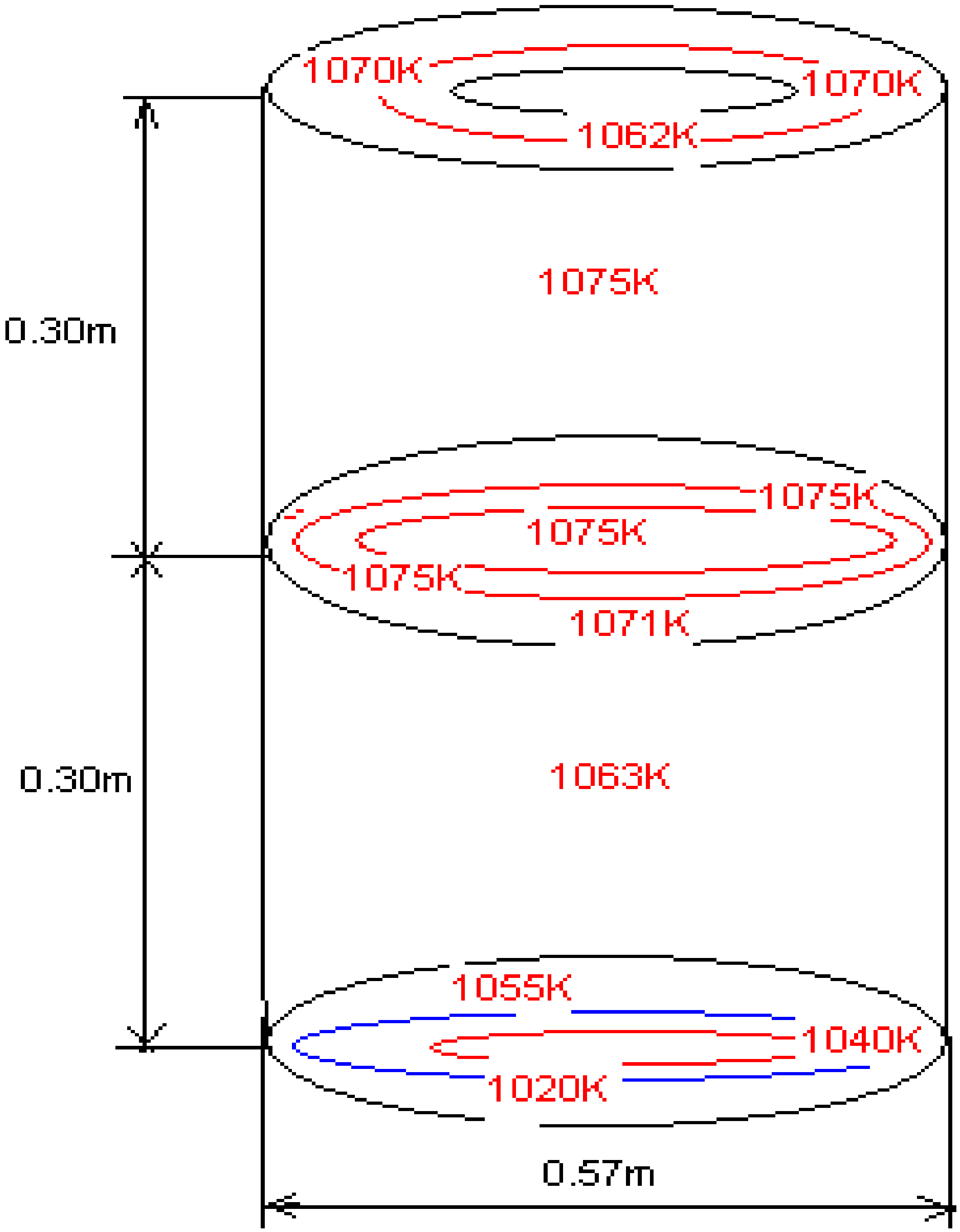

Figure 7.15 Experimental- Temperature Distribution for Blend B15 at a slurry inlet temperature of 328K

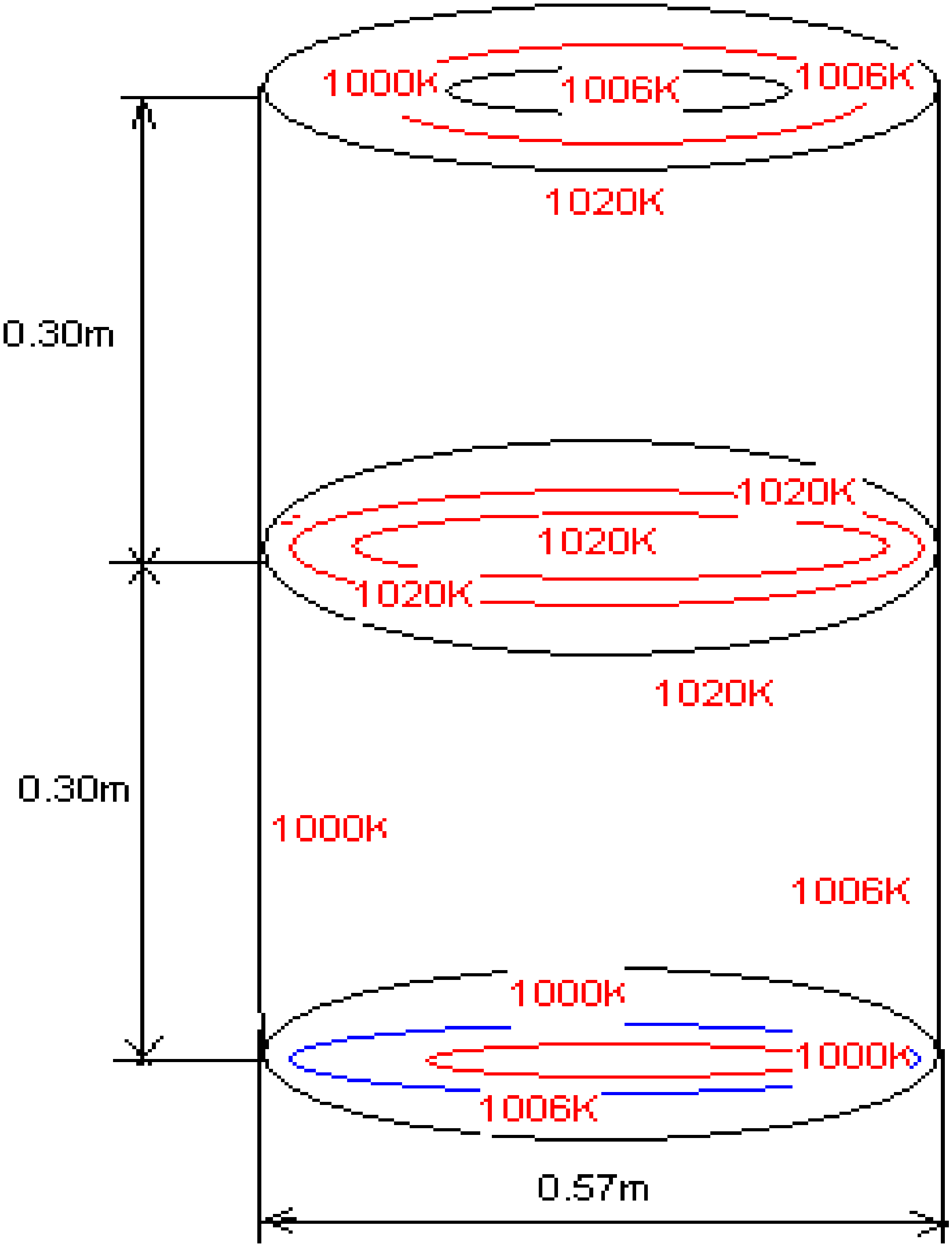

Figure 7.16 Experimental- Temperature Distribution for Blend B20 at the inlet of fuel at room temperature.

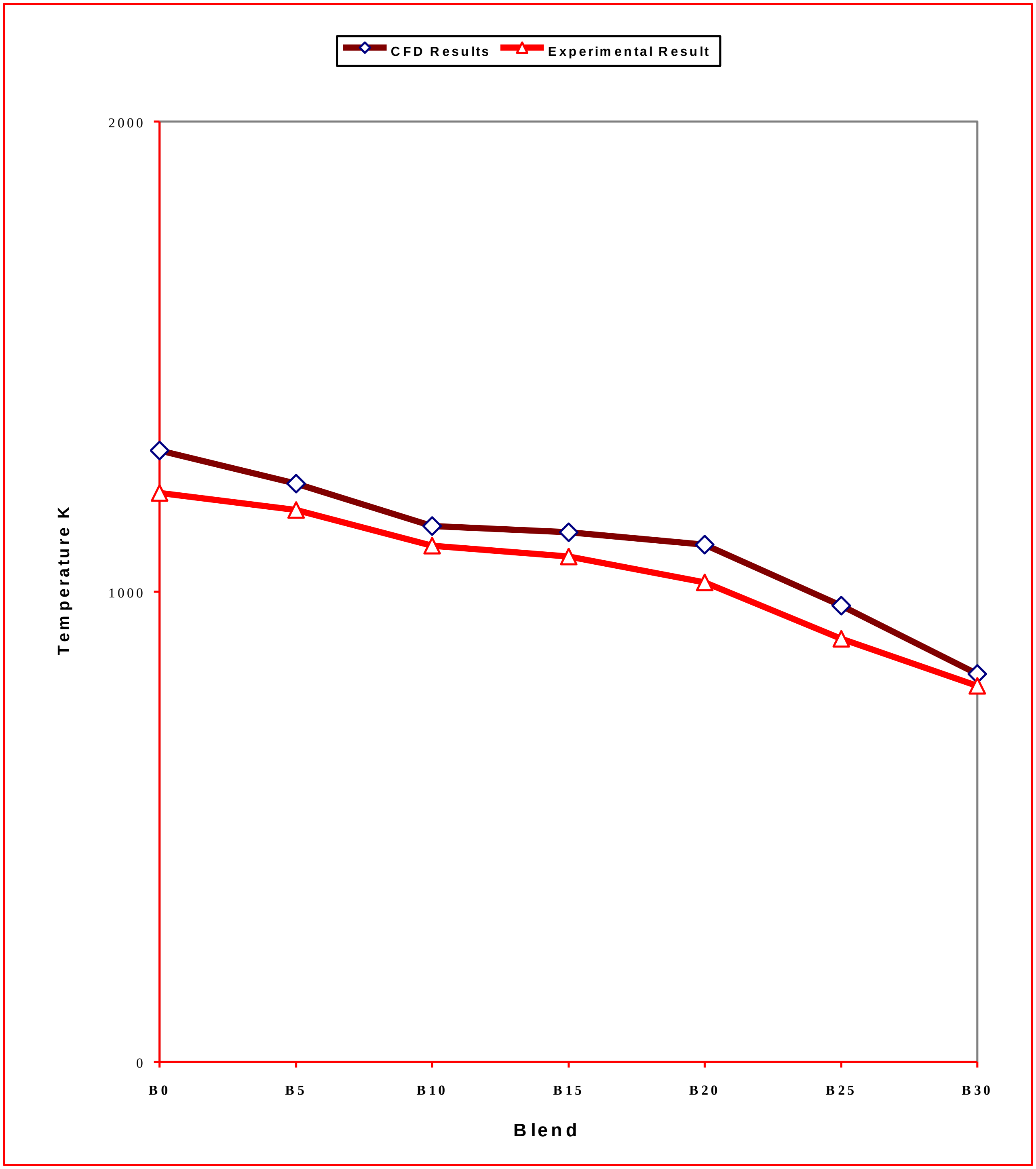

Figure 7.17 Comparison of CFD and Experimental results for the effect of Blend on combustion Temperature for fuel inlet at room temperature

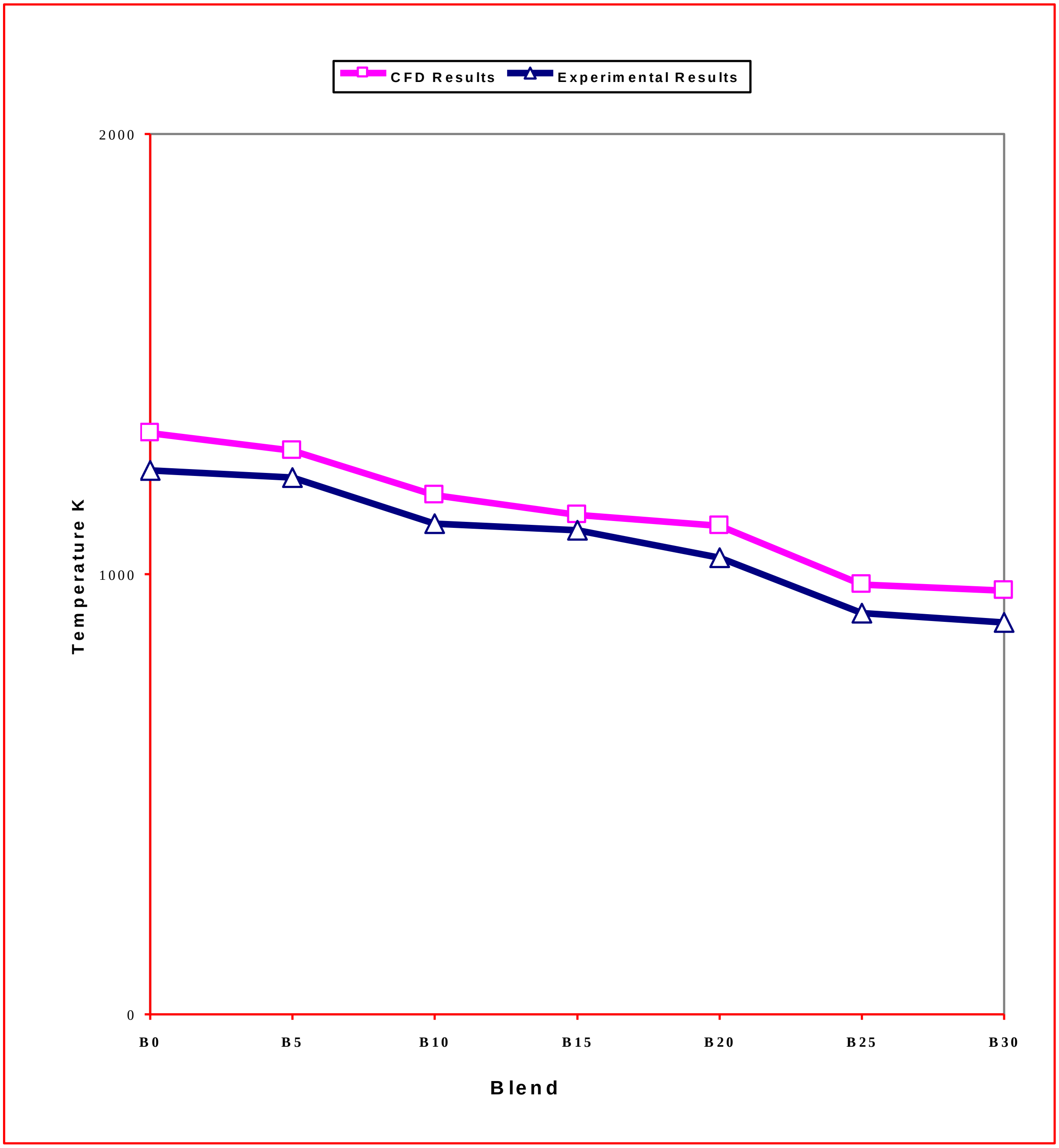

Figure7.18 Shows the variation of combustion temperature for effect of blend on temperature, when the fuel is let into the furnace by preheating the slurry

Figure 7.17 shows the variation of maximum temperature as a function of slurry. The predictions of temperatures from CFD for both the slurry inlet temperatures of inlet of room temperatures are shown. The experimental data corresponding to this case is also shown. It can be observed from Figure 7.17 that the maximum temperatures from the experiments are slightly lower than the predicted temperatures as expected in view of the heat loses from the furnace and from the thermocouple bead. The maximum temperature in the furnace reduces as the percentage of coconut shell powder increases, because of decrease in the calorific value of the slurry as the percentage of biomass increases.

Figure 7.18 shows the variation of maximum temperature as a function of slurry. The predictions of temperatures from CFD for both the slurry inlet temperatures of inlet at 328K temperatures are shown. The experimental data corresponding to this case is also shown. It can be observed from Figure 7.18 that the maximum temperatures from the experiments are slightly lower than the predicted temperatures as expected in view of the heat loses from the furnace and thermocouple bead to the atmosphere. The maximum temperature in the furnace reduces as the percentage of coconut shell powder increases.

Based on the above Temperature analysis, statistical multiple linear regression analysis is carried out for the maximum temperatures with the slurry at inlet at room temperatures. The correlation coefficient was found to be R^2 = 0.9983 and coefficient of variance R^2 = 0.9974. The Temperature attained during the combustion of biomass slurry can be calculated for any compositions of LDO, CSP and water by using the following relation and the line of best fit for the temperature analysis is shown in Figure 7.19

Temp of biofuels
Temperature K = 12.1 * LDO + 2.797 * CSP + 13.647 * WATER

The range of applicability of this relation are LDO 60 to100%, CSP 0 to 30%, Water =10%.

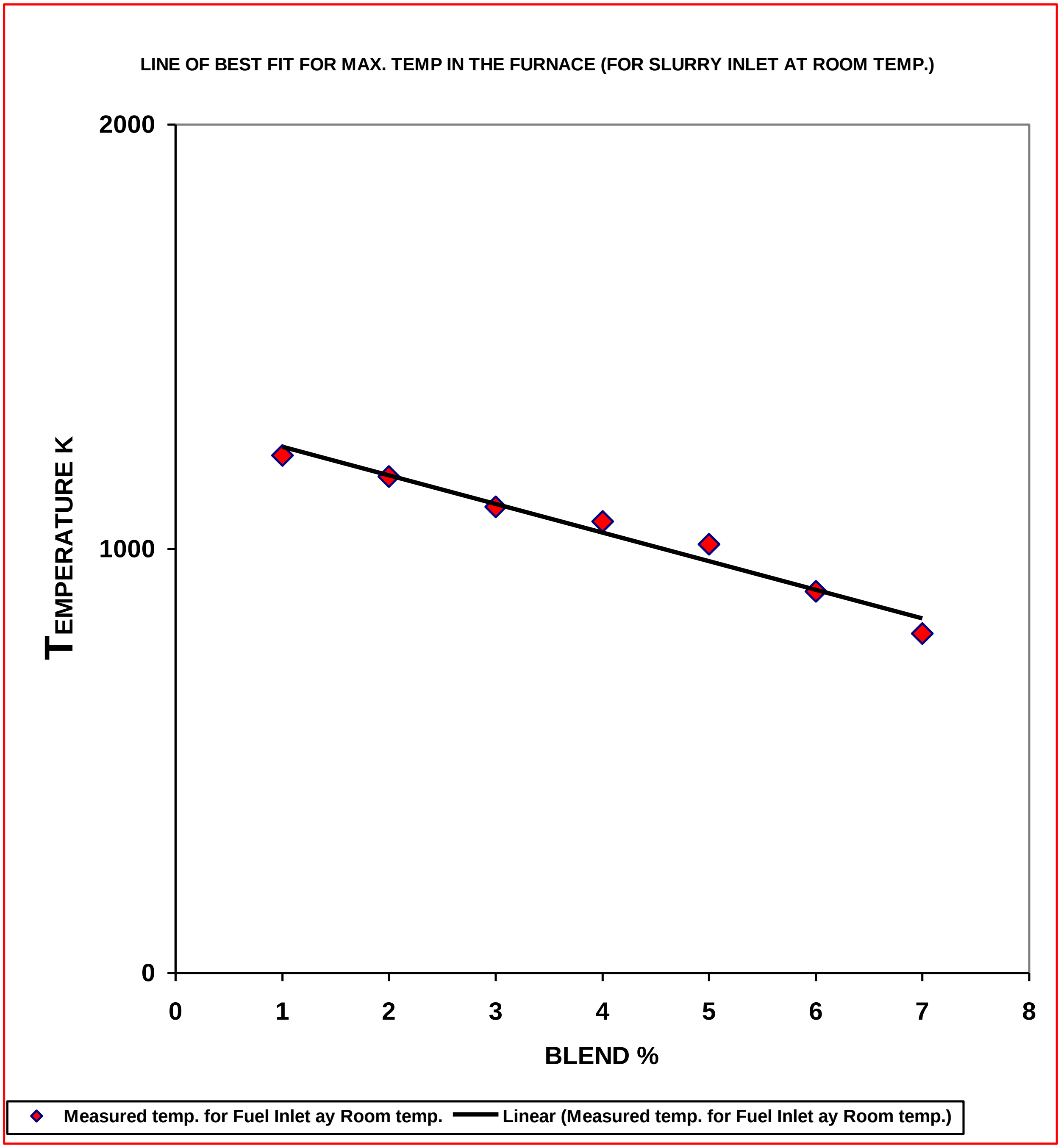

Figure 7.19 Regression analysis for max. Temperature in the furnace (for slurry at Room temperature)

Figure 7.19 shows the variation of temperature with the Blend for the measured values. The trend line is plotted for the same. It is observed from the trend line that the variation of temperature with that of variation of percentage of coconut shell powder is linear.

Table 7.7 Variation of Temperature and CO with Excess of air for Blend B10:

Percentage of Air %	Temperature K	CO Emission %
10	1105	4.4
20	1112	4.2
30	1119	4.2
40	1109	4.1
50	1070	4.0

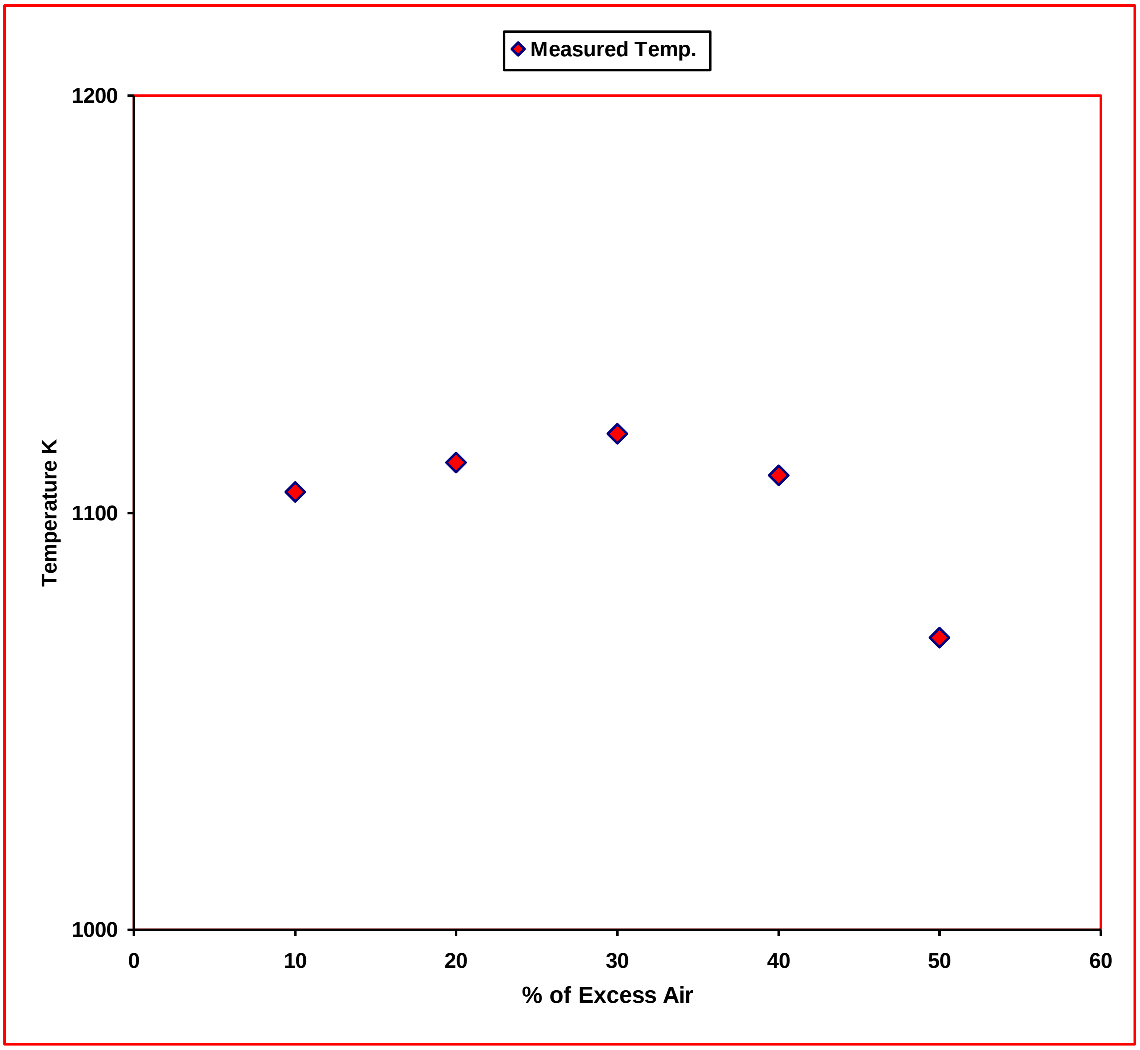

Figure 7.20 Variation of Temperature with Excess air for fuel inlet at Room Temperature

Figure 7.20 shows the variation of maximum Temperature in the furnace plotted against excess air. It can be observed from the figure that the temperature increases with the increase in percentage of air up to 30% and then decreases.

Plate.3 shows Combustion of Biomass slurry in the open furnace for the case of stochiometric air flow. It can be observed from this plate the flame is contained within the furnace. Plate.4 shows an alternative view of the combustion of Biomass slurry at stochiometric air flow. This also shows that the flame is contained with in the furnace. Plate.5 shows the combustion of Biomass slurry for 20% excess air with the furnace top being open. It can be observed from plate.5 that the flames come out of the furnace top in a conical shape. Plate.6 shows combustion of Biomass slurry for 30% excess air flow with top open. It can be observed from plate.6 that the flames escaping from the furnace exit are spread out compared to plate.5 in view of additional air flow.

Plate.7 shows the combustion of Biomass slurry with top partially closed for 20% excess air. It can be observed from plate.7 that the flames are constrained by a smaller exit and tapers. Plate.8 shows the combustion of Biomass slurry with top partially closed for 30% excess air. It can be observed from plate.8 that the flame is wider and extents to a longer length beyond the exit of the furnace. The thermocouple used for measurement of temperature can also be seen in plate.8.

Plate.9 shows power generation using Steam generated in the Once through Copper coil inserted in the furnace. The exhaust steam living the turbine can be observed in the plate.9.

Plate.10 shows the digital display used in the Temperature measurement in the furnace.

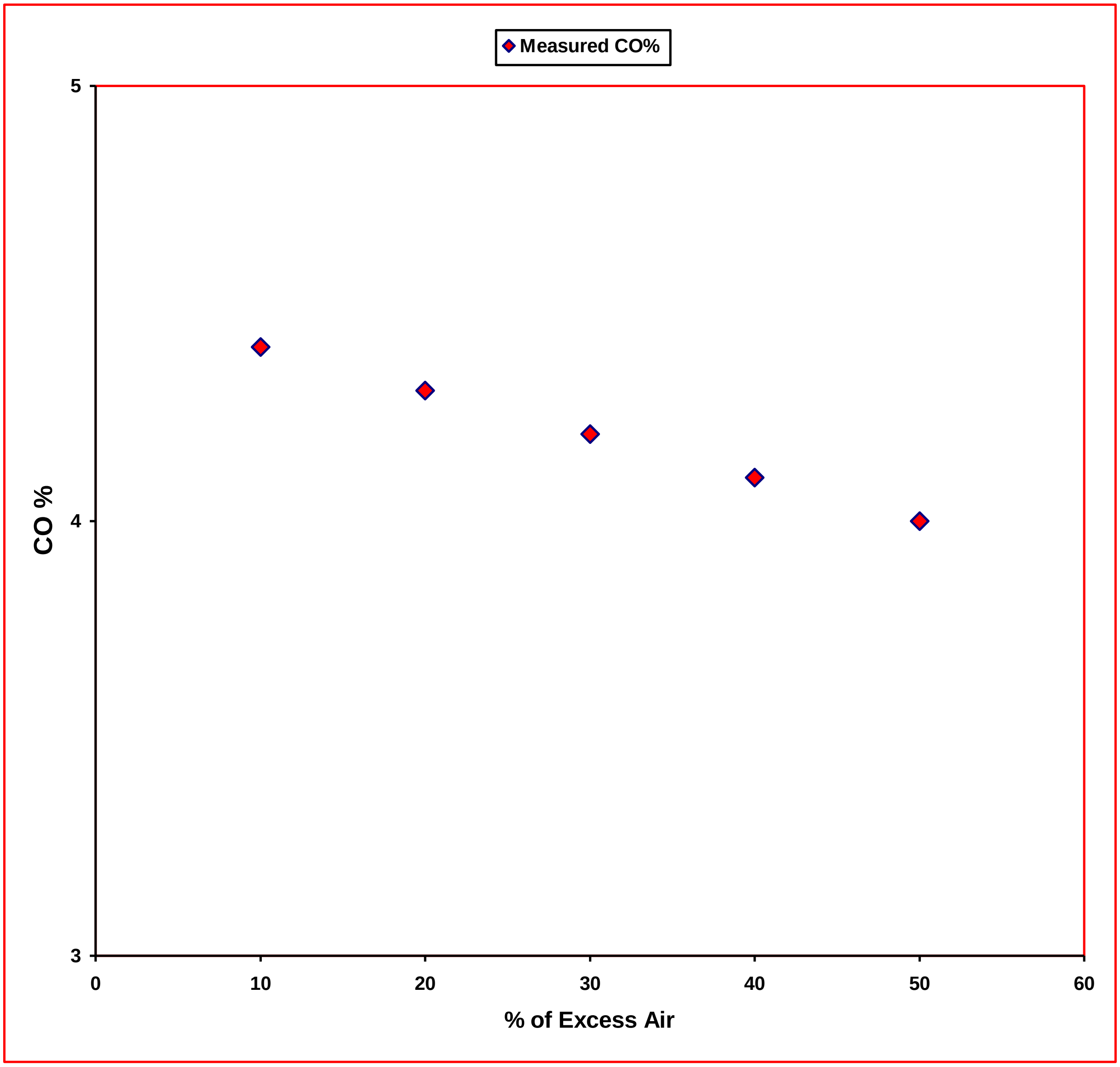

Figure 7.21 Variation of CO percentage with Excess air for B10 fuel inlet at Room Temperature

Figure 7.21 shows the variation of CO against the percentage of excess air. It can be observed that the emission of CO percentage decreases with the increase in percentage of excess air.

Table- 7.8 Emission Analysis

Blends	**CO ANALYSIS %**			
	CFD results for fuel inlet at		**Experimental results for fuel inlet at**	
	ROOM (298K)	**ELEVATED (328K)**	**ROOM (298K)**	**ELEVATED (328K)**
LDO	4.4	4.0	4.8	4.2
B05	4.3	3.8	4.7	4.0
B10	4.1	3.5	4.5	3.7
B15	4.0	3.4	4.3	3.6
B20	4.0	3.3	4.2	3.5
B25	4.2	3.5	4.4	3.7
B30	4.3	3.7	4.4	3.9

(* Blends in percentage of weight)

Table 7.8 shows the variation of CO against the composition of the slurry. The table shows the predicted results from CFD for both the cases of slurry inlet at room temperature as well as at an elevated temperature of 328K. The corresponding values for the experimental investigation are also given in the Table 7.8. It can be observed from the table that the predictions from CFD and experimental data agrees reasonably. As the composition of the coconut shell powder increases, the CO emission reduces up to B20 and then slightly increases again. This trend is observed in both CFD predictions and Experimental data. The reason for this is as the percentage of CSP increases in the blend above 25%, the slurry becomes highly viscous. There is no proper flowing of the slurry from the nozzle. Which results in incomplete combustion of the slurry fuel and thus leads to more emission, since only the LDO is getting burnt and CSP can be observed settling on the base of the furnace in a pasty form. It is interesting to note that the preheating of the slurry from 298K to 328K reduces the CO emissions to an extent of 10 to 15%, because of complete combustion of biomass slurry and water. Both the CFD predictions and the experimental data illustrate this point. For a better feeling of the results, the same is plotted in Figure 7.22.

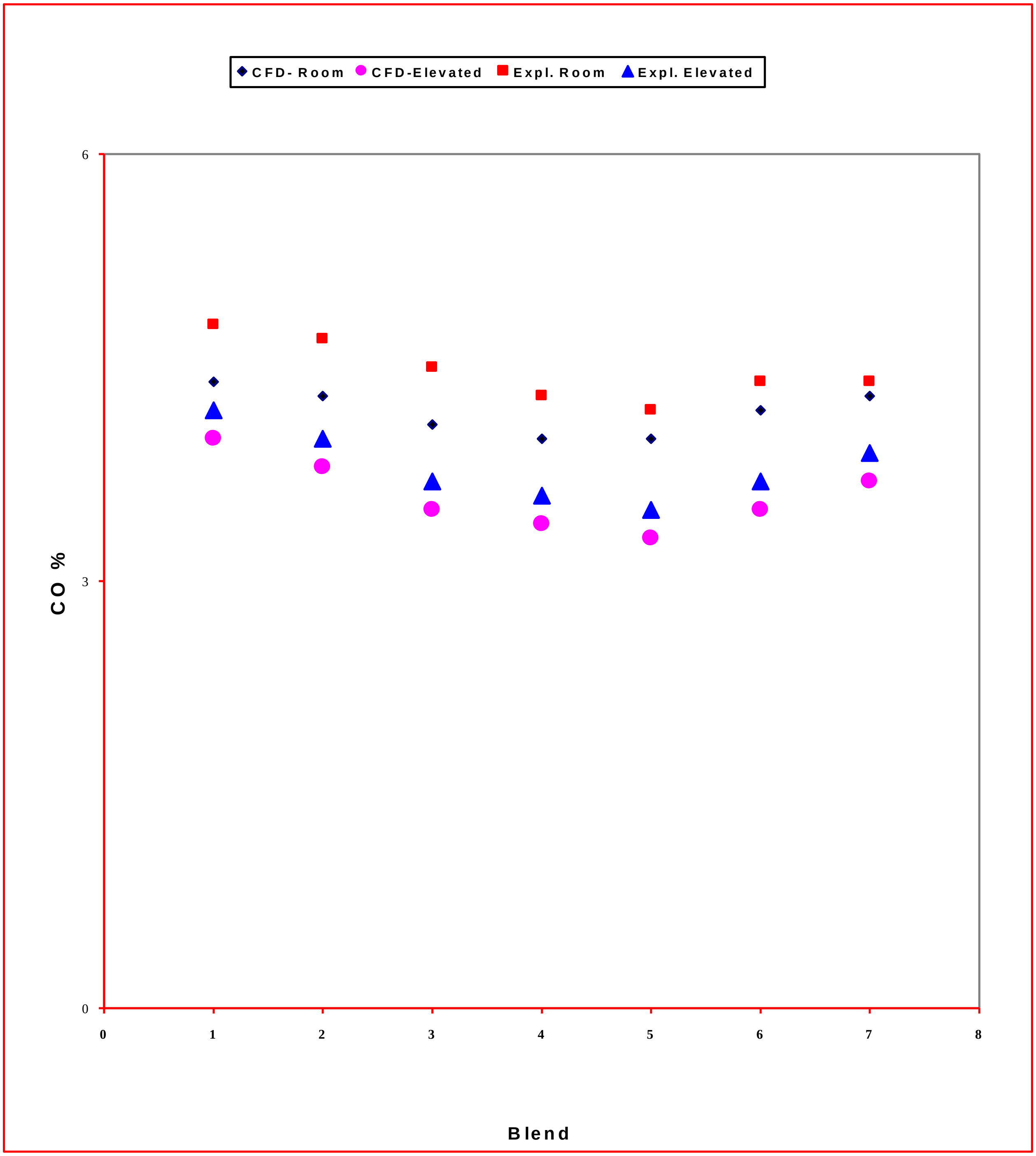

Figure 7.22 CO emission analysis for various blends of Biomass slurry

TABLE-7.9 Cost analysis

Blends	Composition in terms of LDO+CSP+WATER	Viscosity kg/m-s	Measured Calorific Value kJ/kg	Cost/Liter	Fuel cost index
B00	100+0+0	0.50	39800	23.00/-	3461
B05	85+5+10	0.52	39000	19.90/-	3769
B10	80+10+10	0.60	38300	18.90/-	3378
B15	75+15+10	0.86	37500	18.00/-	2423
B20	70+20+10	0.96	36900	17.10/-	2248
B25	65+25+10	1.32	36200	16.20/-	1693
B30	60+30+10	1.68	35700	15.30/-	1389

(* Blends in percentage of weight)

The cost of the Biomass slurry is calculated based on the cost of LDO = Rs.23/- and CSP = Rs.5/-/kg. Table 7.9 shows the cost against the blend.

Based on the above cost analysis, statistical-multiple linear regression analysis was done and the correlation coefficient was found to be $R^2 = 0.9983$ and coefficient of variance $\underline{R^2}$ = 0.9974, the cost of the Biomass slurry for any composition can be calculated by using the relation

COST Rs/- = 0.23 * LDO + 0.042 * CSP + 0.002 * H2O

The range of applicability of this relation are LDO >60 and <100, CSP >0 and < 30, Water =10

It is worth while to explore the possibility of an index, which reflects the calorific value (should be as high as possible), viscosity (should be as low as possible) and cost (should be as low as possible) of the biomass slurry. Thus fuel cost index is defined as

$$\textbf{Fuel Cost Index} = \frac{\textbf{Calorific value}}{\textbf{(Viscosity) (Cost)}}$$

Thus, we expect the most appropriate biomass slurry to have a maximum value of the fuel cost index. Table 7.9 shows the fuel cost index against the composition of the biomass slurry. From the Table 7.9 it can be observed that B5 is the most appropriate biomass slurry. However, it is to be pointed out that, fuel cost index is dimensional and can be used in the absence of any other suitable index being defined at present.

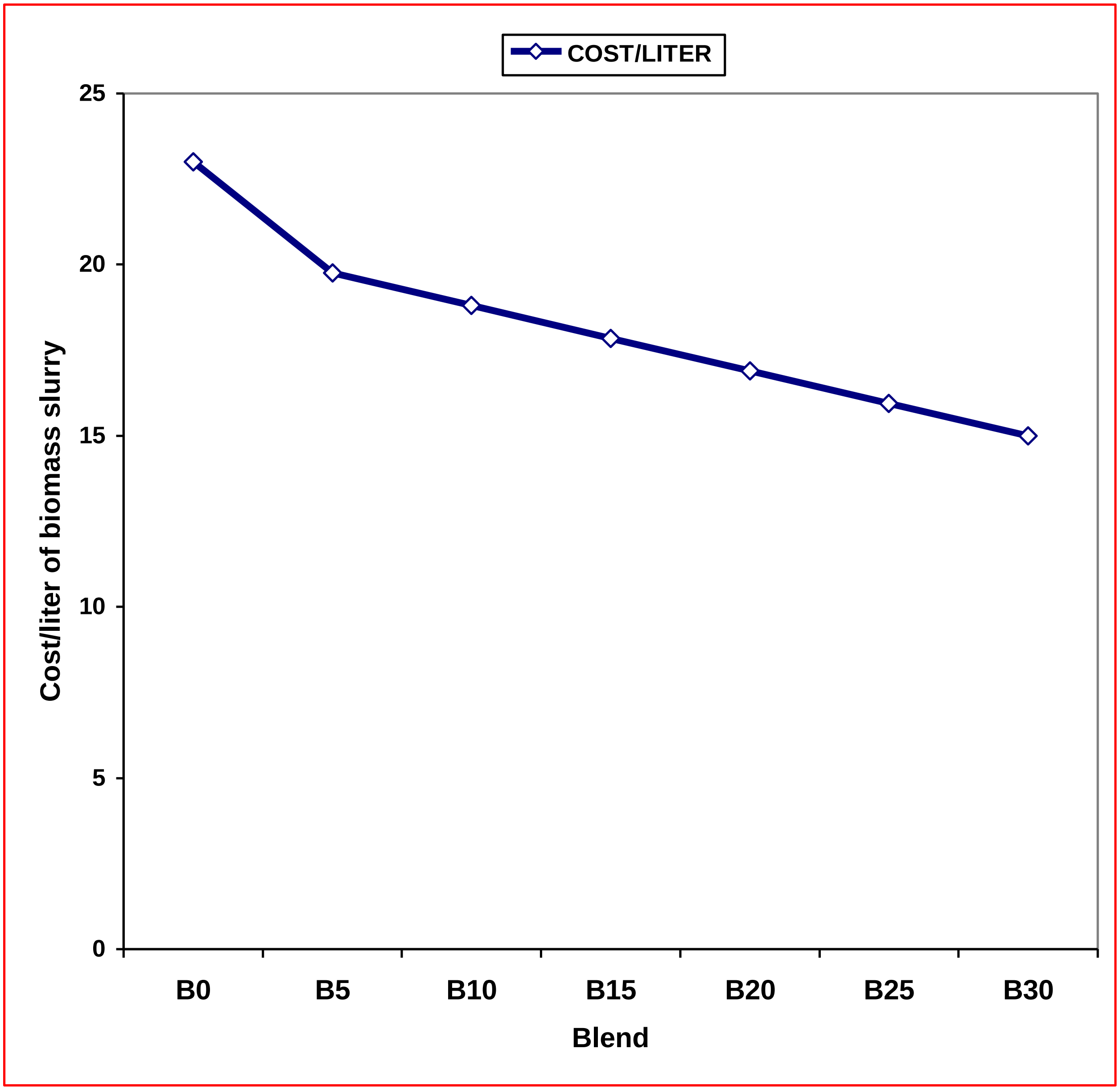

Figure 7.23 Cost of biomass slurry v/s composition of the fuel

Figure 7.23 shows the variation of cost of biomass slurry with the blend, it can be seen that the cost decreases linearly as the percentage of coconut shell powder increases in the blend.

With the above combustion analysis, the overall performance of the furnace was evaluated based on the Equivalence Ratio.

7.4 Results in terms of Equivalence ratio:

Several of the experiments carried out with varying quantity of excess air can all be combined, by using the definition of Equivalence ratio [88].

$$\boxed{\mathbf{\Phi = \frac{(Fuel/air)_{actual}}{(Fuel/air)_{stochio.}}}}$$

Φ > 1- fuel rich; Φ = 1- Stoichiometric; Φ < 1- Fuel is lean mixture,

based on this relation the overall performance of the furnace can be evaluated for different blends of biomass slurry

For B10, the Equivalence ratio is given by

The percentage O_2 needed for C is = 0.7172(32/12) = 1.92 kg of O_2

The percentage O_2 needed for H is = 0.1444(32/4) = $\underline{1.16 \text{ kgs of } O_2}$

Total amount of O2 = $\underline{3.07 \text{ kgs of } O_2}$

Total air = 3.07/0.23 = 13.34 kgs of air

Therefore $\varphi_{stochiomatric}$ = 1/ 13.34 = 0.08

For 10% excess air = 1.1(13.34) = 14.67 kgs of air

Therefore the Equivalence ratio = $\frac{1/\ 12.07}{1/\ 13.34}$ = 0.90

For 20% excess air = 1.2(13.34) = 13.86 kgs of air

Therefore the Equivalence ratio = $\frac{1/\ 13.86}{1/\ 13.34}$ = 0.84

For 30% excess air = 1.3(13.34) = 17.35 kgs of air

Therefore the Equivalence ratio = $\frac{1/\ 17.35}{1/\ 13.34}$ = 0.77

For 40% excess air = 1.4(13.34) = 18.68 kgs of air

Therefore the Equivalence ratio = $\frac{1/\ 18.68}{1/\ 13.34} = 0.72$

For 50% excess air = 1.5(13.34) = 20.02 kgs of air

Therefore the Equivalence ratio = $\frac{1/\ 20.02}{1/\ 13.34} = 0.67$

For the blend of B10 slurry, the various quantities are plotted against the equivalence ratio.

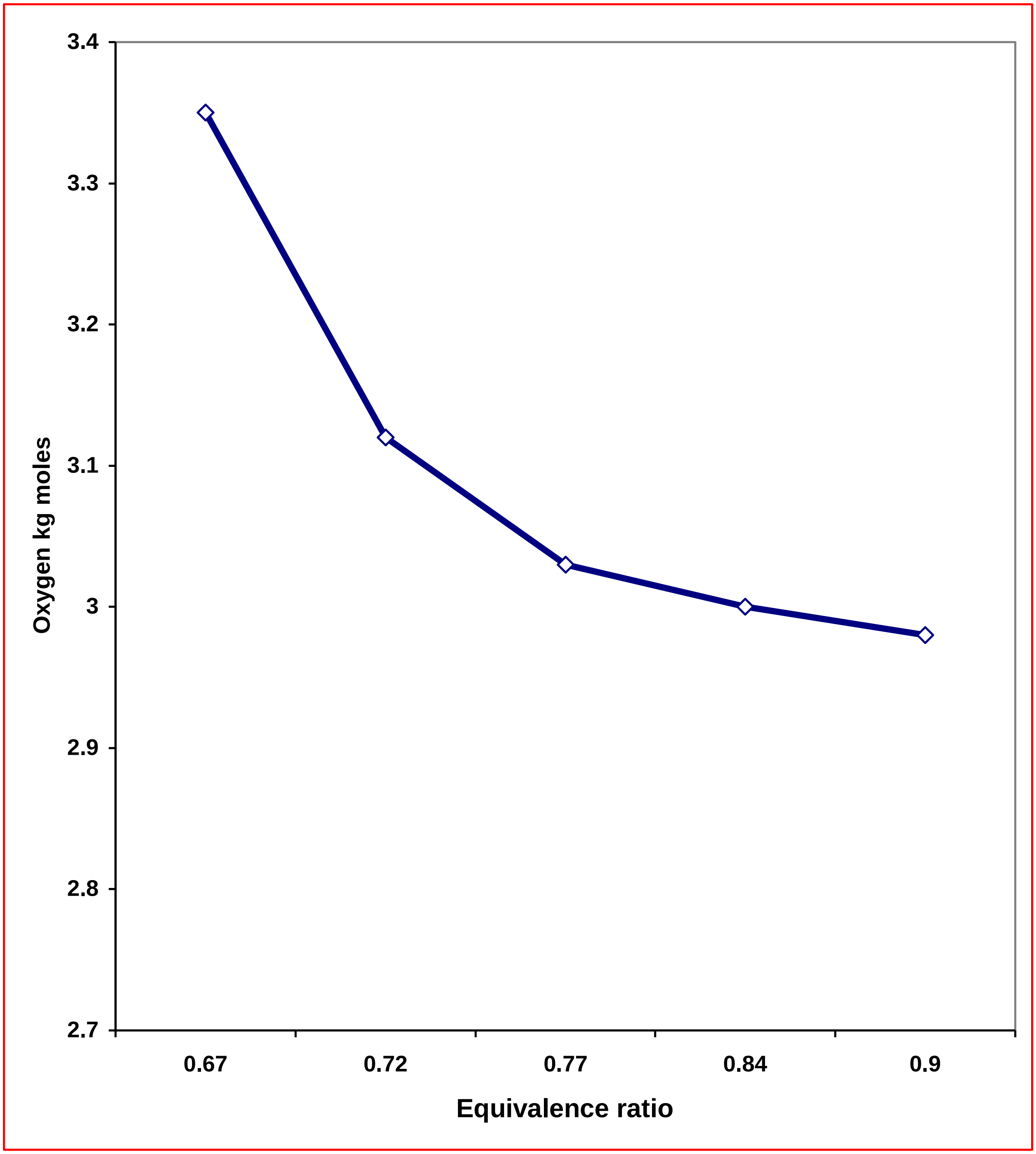

Figure7.24 Variation of O_2 with Equivalence ratio for B10

Figure 7.24 shows the variation of oxygen plotted against the Equivalence ratio. It can be seen from Figure 7.23 that as the equivalence ratio increases the oxygen in the exhaust decreases continuously.

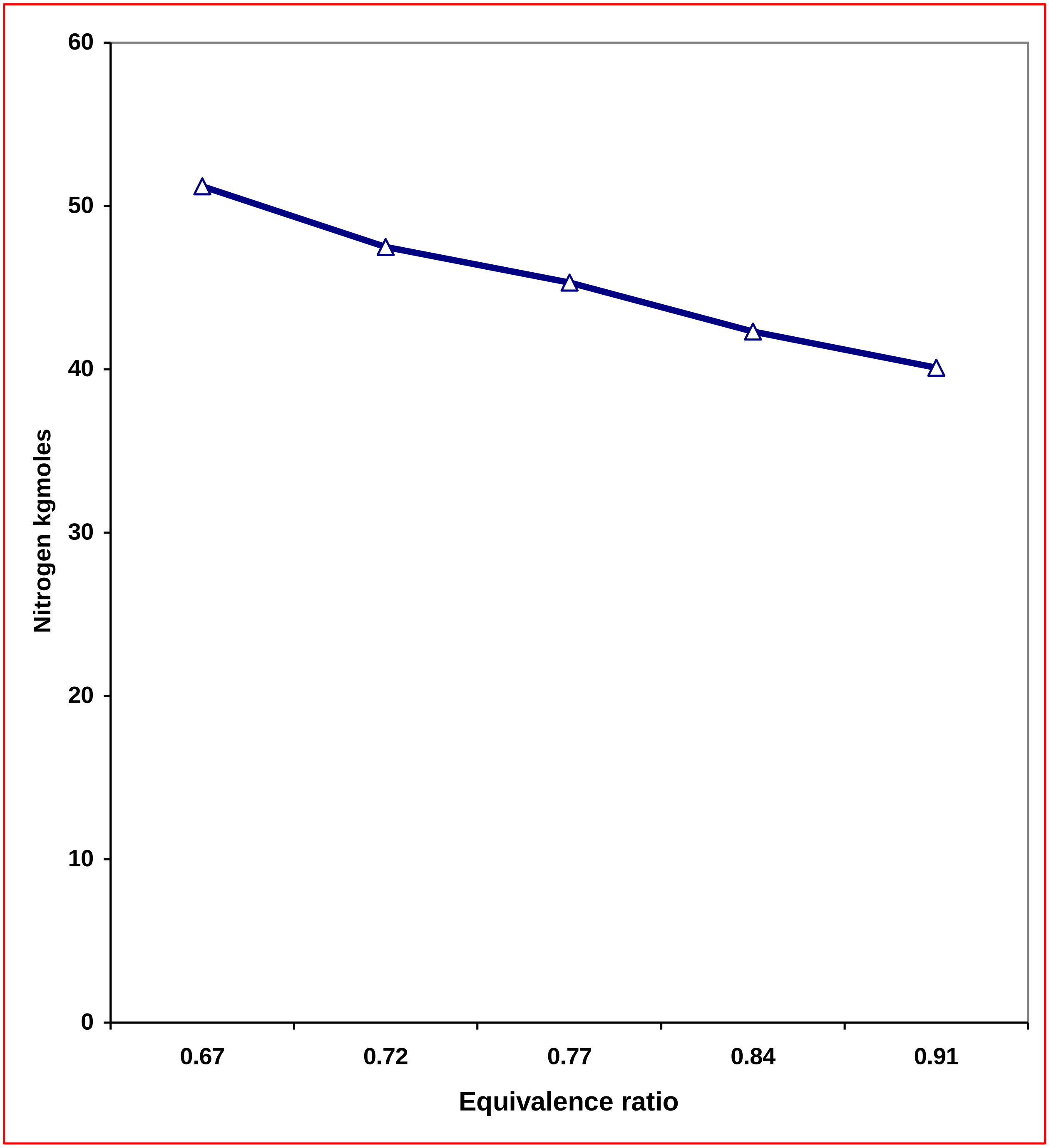

Figure 7.25 Variation of N_2 with Equivalence ratio for B10

Figure 7.25 shows the variation of nitrogen plotted against the Equivalence ratio. It can be seen from Figure 7.25 that as the equivalence ratio increases the nitrogen in the exhaust decreases continuously.

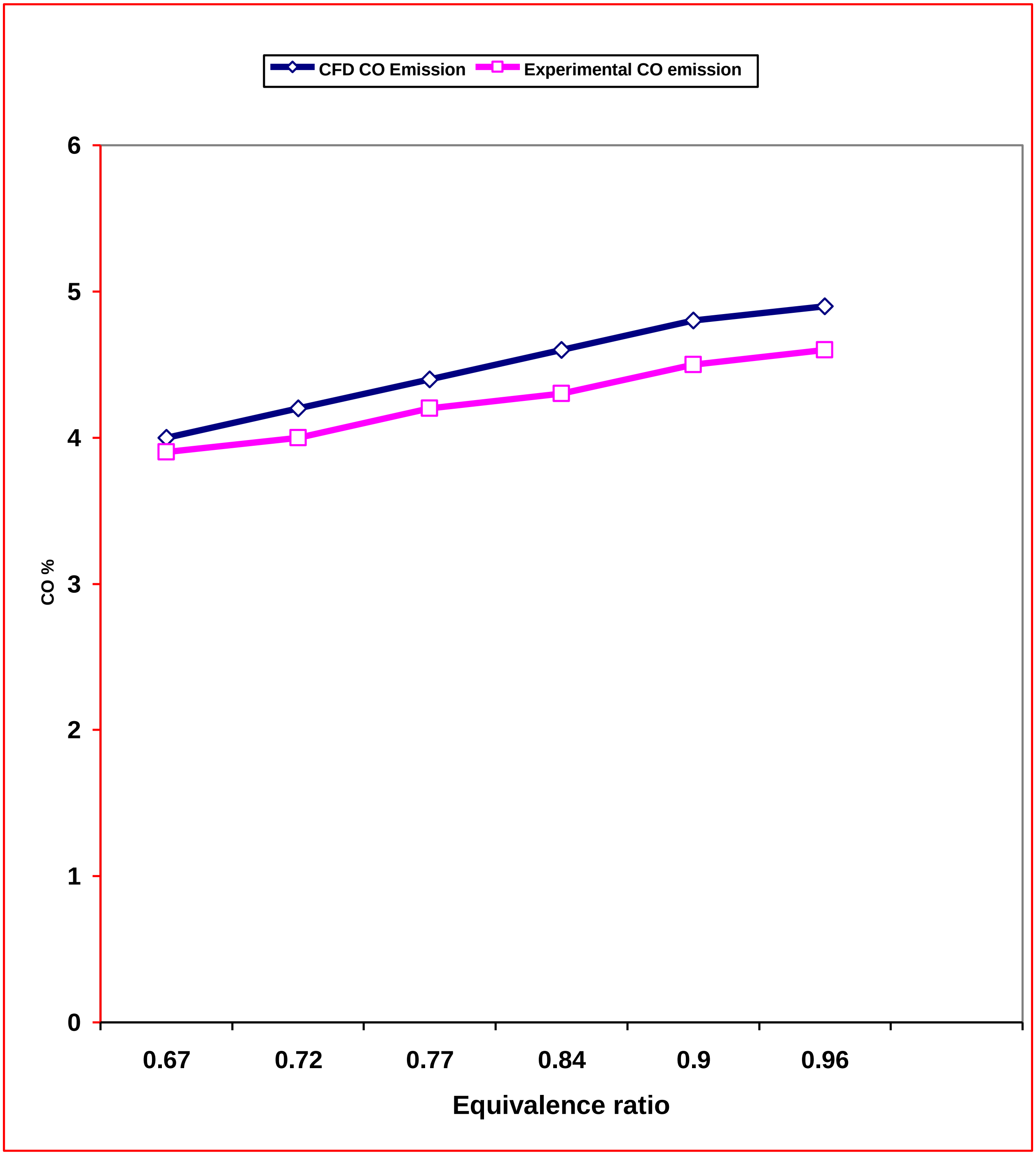

Figure 7.26 Variation of CO with Equivalence ratio

Figure 7.26 shows the variation of CO against the equivalence ratio for the fuel inlet at room temperature and elevated temperature. It can be observed that CO emission increases with the equivalence ratio as expected, because of the increase in percentage of air.

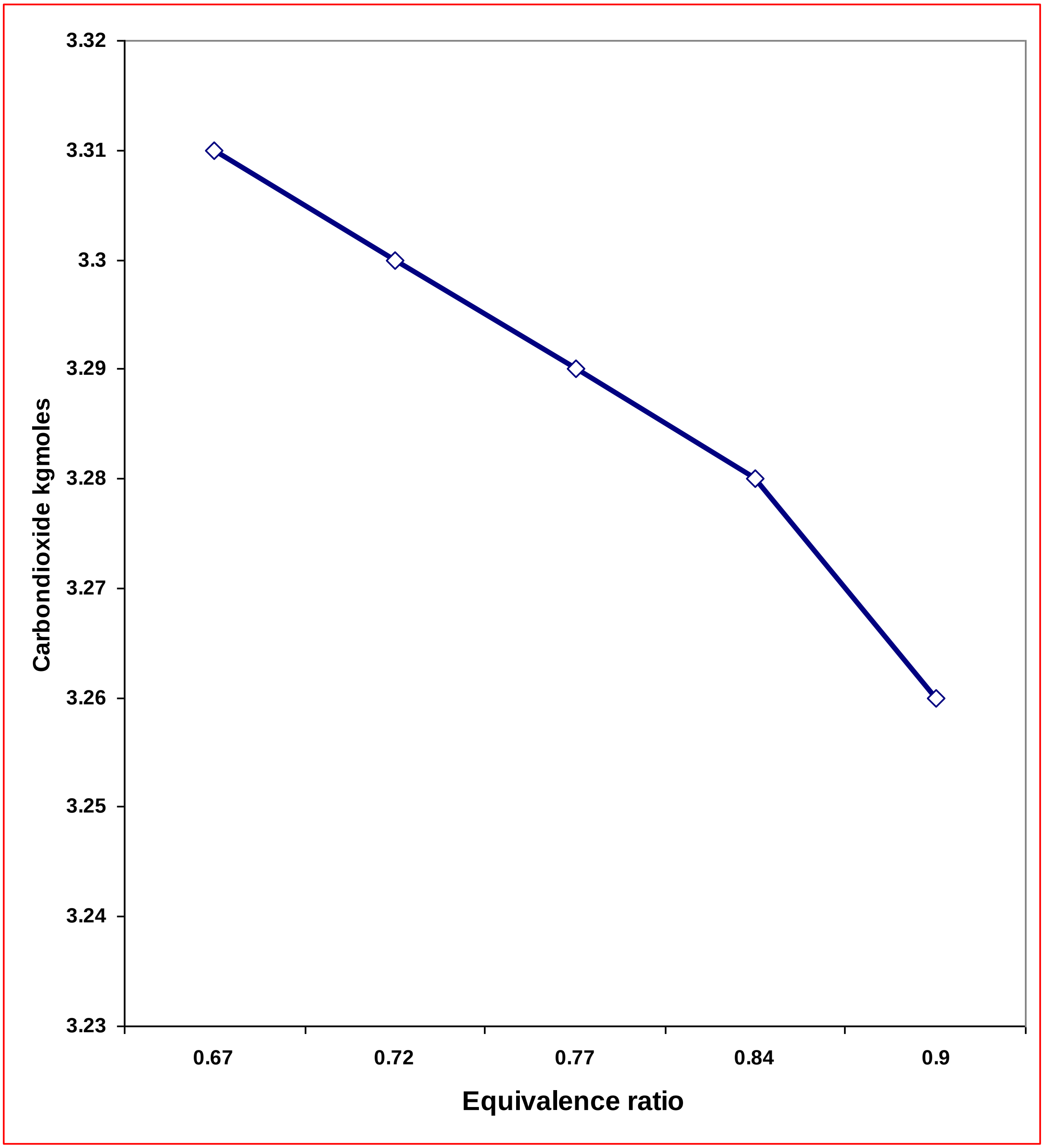

Figure 7.27 Variation of CO_2 with Equivalence ratio for B10

Figure 7.27 shows the variation of CO_2 against the equivalence ratio. It can be observed that CO_2 emission decreases marginally with the equivalence ratio.

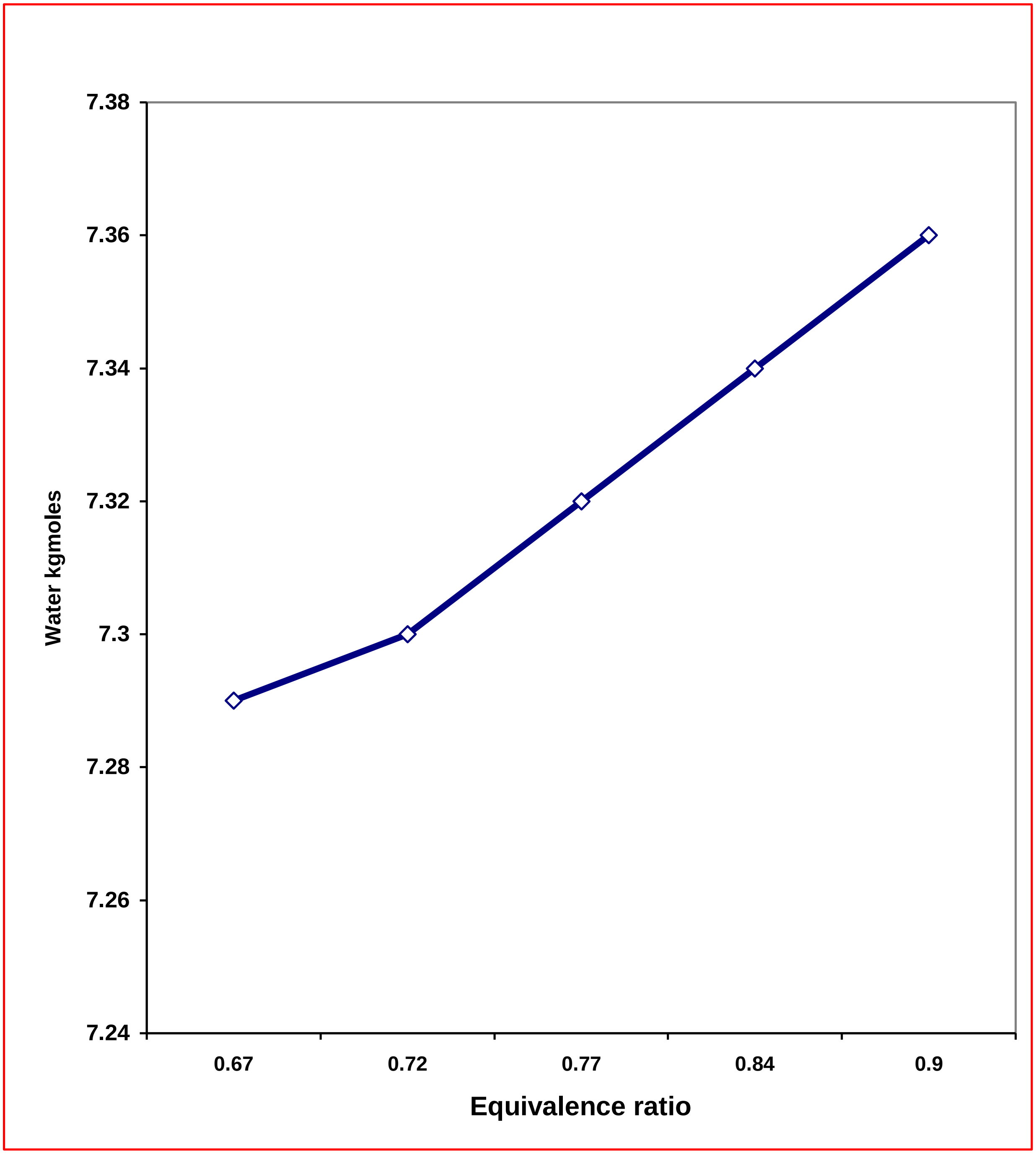

Figure 7.28 Variation of H_2O with Equivalence ratio for B10

Figure 7.28 shows the variation of H_2O against the equivalence ratio. It can be observed that H_2O emission increase with the equivalence ratio.

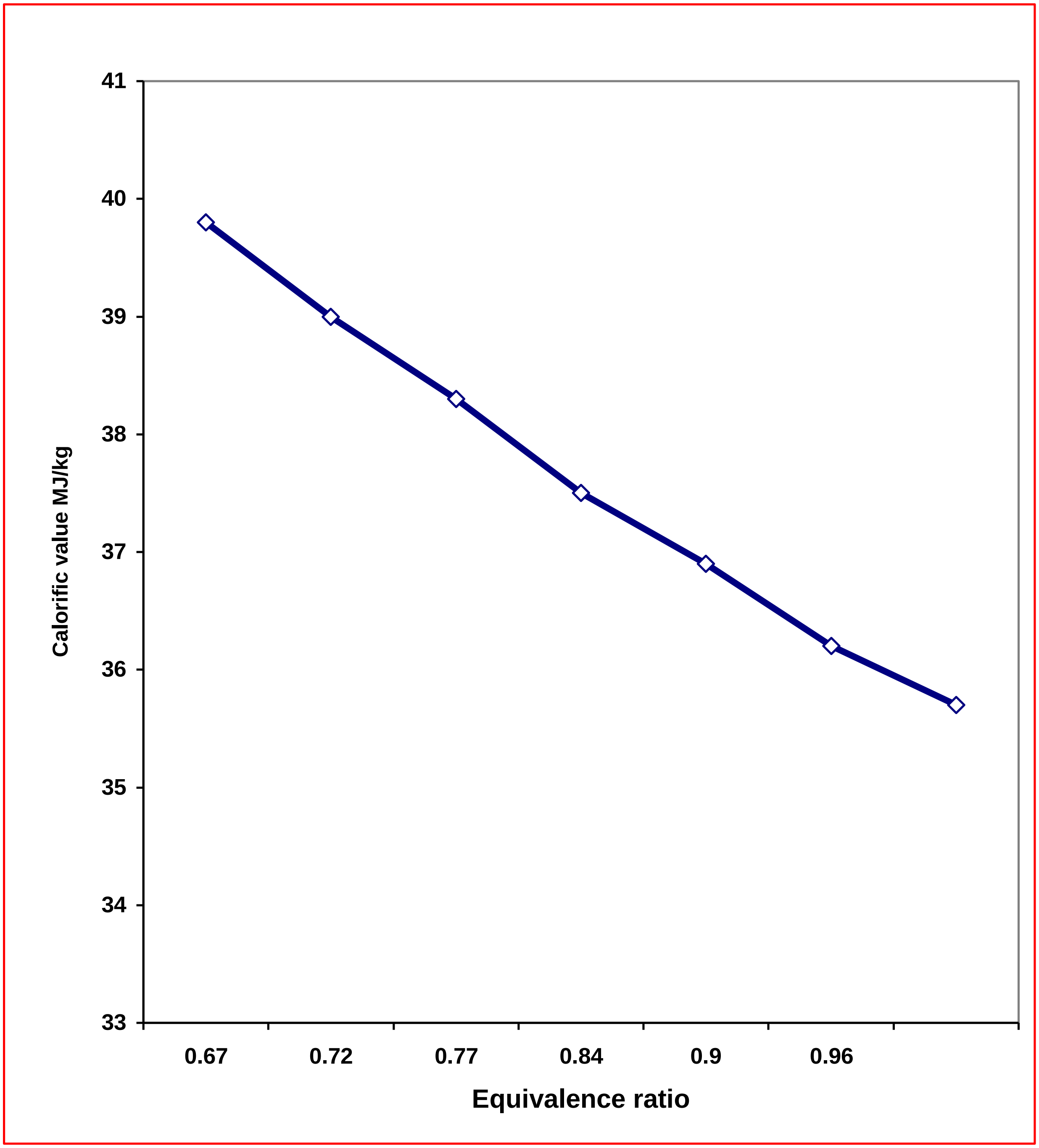

Figure 7.29 Variation of calorific value with Equivalence ratio

Figure 7.29 shows the variation of calorific value against the equivalence ratio. It can be observed that calorific value decreases with the equivalence ratio in almost a linear fashion.

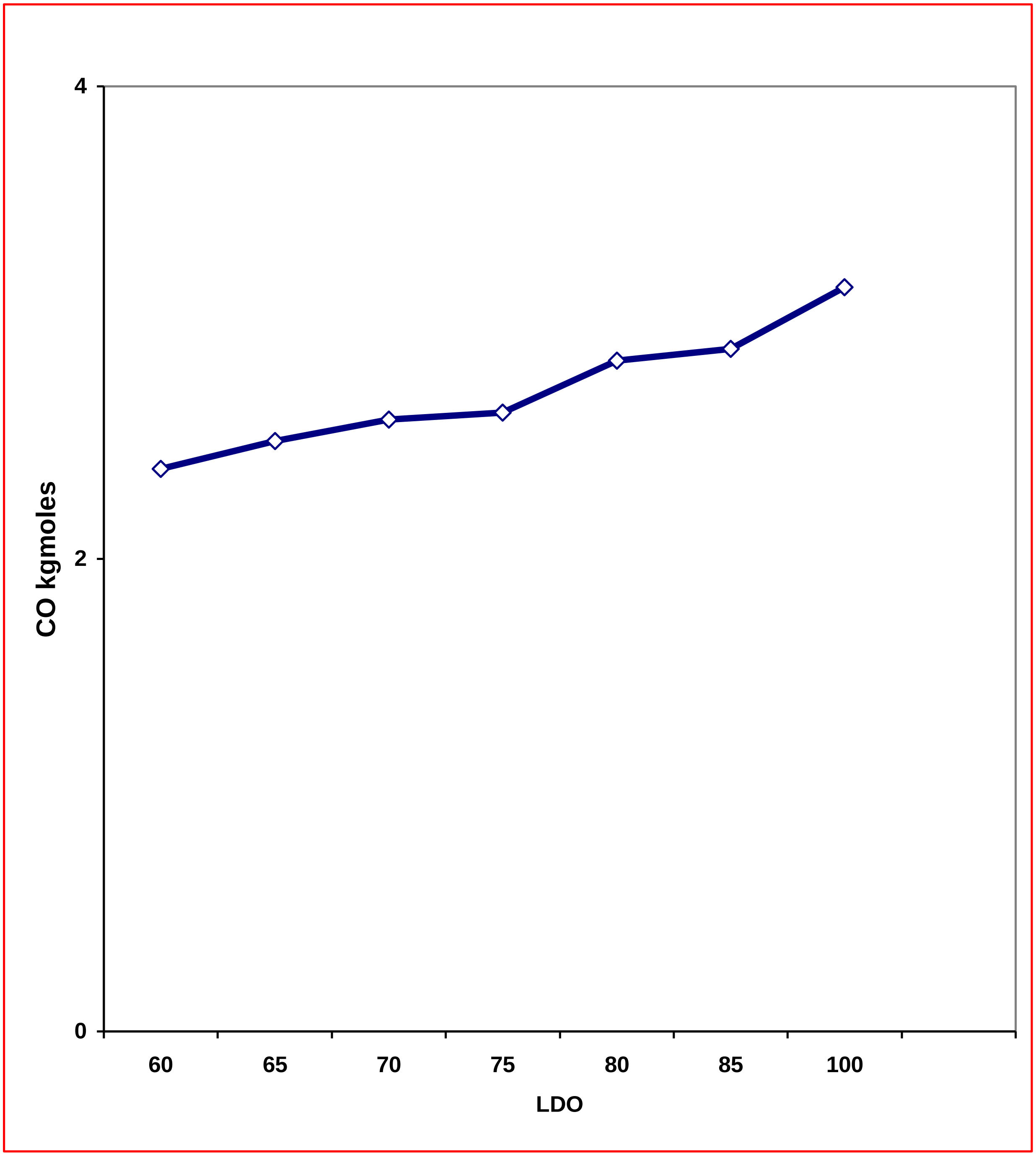

Figure 7.30 Effect of percentage of LDO on carbon monoxide emission

Figure 7.30 shows that the CO plotted against the percentage increase in LDO. It can be observed that the emission of CO increases with the increase in percentage of LDO in the blend.

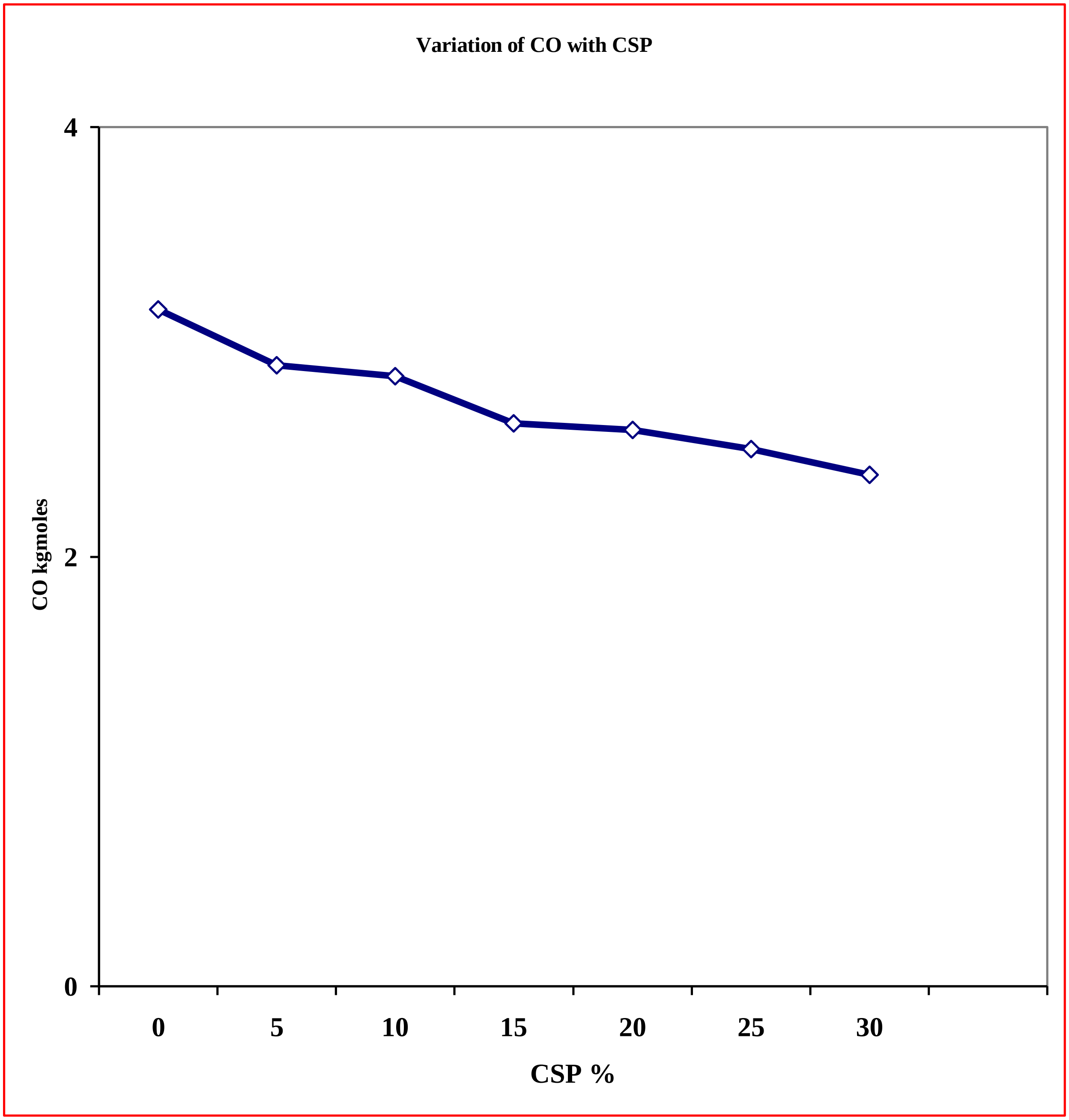

Figure 7.31 Effect of CSP on carbon monoxide emission

Figure 7.31 shows the CO plotted against the percentage of CSP in the blend. It can be observed that percentage emission of CO decreases, with the increase in percentage of CSP in the blend.

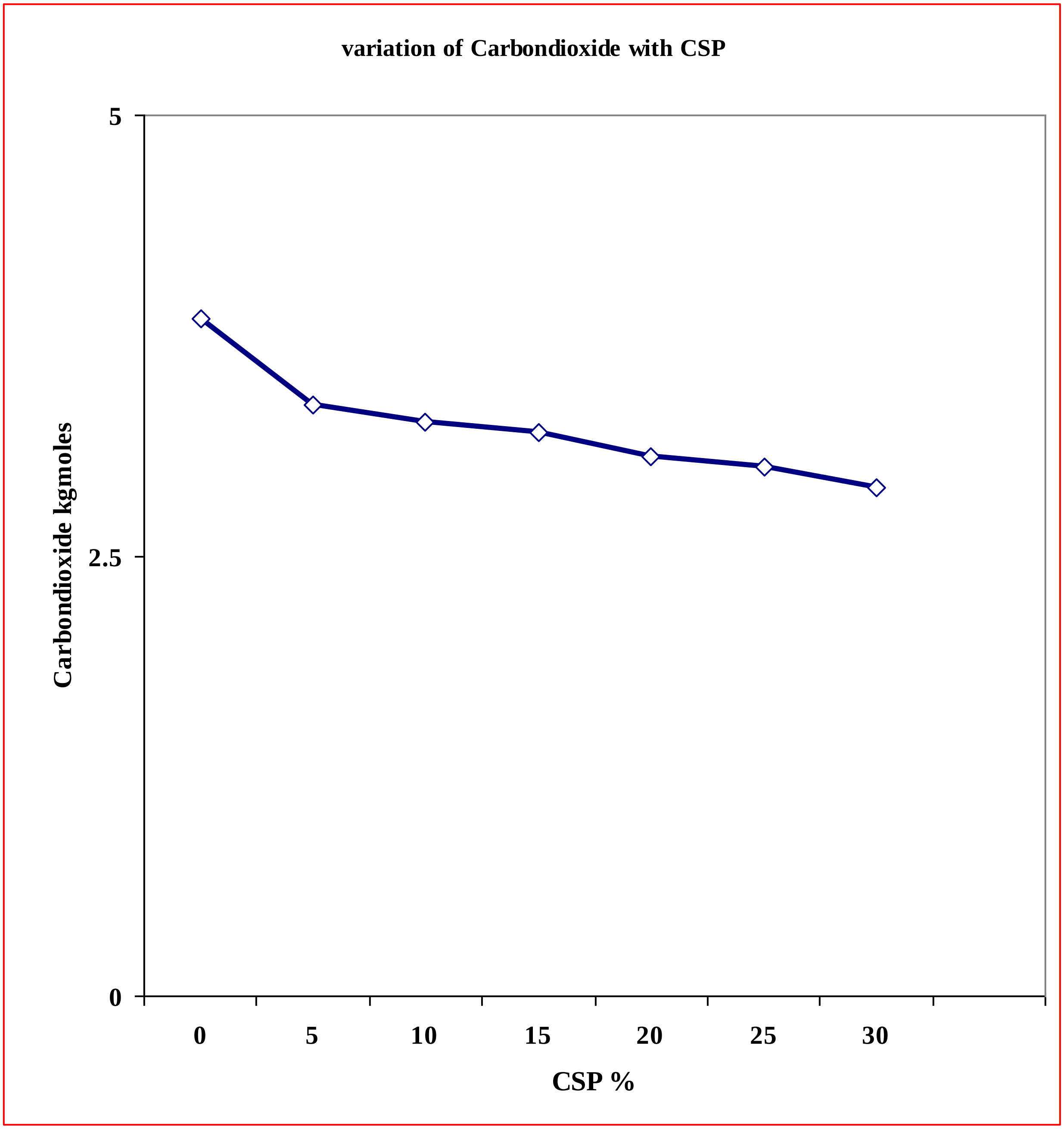

Figure 7.32 Effect of variation CSP on carbon dioxide emission

Figure 7.32 shows the effect of blend of CSP on the CO_2 emission of the slurry. It can be observed that percentage of CO_2 emission decreases with the increase in percentage of CSP in the blend and the variation of carbon dioxide is almost linear with the CSP.

7.5 Melting of Aluminum using Biomass slurry

The same furnace setup is used to melt Aluminum of 1kg weight, by making use of crucible of proper size. The total fuel consumed and the cost analysis is done for different blends of the fuel. It was observed that there was no substantial change in the emission of the slurry fuels compared to the previous studies.

Table-7.11 Melting of aluminum

Sl. No.	Blends	Consumption of fuel in liters for melting 1 kg of AL*	Cost of fuel to** melt 1 kg of fuel in Rs.	CO % Emission
1	LDO	2.00	46.00/-	4.80
2	B05	2.05	40.60/-	4.70
3	B10	2.10	39.69/-	4.50
4	B15	2.15	38.70/-	4.30
5	B20	2.20	37.62/-	4.20
6	B25	2.25	36.45/-	4.25
7	B30	2.30	35.19/-	4.30

(* Blends in percentage of weight)
(** Cost of LDO=23/-/Liter and CSP = 5/-/kg in the year 2004)

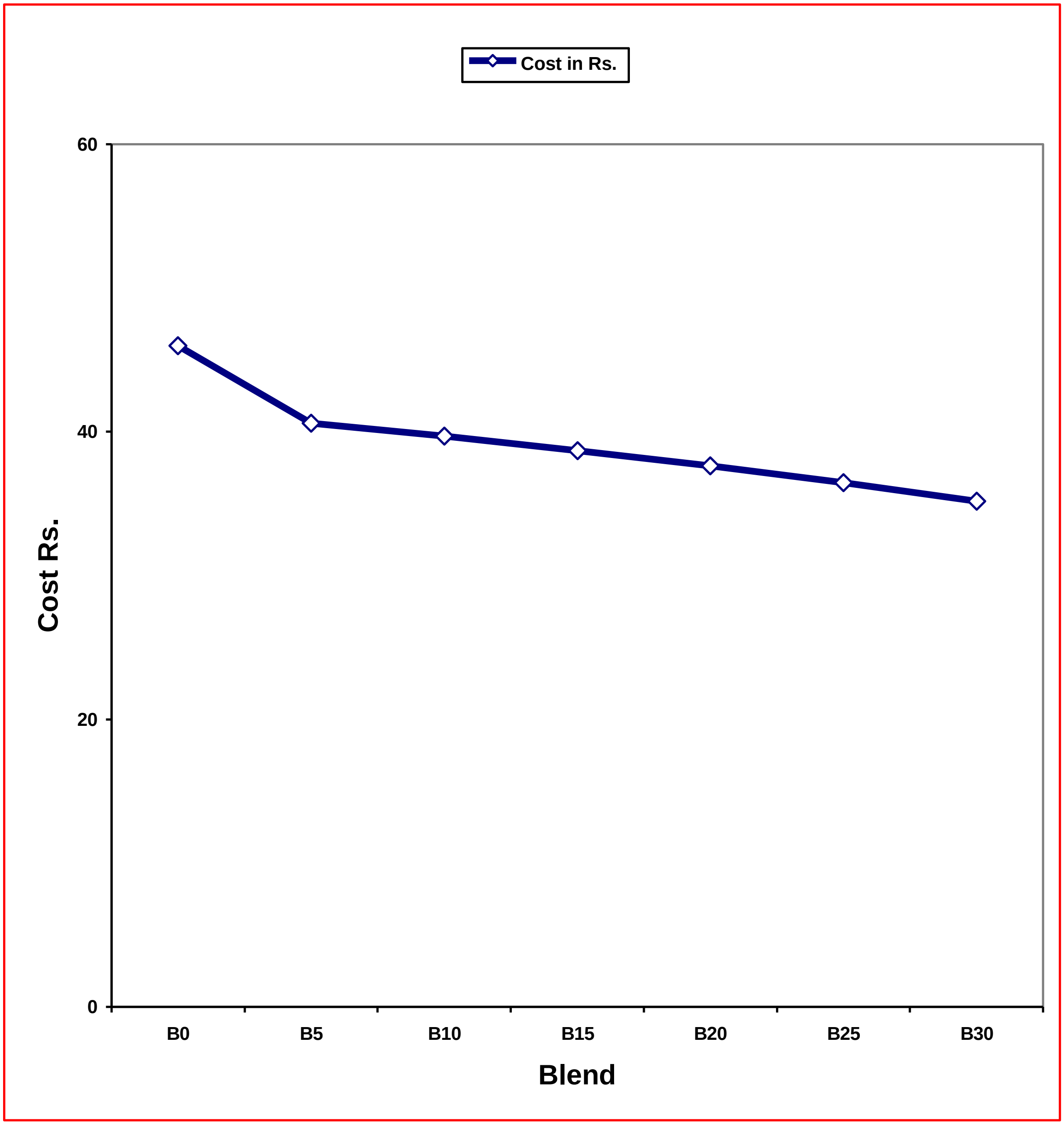

Figure7.33 Cost analysis of melting 1 kg of Al using various blends of the biomass slurry

Figure 7.33 shows that the cost decreases as the blend of CSP increases, the cost of melting 1kg of Aluminum is found to be minimum as can be seen from the Figure 7.33 to a blend of B30.

7.6 Combustion of slurries in the oil fired steam generator for power generation

A copper-coiled tube was introduced in the furnace to generate steam by passing the water through the copper tubes and the steam generated in turn is passed into the steam generator for generation of power. The setup is shown in the plate 9 and the total cost of the fuel for generation of power is shown in Table-7.12

Table-7.12 Steam generation analysis for the furnace setup with respect to cost and emission

Blends	**Consumption of oil (in liters)to maintain a constant steam pr. of 4 kg/cm^2/hr at a Flame temperature of 1073 ^{0}k**	**Cost of fuel for /hr for maintaining a pressure of 4kg/ cm^2/hr ****	**CO % Emission**
B00	5.00	125.00/-	4.80
B05	5.80	123.00/-	4.70
B10	6.00	121.50/-	4.50
B15	6.10	119.00/-	4.30
B20	6.30	116.30/-	4.20
B25	6.50	113.20/-	4.28
B30	7.00	111.00/-	4.36

(* Blends in percentage of weight)
(** Cost of fuel LDO = 23/-/ liter, CSP = 5/-/kg in the year 2004)

It can be seen from Table 7.12 that the cost of generation of steam decreases with the increase in use of biomass slurry fuel to a blend of B25, but the emission level decreases to a marginal extent. It can be seen from the Table 7.12 that B30 happens to be the fuel with the minimum cost and at the same time yielding a minimum of CO emissions.

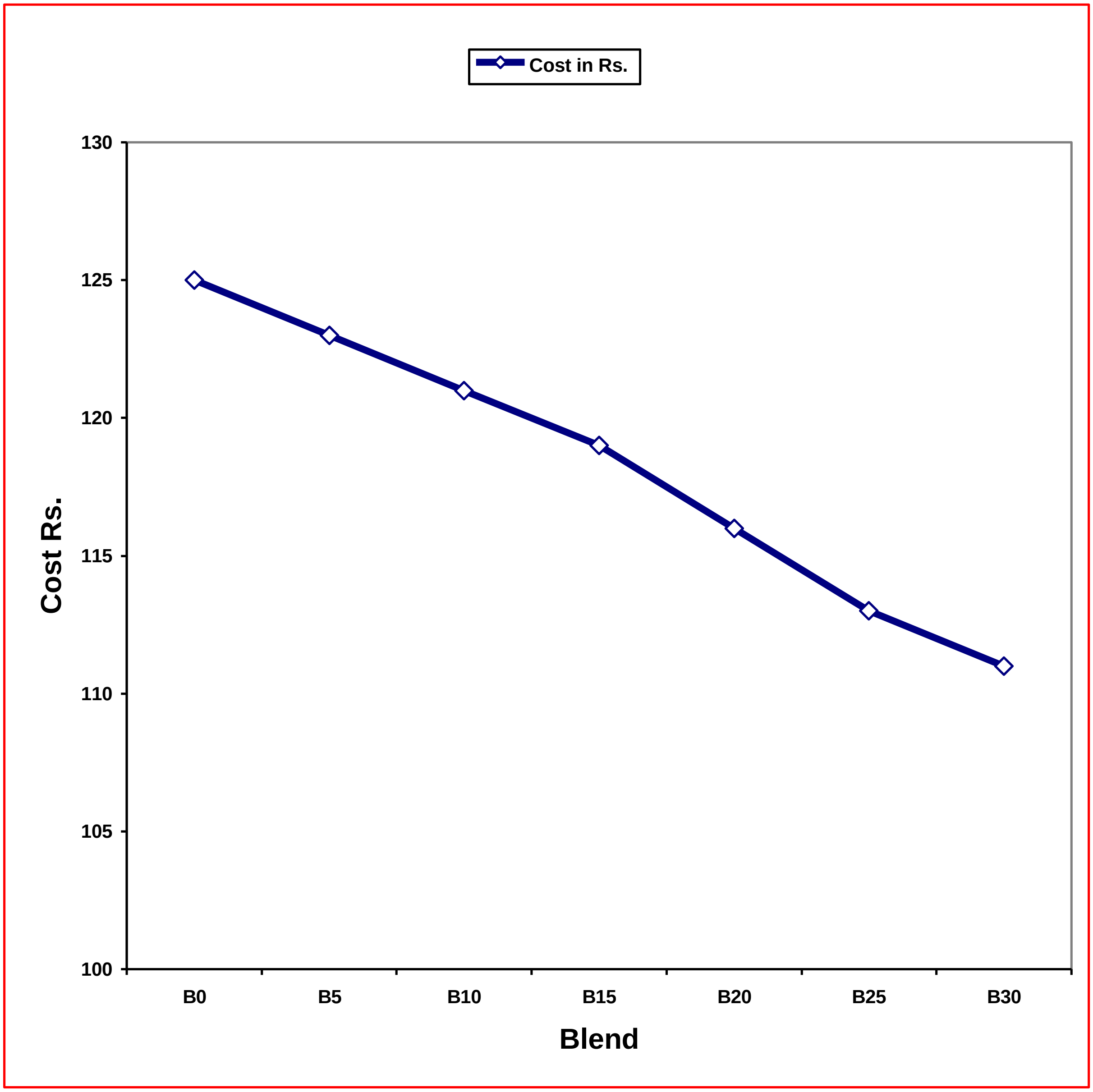

Figure7.34 cost of production of steam per hour

Figure 7.34 shows the variation of cost for production of steam per hour for the given setup. It can be seen that the cost required to produce the steam decreases, than that of LDO and it can also be seen that the blend of CSP to a percentage of 30 percent can be easily used.

7.7 Testing of diesel engine with biomass slurry

Research work has been done on coal water slurry as a fuel for diesel engines [60, 61, and 62]. The diesel engine whose specifications are given in the Table 7.11.was tested for its performance by conducting load tests. The engine was run with diesel and then with slurries prepared by mixing pulverized coconut shell powder. The load tests were conducted [63]. The variation of specific fuel consumption, Indicated Thermal efficiency, Brake Thermal efficiency and Mechanical efficiencies of the fuel on the engine are evaluated by varying the load on the engine and the results are tabulated as shown in Table 7.13. All combinations of the slurries up to 20% blend showed better performance as that of diesel oil. The slurries containing higher fraction became more viscous and clogged the fuel passages resulting in the stoppage of the engine.

Table: 7.13 Engine specifications

Engine Specifications **Make- Bullet Diesel Engine**
1 Bore Diameter = 78mm
1. Stroke Length = 68mm
2. Displacement = 325cc
3. Compression Ratio = 18:1
4. Fuel Tank Capacity = 4.5liters
5. Oil Sump Capacity = 1.0 liters
6. Lubrication oil Consumption = 0.012 kg/hr
7. Dry weight = 38kgs
8. Rated power = 5.0HP
9. Specific Fuel Consumption = 205 gm/bph/hr
10. Brake drum Radius = 87mm

7.8 Performance testing of diesel engine with biomass slurry fuel

The various parameters like specific fuel consumption, Indicated Thermal efficiency and Mechanical Efficiencies of the fuel on the engine are evaluated by varying the load on the engine. The tests were conducted on standard conditions.

Table 7.14 Properties of the diesel blends

Blend	Calorific value kJ/kg	Specific gravity
B0(Diesel)	42800	0.82
B05	39385	0.85
B10	38604	0.86
B15	38222	0.87
B20	37920	0.90

Table 7.15: Performance testing of the diesel engine for various blends:

Blend	BP-kW	TFC kg/h	SFC kg/kW-h	η_{BTE} %	Emission of Biomass slurry %
B0(Diesel)	0.67	0.26	0.38	21.67	3.60
B05	0.67	0.29	0.43	21.12	3.40
B10	0.67	0.31	0.46	20.16	3.30
B15	0.67	0.35	0.52	18.03	3.10
B20	0.67	0.66	0.53	9.63	3.00

Table 7.15 shows the performance testing of the diesel engine for various blends at a load of 5kgs, and SFC of 10c.c

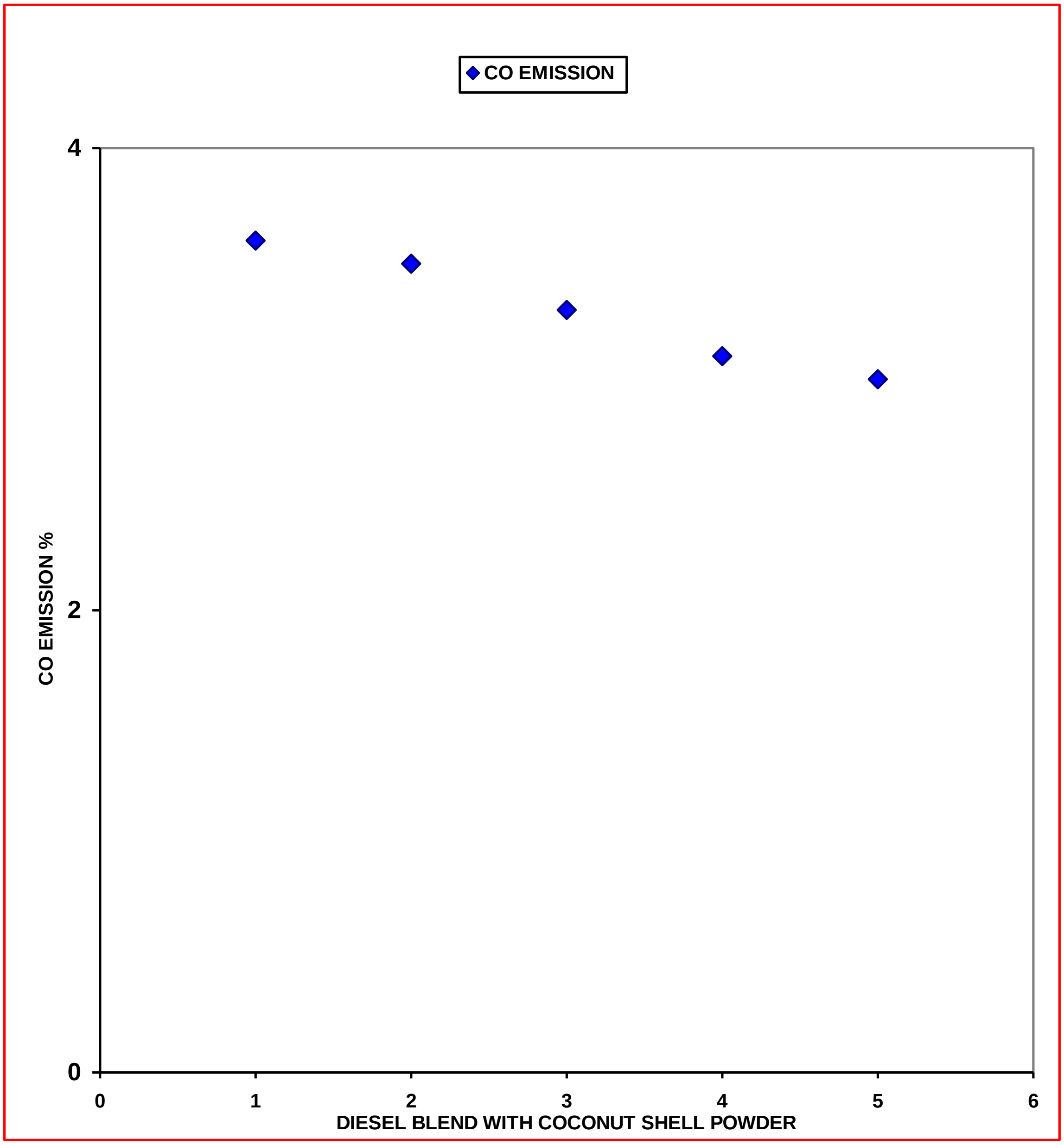

Figure 7.35 CO Emission for various Diesel Blends in Diesel Engine

Figure 7.35 shows the plot of measured CO emission against various diesel blends. It can be observed from the Figure 7.35 that the CO emission decreases, with the increase of coconut shell powder percentage in diesel. It can be seen from the figure 7.35 that the decrease in CO percentage is almost linear. It can also be observed that the decrease in CO percentage is almost linear with respect to decrease in diesel percentage.

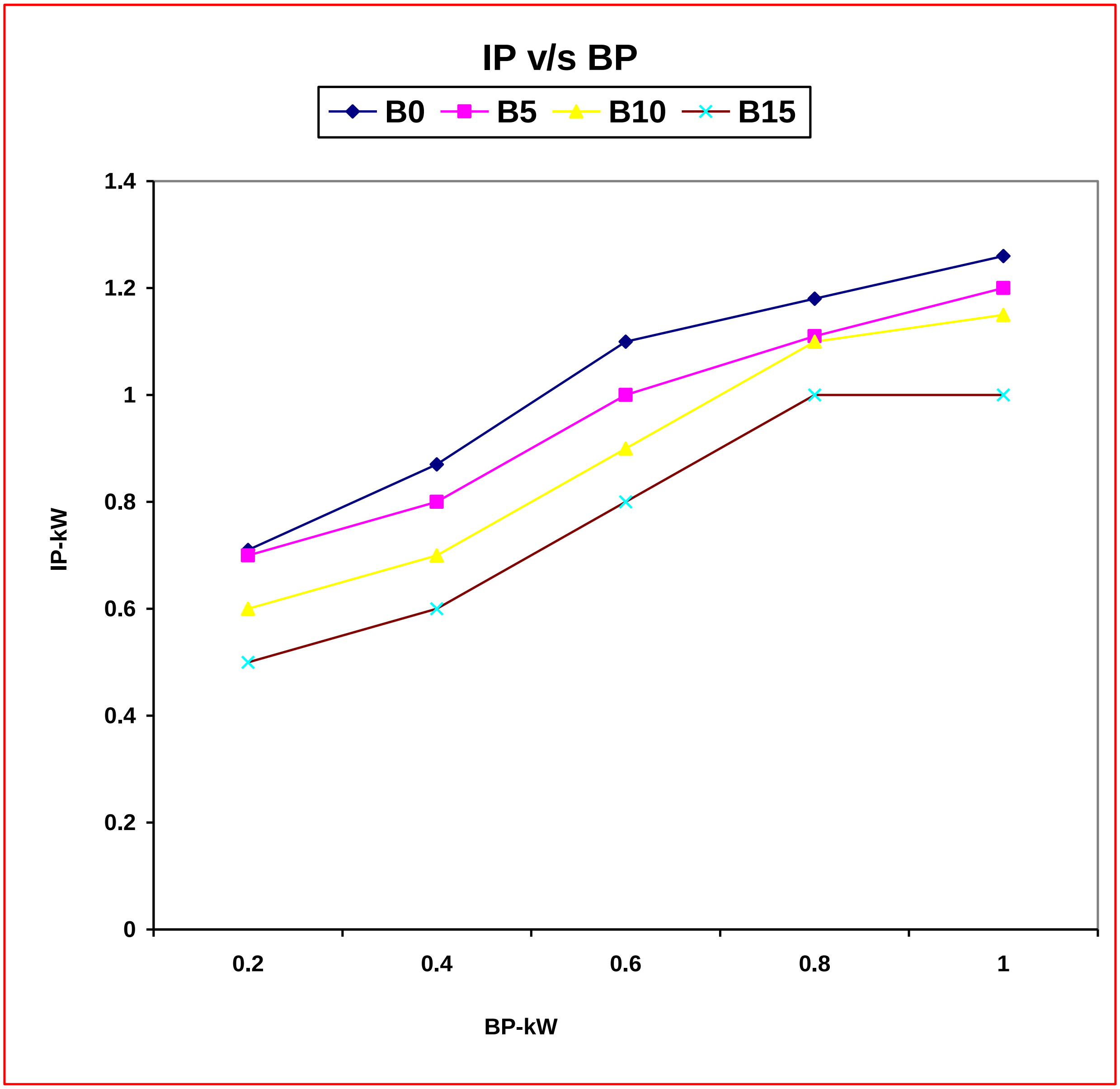

Figure 7.36 Indicated power v/s Brake power

Figure 7.36 shows the variation of indicated power v/s brake power for different blends of biomass slurry, it can be seen from the Figure 7.36 that the variation of indicated power varies linearly to brake power for all the compositions of the biomass slurry. For a given brake power the indicated power increases with coconut shell powder and it can also be seen that the indicated power increases linearly with the brake power. For the case of the diesel blend B20 the loading could not be continued beyond a BP of 10KW, as is shown by an incomplete line.

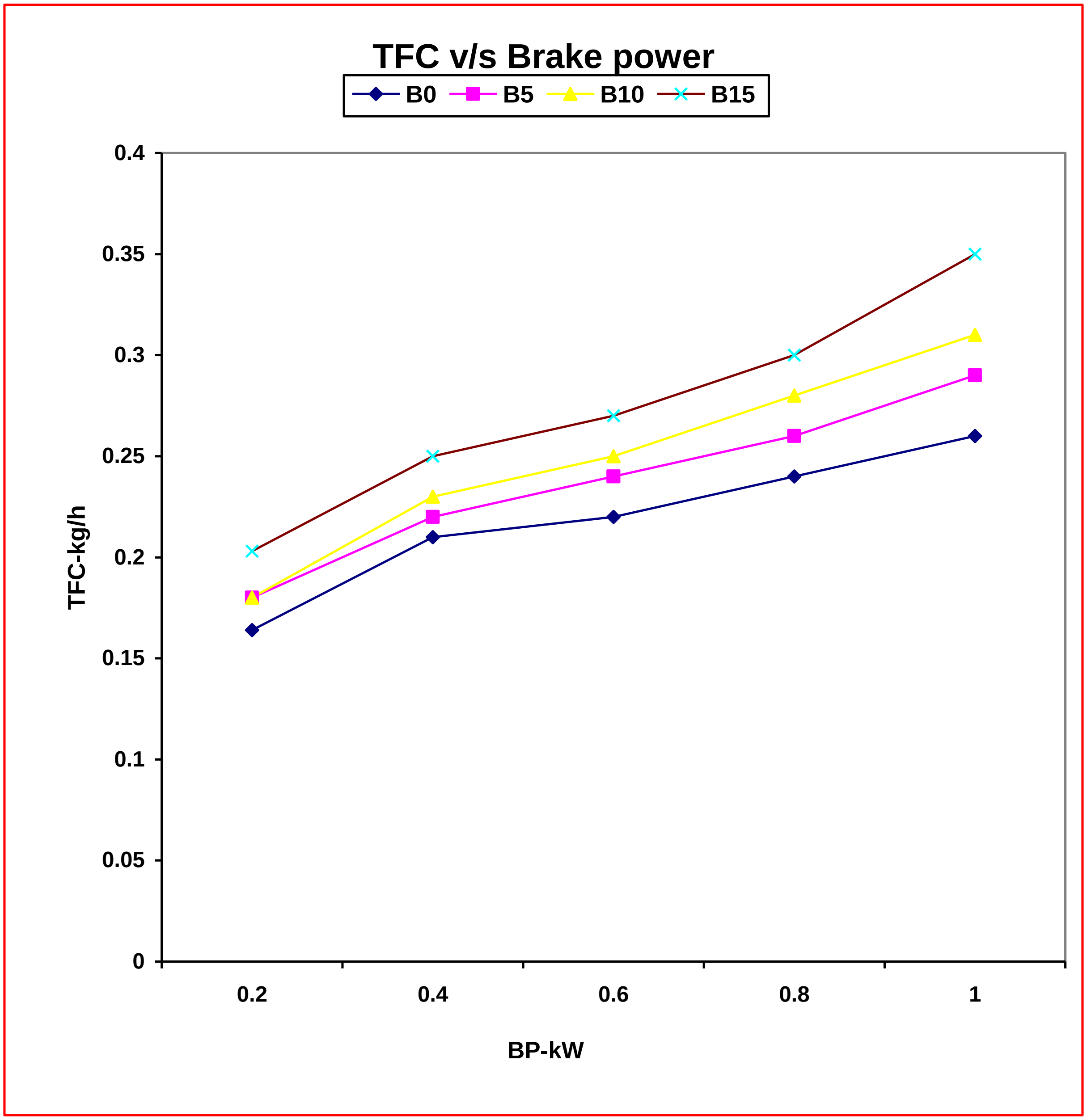

Figure 7.37 Total Fuel consumption v/s Brake power

Figure 7.37 shows the variation of total fuel consumption of the slurry fuel against the brake power. It can be observed from the figure that as the coconut shell powder composition increases n the slurry the total fuel consumption also increases. In addition, as the brake power increases for any given slurry the total fuel consumption increases with brake power.

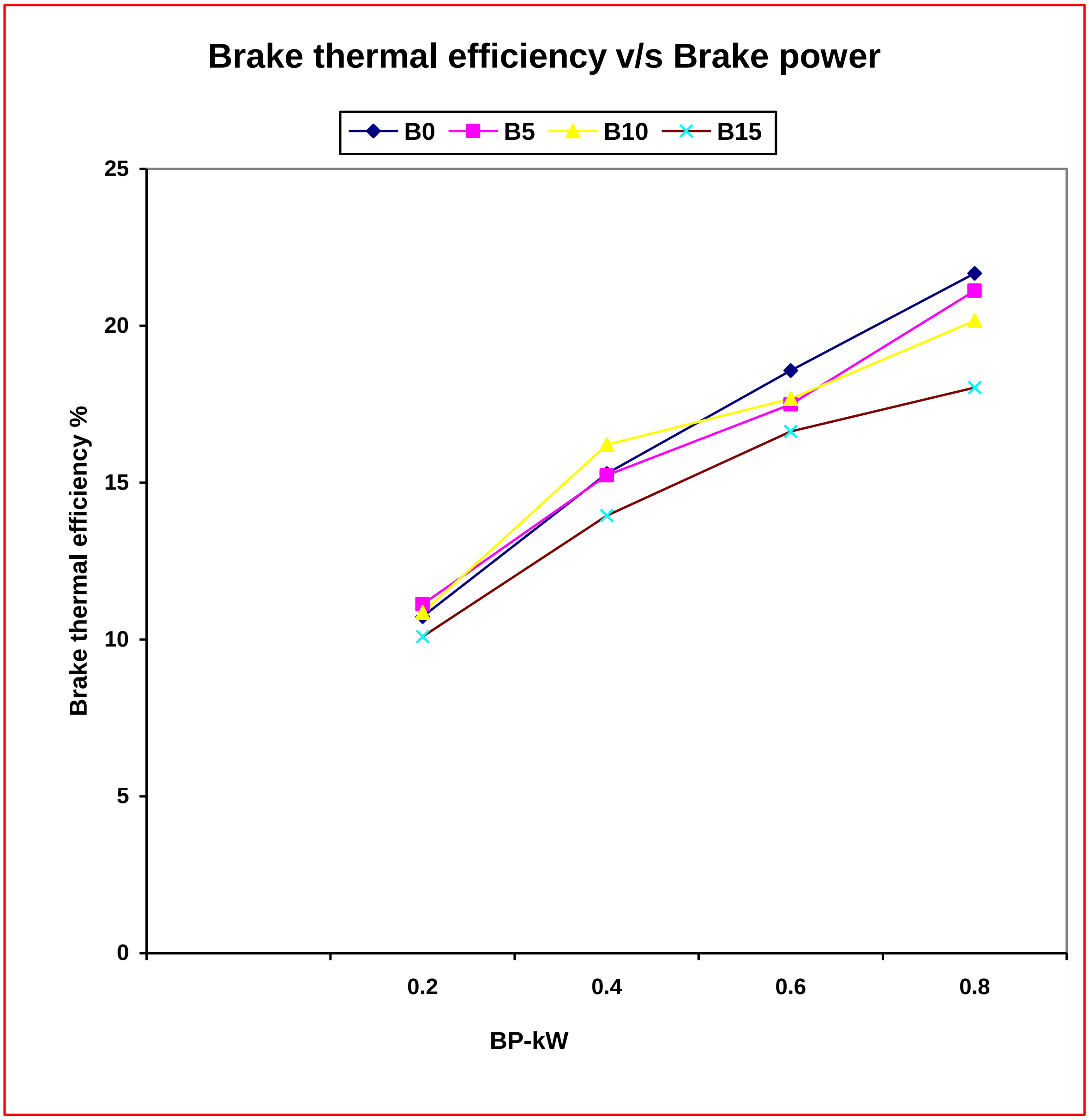

Figure 7.38 Brake Thermal Efficiency v/s Brake power

Figure 7.38 shows the variation of brake thermal efficiency with the brake power. it can be observed that the brake thermal efficiency increases as the brake power increases up to certain extent and remains almost constant after that.

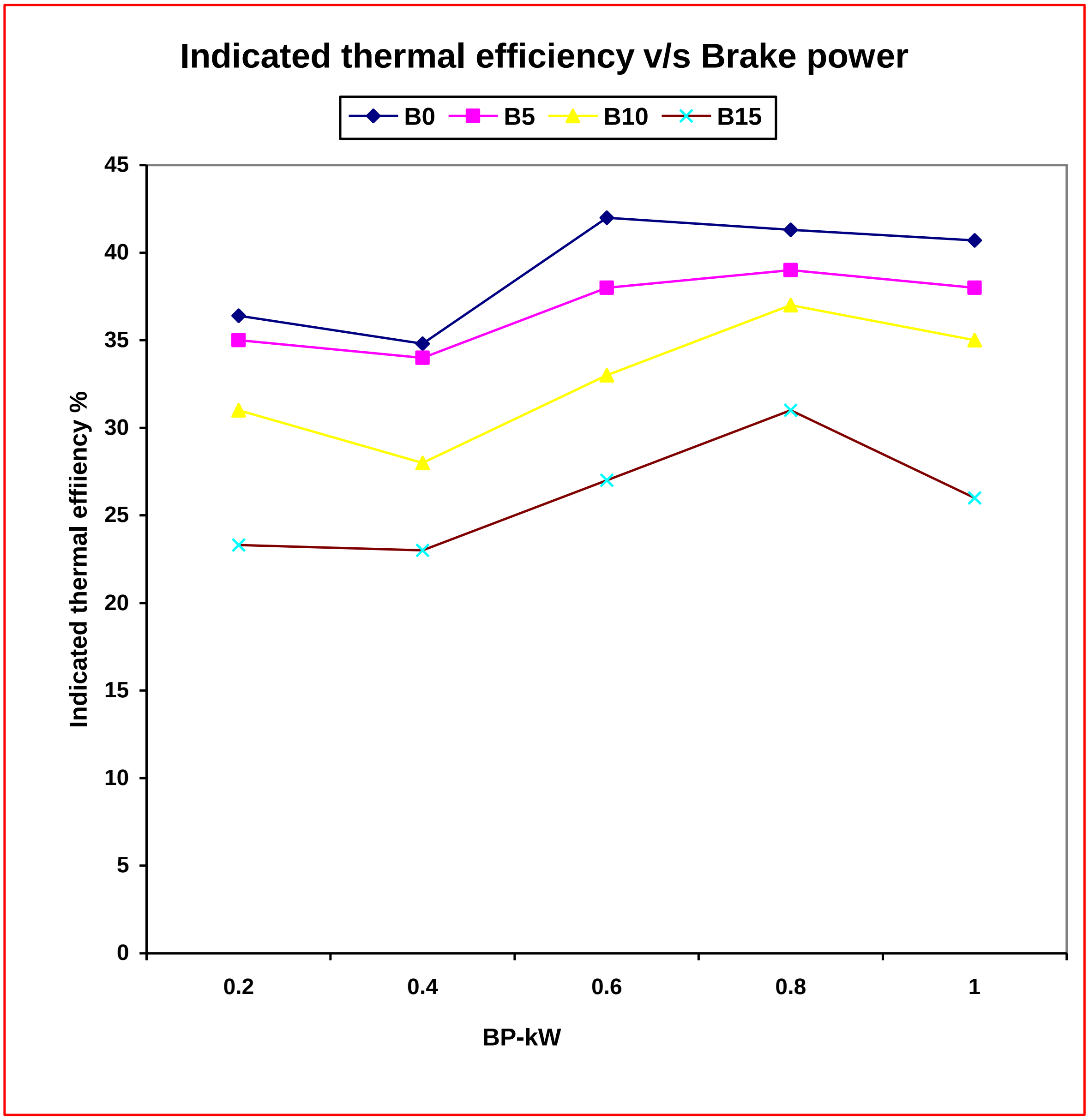

Figure 7.39 Indicated thermal efficiency v/s Brake power

Figure 7.39 shows the variation of indicated thermal efficiency with respect to variation of brake power. It can be observed that the indicated thermal efficiency increases with the increase in brake power for different composition of biomass slurry. For a given brake power indicated thermal efficiency decreases as the coconut shell powder percentage increases.

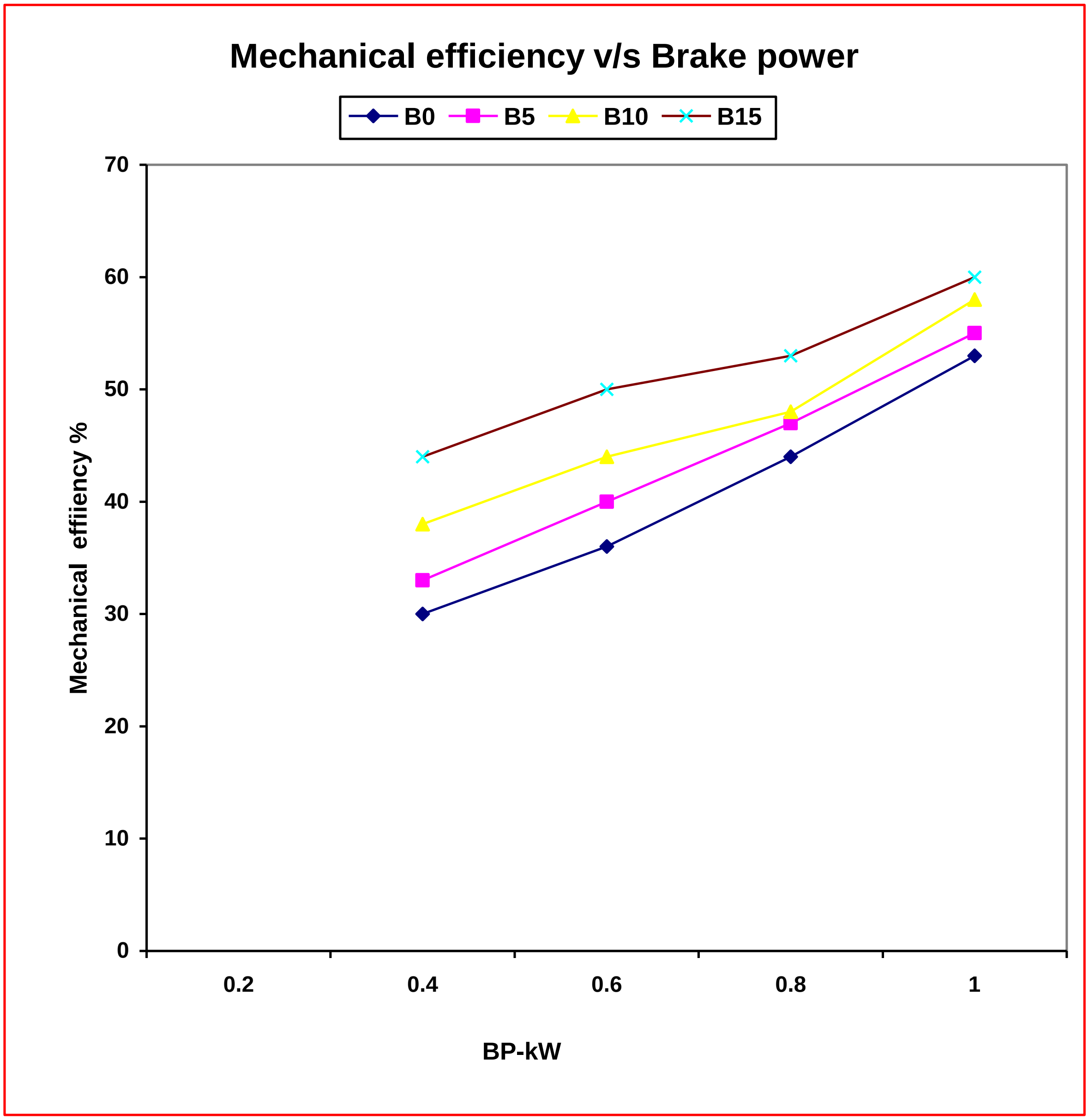

Figure 7.40 Mechanical efficiency v/s Brake power for various blends.

Figure 7.40 shows that the mechanical efficiency increases for any given slurry in a nonlinear way as expected. For any given brake power the mechanical efficiency decreases with increase in coconut shell powder percentage.

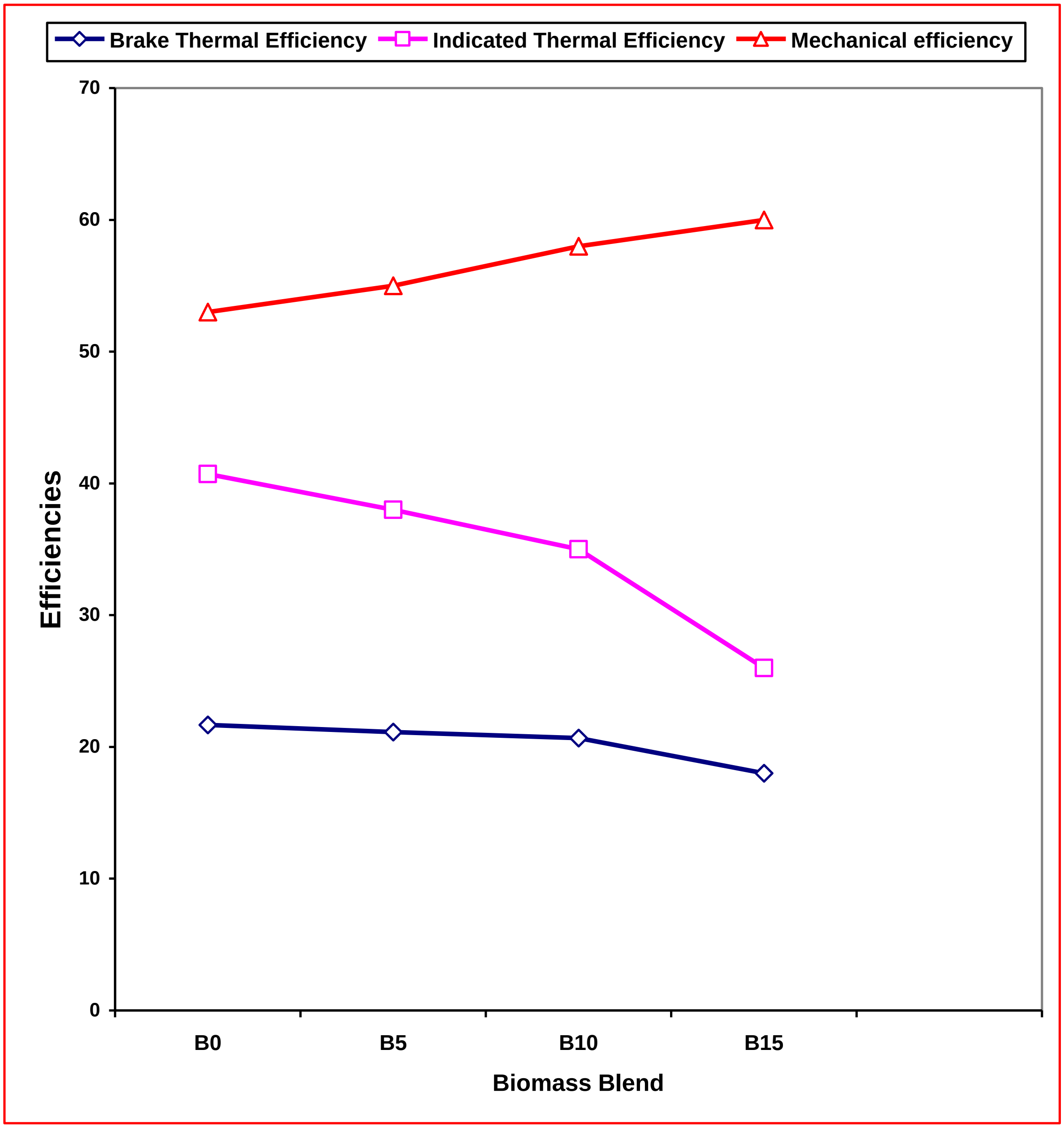

Figure7.41 Effect of blend on the efficiencies

Figure 7.41 shows the variation of several efficiencies, the Indicated Thermal efficiency and mechanical efficiency are almost same as that of diesel oil combustion, but where as the Brake Thermal efficiency of the biomass slurry decreases after a blend of 15%, due to improper combustion and blocking of the nozzle in the fuel jet.

CHAPTER 8

SUMMARY, CONCLUSIONS AND DIRECTION FOR FURTHER WORK

8.1 SUMMARY

Pulverised coconut shell powder based slurry fuels were prepared with different liquid medium. The liquid medium chosen are Light Diesel oil, Diesel and water. The slurries were prepared with different blending ratios. There Proximate, Ultimate and thermal properties are determined. Combustion studies using both Computational fluid dynamics approach and experimentation were carried out. The suitability of the slurry made up of Light diesel oil, coconut shell powder and water, to burn in oil fired foundry furnace and boiler as well as the slurry consisting of diesel and coconut shell powder as a fuel in diesel engines are experimentally demonstrated.

8.2 CONLUSIONS

Based on the experimental investigations the following conclusions were drawn.

1. Simple correlations to find the properties of the slurry are developed.

Calorific value

Calorific value = 410.781(LDO) + 199.6 (CSP) + 358.6(water) KJ/kg

Specific heat

Specific heat =20.6(LDO) +14.406(CSP) +20.14(H_2O) kJ/kg K

Density

Density = 0.004(LDO) +0.08(CSP) + (-0.023) (H_2O) gm/cm^3

Thermal conductivity

Thermal conductivity = 0.001(LDO) + 0.019(CSP) + (-0.005)(H_2O)W/m-K

Viscosity

Viscosity = 0.005(LDO) +0.051(CSP) + (-0.027)(H_2O) kg/m-s

The range of applicability of this relation are LDO 60 to 100%, CSP 0 to 30%, Water 2 to 10%.

2. The Computational fluid dynamics simulation of the Combustion process in the furnace was carried out using the commercial software Fluent. The maximum temperature in the furnace and the emission from the furnace outlet agree reasonably well with the experimental values.
3. As the coconut shell powder percentage in the slurry (LDO +CSP+ water) increases the maximum temperature in the furnace reduces.
4. As the coconut shell powder percentage in the slurry (LDO +CSP+ water) increases, the CO emissions decrease as determined from both CFD and experimentally.
5. As the coconut shell powder percentage in the slurry increases, the cost of the slurry fuel decreases.
6. Experimental combustion investigations were carried out and the results were compared with the CFD analysis
7. The temperatures measured in the experiment results showed that the temperature decreased with the increase in coconut shell powder blend.
8. Correlation equation was developed to find the Temperature of the biomass slurry. By using this equation, the maximum temperature in the furnace for any composition of biomass slurry can be found.

Temperature K = 12.1 * LDO + 2.797 * CSP + 13.647 * WATER

9. The range of applicability of this relation are LDO 60 100%, CSP 0 to 30%, Water 2 to 10%.
10. The biomass slurry was used for melting of aluminum and it was observed that the cost of slurry fuel was less than that of LDO.
11. It is demonstrated experimentally that the biomass slurry can be used to generate steam, which can be used in turn to generate power.
12. Diesel slurries with coconut shell powder were prepared and tested in Diesel engines with out any hardware modifications.
13. With the increase in coconut shell powder in the diesel slurry. There is a reduction in the CO emission from the diesel engine.
14. Equivalence ratio is being used as a parameter to present the emission characteristics from the furnace, especially with excess air used for combustion.
15. Fuel cost index is introduced as a guide to select the most appropriate biomass slurry.

8.3 SPECIFIC CONTRIBUTIONS

1. Simple **correlations have been developed** to calculate the various properties of the biomass slurry, once the composition of the slurry is known. It may be mentioned that Fluent-Pune requested for the properties of the Biomass slurry to incorporate in to the software for the future use.

2. **Application** of the **computational Fluid Dynamics tool**- **Fluent** has been carried out for the **first time**, for study of the **Combustion of the biomass slurry** in a Furnace and the **predictions agree reasonably** with the data obtained from the experiments carried out.

3. Correlation equation was developed to find the Temperature of the biomass slurry.

4. It has been demonstrated that the **CO emission reduces** with the **increase in coconut shell powder** percentage in the slurry up to 30%.

5. The suitability of using slurry based on LDO, CSP and WATER in a furnace, for melting of Aluminum and generation of steam was demonstrated experimentally

6. The suitability of using coconut shell powder along with diesel, to run the mobile-Bullet diesel engine successfully is demonstrated.

7. Fuel cost index was introduced as a guide to select the most appropriate biomass slurry.

8.4 SCOPE FOR FUTURE WORK

1. The biomass slurry fuel can be tested in Diesel Generators

2. When the paper was presented in Germany there was an offer to give Suggestions for a particular type of Biomass feed stock (dry leaves) which was abundantly available in Europe and which had a better Calorific value compared with coconut shell powder. Thus, the work can be extended with dry leaf powder in place of coconut shell powder.

3. Similarly in U.S.A. there was a particular type of wood available in Arizona desert with very less moisture and ash content, which will be a very good fuel for blending with diesel and for direct combustion in I.C. Engines

4. There are many types of biomass materials available with high calorific value, which can be made use to prepare slurries and use it as a liquid fuel.

5. Through out the study, if the biomass was allowed for more than 4 hours or so with out stirring, settling of solid particles at the bottom of the container was observed. This problem can be overcome, by using proper oxidisers, reactants, emulsifiers and surfactants.

6. A detailed study of combustion of fuel slurries inside a Diesel engine must be studied and its effect on engine components must be looked into.

Appendix-I

Tables

Table 4.1 Particle Size Distribution of Coconut- Shell powder

Sieve Size (Microns)	Amounts of 50gm sample Retained on sieve	Percentage Retained	Cumulative Percentage retained
Pan	14.23	28.46	100.00
37	11.26	22.52	71.54
44	14.31	28.62	49.02
53	07.62	15.24	20.40
62	02.58	05.16	05.16

Table 5.2 Properties of biomass slurry

Blends	Fixed Carbon kg atom	Density (g/cm^3)	Viscosity kg/m-s	Specific heat kJ/kg K	Thermal conductivity W/m-K	Measured Calorific Value kJ/kg
LDO	7.00	0.400	0.50	2060	0.115	42100
85+05+10	6.15	0.438	0.52	2019	0.123	39600
80+10+10	5.98	0.875	0.60	1990	0.230	38900
75+15+10	5.82	1.322	0.86	1963	0.330	38100
70+20+10	5.65	1.750	0.96	1952	0.430	37400
65+25+10	5.49	2.190	1.32	1899	0.530	37100
60+30+10	5.32	2.231	1.68	1859	0.540	35256

(* Blends in percentage of weight)

Table 7.10 Predicted Exhaust gas analysis with respect to percentage variation of air as an extension of the Table 7.4 by adding the Equivalence ratio in to the tables

% air	Equivalence Ratio	B5**	B10**
	φ	CO CO_2 H_2O O_2 N_2	CO CO_2 H_2O O_2 N_2
10%	0.90	2.79 3.34 7.51 1.14 39.05	2.74 3.26 7.36 2.98 40.1
20%	0.84	2.77 3.36 7.52 1.80 42.67	2.72 3.28 7.34 3.00 42.3
30%	0.77	2.75 3.36 7.56 2.85 46.62	2.70 3.29 7.32 3.03 45.3
40%	0.72	2.74 3.37 7.58 3.01 49.18	2.69 3.30 7.30 3.12 47.5
50%	0.67	2.73 3.38 7.59 4.75 53.73	2.68 3.31 7.29 3.35 51.2

%air	**Equivalence Ratio**	**B15****					**B20****				
	φ	CO	CO_2	H_2O	O_2	N_2	CO	CO_2	H_2O	O_2	N_2
10%	0.90	2.62	3.20	7.31	1.98	6.8	2.59	3.06	6.91	2.90	38.5
20%	0.84	2.61	3.24	7.29	1.99	7.0	2.57	3.08	6.93	2.92	39.2
30%	0.77	2.59	3.25	7.28	2.12	7.7	2.56	3.09	6.95	2.93	43.2
40%	0.72	2.58	3.26	7.25	2.16	8.5	2.55	3.10	6.98	3.40	45.7
50%	0.67	2.58	3.30	7.24	2.20	8.9	2.53	3.12	6.99	3.46	45.9

%air	**Equivalence Ratio**	**B25****					**B30****				
	φ	CO	CO_2	H_2O	O_2	N_2	CO	CO_2	H_2O	O_2	N_2
10%	0.90	2.50	3.20	7.31	1.98	6.8	2.38	2.89	7.81	1.90	38.5
20%	0.84	2.49	3.22	7.29	1.99	7.0	2.37	2.91	7.80	1.92	39.2
30%	0.77	2.49	3.23	7.28	2.12	7.7	2.37	2.90	7.79	1.93	43.2
40%	0.72	2.48	3.24	7.25	2.16	8.5	2.38	2.91	7.78	2.40	45.7
50%	0.67	2.47	3.25	7.24	2.20	8.9	2.38	2.92	7.78	2.86	45.9

(**Exhaust gas analysis in Kg moles) (* Blends in percentage of weight)

Appendix-II

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Appendix-III

LIST OF PUBLICATIONS AND PRESENTATIONS

Journal:

1. S.V.Prakash and S.R.Shankapal, ‘Combustion Analysis of Biomass slurry in oil fired furnaces at an elevated temperature’, using CFD Tool’, Enfuse journal, 2005, p32-40
2. S.V.Prakash and S.R.Shankapal, ‘Coconut sell powder based biomass slurries and their properties’, Biomass and Bioenergy-Journal, under review
3. S.V.Prakash and S.R.Shankapal, ‘Application of CFD to the combustion of Coconut shell powder based Biomass slurry’, ASME-Journal of solar energy, under review
4. S.V.Prakash and S.R.Shankapal, ‘ Experimental Investigations on the combustion of coconut shell powder based biomass slurry’, Journal of flame Research, under review

International Conferences:

1. S.V.Prakash and S.R.Shankapal, "Cold Flow Analysis of Biomass Based Slurry in oil Fired Furnace using CFD –Tool", International Conference on Alternate fuels at Germany- Freiburg- EUROSUN-2004, JUNE-2004

2. S.V.Prakash and S.R.Shankapal, ‘Combustion Analysis of Biomass Based Slurry fuels in oil Fired Furnace using CFD –tool’, ASME Conference on Alternative fuels at Orlando-Florida-U.S.A., ASME/ISEC-2005

National conferences

1. S.V.Prakash and S.R.Shankapal, "CFD analysis of non-premixed combustion of Biomass slurry in oil fired Furnaces" at National Conference on Fluid Mechanics and Fluid Power-NITK- Surathkal Dec-2003, p126-134
2. S.V.Prakash and S.R.Shankapal, “Preliminary Investigations on CFD Analysis of Non Pre-mixed Combustion of Biomass Slurry" at National Conference on Advanced Mechanical Engineering. NAME, SJCIT-SHIMOGA. Feb-2004, p257-266
3. S.V.Prakash and S.R.Shankapal, ‘CFD analysis of non-premixed combustion of Biomass slurry in oil fired Furnaces" at National Conference on Mechanical Engineering and Trends, Banaras University, Varanasi, COMET, March-2004, p154-160

4. S.V.Prakash and S.R.Shankapal, "A Review of Renewable Energy and Sustainable Development in India" at National conference on Mechanical Engineering, M.S.R.I.T. - Ban galore, NATCON-ME, March 15th-2004, p99-105

5. S.V.Prakash and S.R.Shankapal, "Combustion Analysis of Biomass Slurry using CFD" at National Conference on Mechanical Engineering, MSRIT, Bangalore, NATCON-ME, March15th-2004, p45-52

6. S.V.Prakash and S.R.Shankapal, ‘Residence time analysis of Biomass based slurries in oil-fired furnaces using CFD tool’ at all India conference on Mechanical Engineering SVU, SVU04,Tirupathi, AUG-2004, p189-195

7. S.V.Prakash and S.R.Shankapal, ‘Flow analysis of biomass based slurries for pre mixed Combustion in oil-fired furnaces using CFD-Tool’, at National Conference on Advanced Mechanical Engineering and sciences. SSIT, Tumkur, NACAMES-04, September-2004, p201- 206

8. S.V.Prakash and S.R.Shankapal, ‘Combustion Analysis of Biomass Based Slurry fuels in oil Fired Furnace using CFD –Tool’, S.V.Prakash & S.R.Shankapal, GCE-Ramnagaram, NATCON-2005, March-2005, p45

9. S.V.Prakash and S.R.Shankapal, CREED-2005, ‘Combustion Analysis of Biomass slurry in oil fired furnaces at elevated temperatures’ using CFD Tool’ –BITS, PILANI- October-2005, p160-165

10. S.V.Prakash and S.R.Shankapal, NCBIC-2006, ‘ Combustion analysis of biomass slurry in Diesel Engine’, NITK, Surathkal, March-2006, p123-135

Appendix-IV

Biography of the Candidate

Mr. S.V. Prakash was born on 25th October 1967. He graduated from Bangalore University in Mechanical Engineering in the year 1991; He obtained his Masters degree from Karnatak University in Production Management in the year 1994.

He has an industrial experience of more than one and half years in a Electromechanical relay switches manufacturing industry at Bangalore. He has more than 12 years of teaching experience.

His areas of interest are Non-conventional energy sources, Operations research, Production and operations management, Industrial management, CAD/CAM & Robotics, Advanced topics in manufacturing management, Flexible manufacturing systems, Computer integrated manufacturing etc.

Mr. S.V. Prakash has supervised 45 undergraduate projects and 2 postgraduate projects. The undergraduate projects are awarded as best projects consecutively from past nine years, the projects have been published in ASME conferences and journals. His achievements includes invention of pedal driven hydraulic pump, water making machine, land mine detector, battery operated two wheeler, device to prevent train head on collision, biomass as liquid fuel, 100CC trike, automated multilevel parking system, because of these achievements Mr.S.V. Prakash made a reference in Marquists Book “Who is Who in the World 2006.

Appendix-IV

Biography of Supervisor

Dr. Surendra Rao Shankapal was born on 8th January 1960. He graduated from University of Mysore in Mechanical Engineering in the year 1982. He obtained his Masters degree from Indian Institute of Technology Madras in Thermal Engineering in the year 1984. He obtained his Doctoral degree in the year 1998 from BITS-Pilani.

He has got an excellent Industrial exposure, he has gone through 2 months training at Coventry University, UK, on Industry Relevant Engineering Education, 2 months practical training at Mysore Kirloskar and BFW (Machine Tools), 2 weeks summer school at IPCL, Baroda, 2 weeks summer school on Microprocessor at UVCE, Bangalore etc. He has more than 22 years of teaching experience and presently he is the Director and Professor at M.S. Ramaiah School of Advanced Studies, Bangalore.

His areas of interest are Heat transfer, Non-conventional energy sources, CAD/CAM & Robotics, Finite element analysis, Computer program using Fortran and C, Vehicle aerodynamics, Vehicle dynamics, Handling and Simulation etc.

Dr. Surendra Rao Shankapal has supervised 3 students for PhD (in progress), 15 students for Postgraduate projects and 55 students for Undergraduate projects. He has been doing various sponsored Research projects for agencies like DST-Govt of India, ISRO (RESPOND), GTRE-CARS, ARDB,TIFAC, the total project amount is Two Crore Rupees. He is actively involved in Industrial Consultancy and solved more than 40 problems for Industry.

He has published more than 13 papers in International and National Journals and Conferences. He has published 13 more journals with his PhD students in various Journals and Conferences on Microgasturbines. He also authored various books and manuals on Non-conventional energy sources, Subhash Publications, 1989. Computer programming and Numerical methods, Subhash Publications, Bangalore, 1988. CAD/CAM & Robotics, Shiva Publications, Bangalore, 1997. Heat and Mass transfer, Shiva publications, Bangalore, 1997.

Engineering Thermodynamics, Subhash Publications, Bangalore, 1992. Applied Thermodynamics, Shiva Publications, Bangalore, 1993. Computer concepts and programming with C, Shiva Publications, Bangalore, 1995. Thermodynamics data handbook, Subhash Publications, Bangalore, 1997. Mechanical Measurements, Subhash Publications, Bangalore, 1990. Laboratory manual for CAD/CAM/CAE Laboratory, MSRIT, Bangalore, 1997, Laboratory manual for Energy Laboratory, MSRIT, Bangalore, 1996.

He is a Member of various Professional bodies and he supervised student's projects awards. He is also involved in Organization development, conceived the concept of M.S. Ramaiah School of Advanced Studies in 1998 and established the school with the financial assistance from GEF-Bangalore in 1999.

He also visited various International Universities like Stanford University (USA), University of Illinois at Urban Champaign (USA), University of Texas at Austin, University of Texas at Arlington (USA), Oxford University (UK), Cambridge University (UK), Birmingham University (UK), University of Warwick (UK), University of Leeds (UK), Coventry University (UK), Sheffield Hallam University (UK).

Plate.1 CSP, LDO & WATER- Slurry preparation

Plate.2 Weighing of Shell powder

Plate.3 Combustion of Biomass slurry at stochiometric air flow – photo taken at an oblique angle- Top open furnace

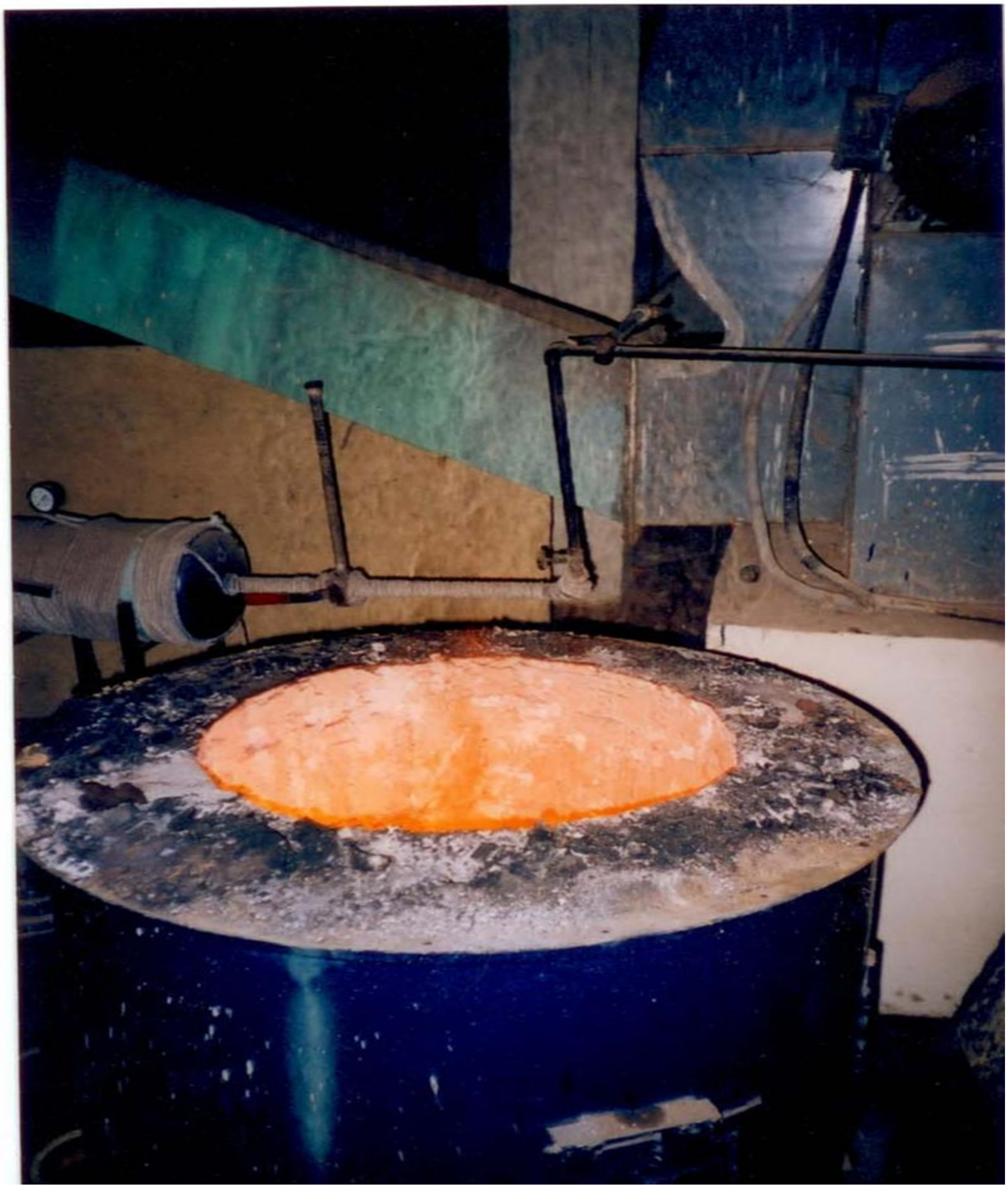

Plate.4 Combustion of Biomass slurry at stochiometric air flow- vertical position – Top open furnace

Plate.5 Combustion of Biomass slurry for 20% excess air-Top open furnace

Plate.6 Combustion of Biomass slurry for 30% excess air flow-Top open furnace

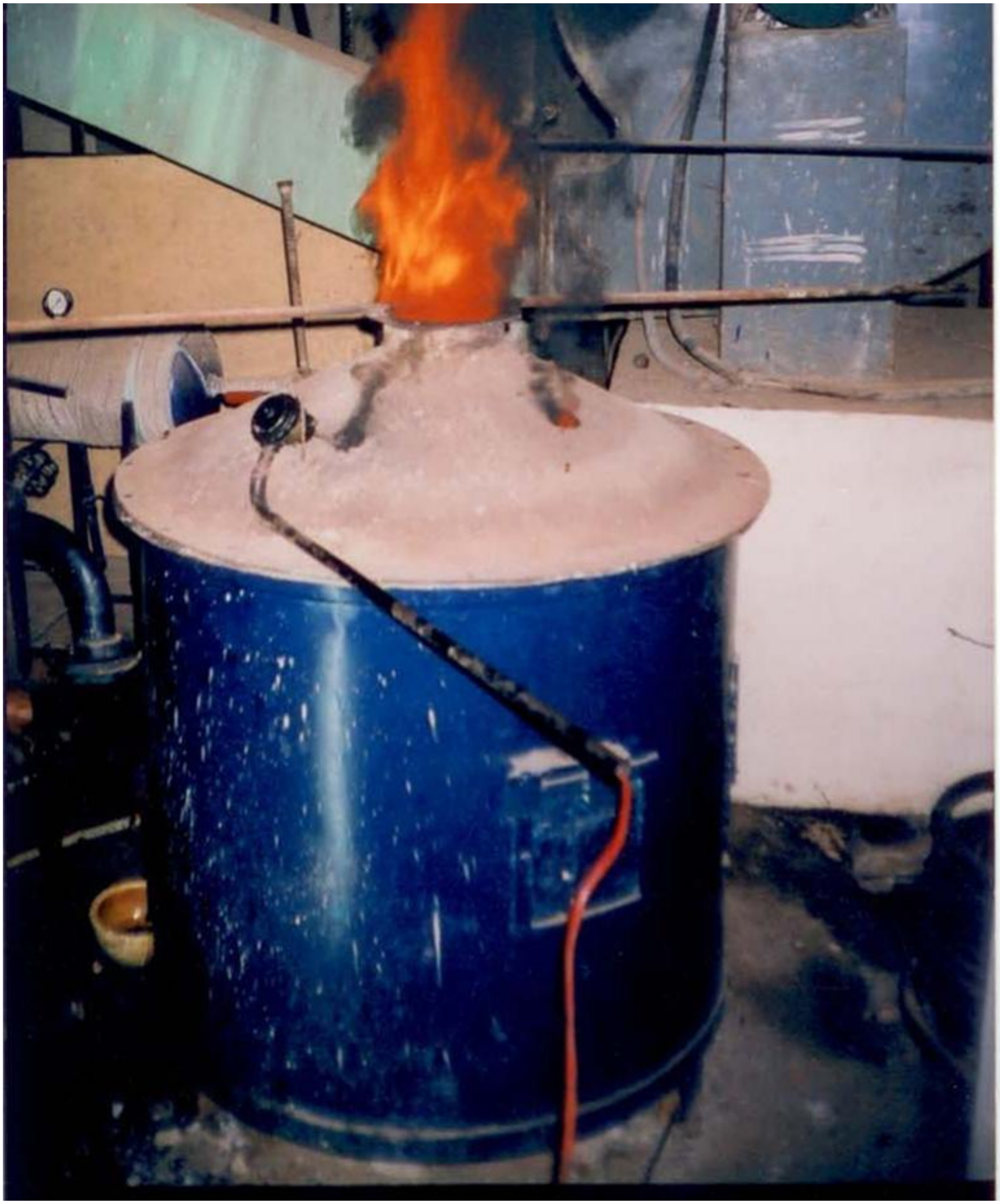

Plate.7 Combustion of Biomass slurry with top partially closed for 20% excess air

Plate.8 Combustion of Biomass slurry with top partially closed for 30% excess air

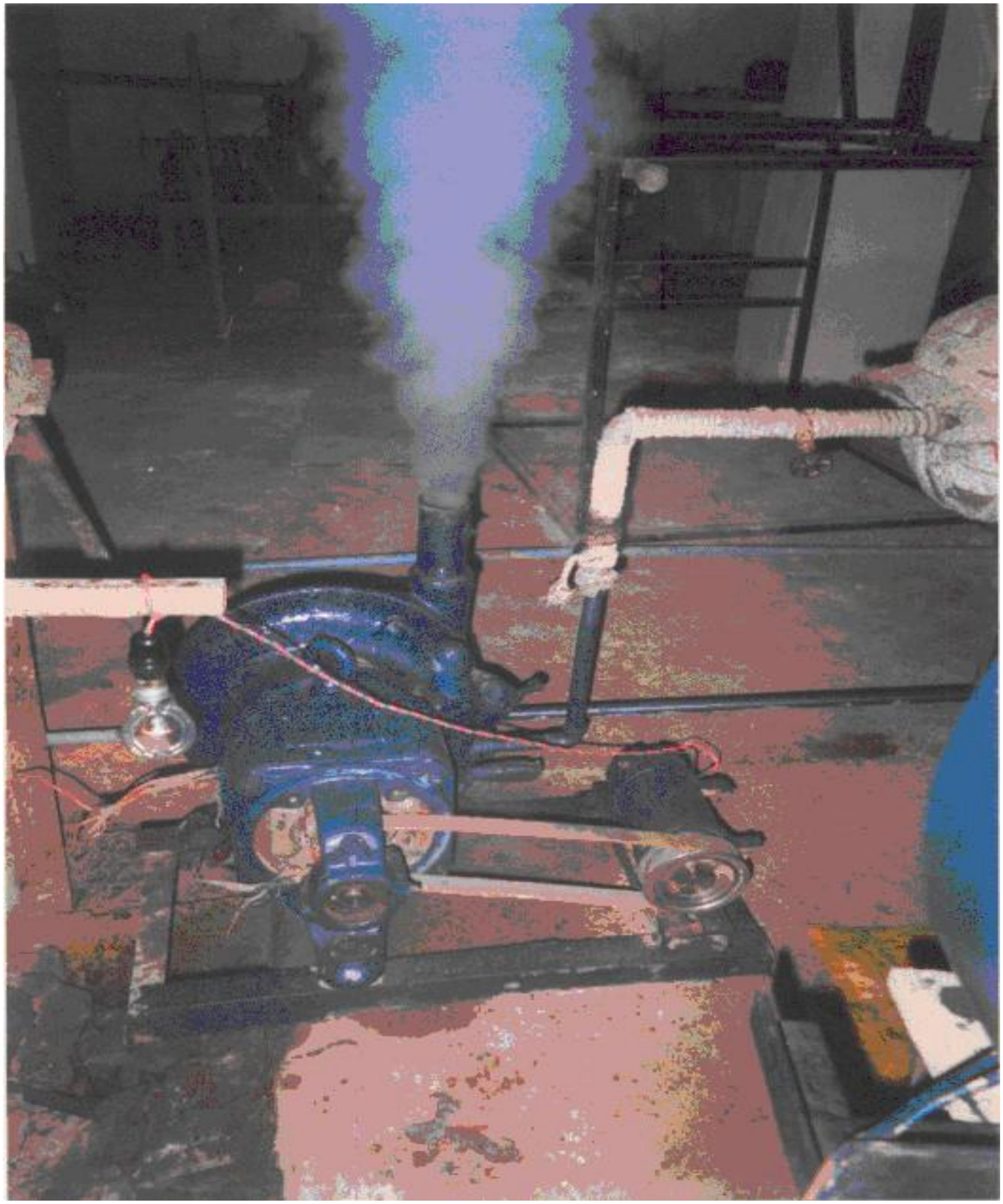

Plate.9 Power Generation using Steam generated in the Once through Copper coil inserted in the furnace

Plate.10 Temperature measurement - digital output

Plate.11 CO Gas Analyser (Chromatography)