

**Co-firing of Lignite with Peat and White Pine
in a Pilot Scale Bubbling Fluidized Bed –
Air Emissions and Feedstock Reactivity**

By Chadi Badour

Supervisors: Dr. Charles Xu and Dr. Allan Gilbert

Co-Supervisor: Dr. Fernando Preto

Environmental Engineering

Lakehead University

Thunder Bay, Ontario, Canada

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Abstract

The increasing awareness of the environmental impact of fossil fuels (mainly coal) combustion, which leads to high levels of CO₂, NO_x, SO₂, mercury and particulate emissions, has motivated research for potential alternatives such as switching from fossil fuels to biomass, or co-firing of both fuels. Co-firing proved to be a promising technology for large scale use of biomass for energy production, as it makes use of the extensive infrastructure associated with the existing coal-based power systems, and requires only relatively modest additional capital investment to achieve a significant CO₂ reduction. The research objectives of the present work were to: (1) Investigate on combustion/cofiring lignite and woodwaste/peat in a 16.19 kW pilot-scale fluidized-bed combustor, and effects of fuel-blending ratios, excess air, particle size and moisture contents on CO₂, CO, SO₂, and NO_x emissions in the combustion/co-combustion; and (2) Study the combustion reactivity of lignite, woodwaste, peat, and the blended fuels using thermogravimetric analysis (TGA).

The effects of particle size (pellets or crushed), the fuel blending ratios (0, 20%, 50%, 80% and 100% on a heat input basis), moisture content and excess air ratio on combustion efficiency and air emissions (CO₂, CO, SO₂ and NO_x) from combustion/co-combustion of woodwaste or peat and lignite were examined in a pilot-scale bubbling fluidized bed combustor. The results showed that properly controlling the co-firing parameters could achieve an increase in combustion efficiency and a reduction of air emissions. Compared to solid fuels in fine particles (< 4mm), fluidized-bed combustion of solid fuels in the pellet form could obtain higher dense-phase temperatures and a more uniform temperature profile along the fluidized-bed column and achieve a much higher efficiency (>94%), while yielding minimal effects on the

emissions of SO₂ and NO_x. Co-firing of lignite and white pine pellets at an increasing blending ratio led to a proportional reduction in both SO₂ and NO_x emissions. Co-firing of peat and lignite led to an increase in SO₂ emission, but co-combustion of peat (0-100%) and lignite resulted in a reduction in NO_x emission. The presence of moisture in the fuels promotes the combustion of solid fuels by the steam gasification/reforming and gas-water shift reactions, leading to increases in combustion efficiency and CO emissions, and the combustion of fuels of a higher moisture content led to a decrease in SO₂ emission, but an increase in NO_x emission. To achieve higher combustion efficiency and lower air emissions for combustion/co-combustion in a fluidized bed combustor, a too high excess air ratio (>40%) should be avoided.

The combustion/co-combustion behaviour and kinetics of lignite, peat and woodwaste (white pine sawdust) and their blends were investigated using non-isothermal thermogravimetric analysis (TGA) technique. The TGA experiments were performed for pure fuels and compared to blended fuels with respect to their performance in air over a temperature range of 25-700 °C and at a heating rate of 20°C/min. The overall kinetic de-volatilization-combustion reactions for these fuels and their blends were evaluated using the power law model. Using the differential thermal analysis (DTA) data and applying the least square multi-linear regression method, kinetic parameters for the overall devolatilization/combustion reactions including the apparent activation energy (E_a), reaction order (n) and the pre-exponential (A) factor were calculated for each homogeneous fuel and the lignite-peat or lignite-pine sawdust blended fuels (50 wt%-50 wt%%). The wood waste and peat demonstrated a higher reactivity when compared to lignite. The activation energies for lignite, peat, and white pine were determined to be 124.10 kJ/mol, 83.95 kJ/mol, and 98.23 kJ/mol, respectively. Compared with the devolatilization/combustion of

homogenous solid fuels, blending peat/white pine with lignite resulted in synergistic effects, enhancing the combustion reactivity of each component fuel.

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Table of Contents

Abstract	II
Acknowledgement	V
Lists of Tables	VII
Lists of Figures	X

Chapter One – General Introduction

1.1 Background	1
1.2 Research objectives	4
1.3 Organization of the thesis	5

Chapter Two – Literature Review

2.1 Properties of solid fuels (coal, biomass, and peat fuel)	8
2.1.1 Coal	8
2.1.2 Biomass fuels	12
2.1.3 Peat fuel	14
2.2 Solid fuel combustion technologies and combustors	15
2.2.1 Solid fuel combustion reactions	16
2.2.2 Fixed-bed combustion	20
2.2.3 Fluidized bed combustion	20
2.2.4 Pulverized fuel combustion	22
2.3 Co-firing technologies	23

2.4 Air emissions from co-firing biomass and coal	25
2.5 Summary of literature review	31

Chapter Three – Air Emissions from Co-firing Woodwaste/Peat and Lignite in a Bubbling Fluidized Bed Combustor

3.1 Introduction	37
3.1.1 Biomass	38
3.1.2 Peat	39
3.1.3 Coal	40
3.1.4 Gaseous emissions	40
3.1.5 Combustion efficiency	42
3.2 Experimental	43
3.2.1 Fuel characterization	43
3.2.2 Fuel preparation	46
3.2.3 CANMET bubbling bed combustor	47
3.2.4 Testing methodology and parameters	48
3.3 Results and discussion	50
3.3.1 Effects of fuel particle size	50
3.3.2 Effects of fuel blending ratio	51
3.3.3 Effects of moisture content	55
3.3.4 Effects of excess air	58
3.4 Conclusion	60

Chapter Four - A Comparative Reactivity and Kinetic Study on the Combustion of Lignite, Woodwaste, Peat and Their Blends

4.1 Introduction	69
4.2 Experimental	72

4.3 Kinetic model	74
4.4 Results and discussion	76
4.4.1 Thermal decomposition and modeling homogenous samples	76
4.4.2 Thermal decomposition and modeling of heterogeneous samples	80
4.5 Conclusion	84

Chapter Five - Conclusions and Recommended Future Work

5.1 Summary and conclusions	87
5.2 Recommendations for future work	90

Lists of Tables

Chapter Two – Literature Review

Table 2.1 Types and ranks of coal	8
Table 2.2 World coal resources and reserves	10
Table 2.3 Typical proximate and ultimate analysis of coals	11
Table 2.4 Physical, chemical and fuel properties of biomass and coal fuels	13
Table 2.5 Ultimate analyses of typical biomass fuel samples	13
Table 2.6 World peat lands distribution	14
Table 2.7 Example environmental impacts of co-firing in power generation applications	27

Chapter Three – Air Emissions from Co-firing Woodwaste/Peat and Lignite in a Bubbling Fluidized Bed Combustor

Table 3.1 Ultimate and proximate analysis of lignite, peat, and white pine	41
Table 3.2 Ash Analysis for lignite, peat, and white pine	42
Table 3.3 Flue gas analyzers measurement ranges	45
Table 3.4 Summary of the testing parameters	48
Table 3.5: Summary of emissions from co-firing of lignite and white pine or peat at various blending ratios at 40% excess air	53
Table 3.6 Effects of fuel moisture content on combustion/co-combustion of crushed lignite and pine/peat pellets at 40% excess air	58
Table 3.7 Effects of excess air ratio on the combustion efficiency and emissions from combustion/co-combustion of crushed lignite and pine/peat pellets	63

Chapter Four - A Comparative Reactivity and Kinetic Study on the Combustion of Lignite, Woodwaste, Peat and Their Blends

Table 4.1 Proximate and ultimate analysis of lignite, peat, and white pine	73
Table 4.2 Representative temperatures for devolatilization/combustion of homogenous solid fuels	78
Table 4.3 Calculated kinetic parameters for devolatilization-combustion of homogeneous Fuels	79

Table 4.4 The representative temperatures for devolatilization/combustion of heterogeneous fuel-blends	81
Table 4.5 Kinetic parameters for combustion of heterogeneous fuel blends	83
Appendix	91

Lists of Figures

Chapter Two – Literature Review

Figure 2.1 Hydrogen/carbon atomic ratio versus oxygen/carbon atomic ratio	12
Figure 2.2 General schematics for various combustion/co-co-firing technologies	16
Figure 2.3 Schematic of a circulating fluidized bed (CFB) combustor	22
Figure 2.4 Variation of stack emission of SO ₂ for different fuel mix ratio in co-firing of bituminous coal with various fuels	29
Figure 2.5 Variation of stack emission of NO _x for different fuel mix ratio in co-firing of bituminous coal with various fuels	29
Figure 2.6 Concentrations of air pollutants in the flue gas versus combustor air ratio for a coal-fired combustor	30

Chapter Three – Air Emissions from Co-firing Woodwaste/Peat and Lignite in a Bubbling Fluidized Bed Combustor

Figure 3.1 Schematic diagram of the CanmetENERGY bubbling bed combustor	44
Figure 3.2 Example of the constant operation for the test #23	47

Figure 3.3 Emissions of CO ₂ (a), CO (b), SO ₂ (c) and NO _x (d) for the as-received/air-dried white pine (sawdust & pellets) and peat (crushed & pellets) at 40% excess air	51
Figure 3.4 Fuel particle size comparative temperature profiles for white pine (a) and peat (b)	52
Figure 3.5 SO ₂ emissions per energy input during co-combustion (at 40% excess air) of as received crushed lignite blended with white pine pellets or peat pellets at 0%, 20%, 50%, 80%, and 100% on a thermal basis.	56
Figure 3.6 NO _x emissions per energy input during co-combustion (at 40% excess air) of as received crushed lignite blended with white pine pellets or peat pellets at 0%, 20%, 50%, 80%, and 100% on a thermal basis.	56
Figure 3.7 Percent reduction in SO ₂ and NO _x emissions (lignite baseline level) versus blending ratio of white pine pellets in co-firing air-dried lignite and white pine pellets.	57
Figure 3.8 Percent reduction in SO ₂ and NO _x emissions (lignite baseline level) versus blending ratio of peat pellets in co-firing air-dried lignite and peat pellets.	57
Figure 3.9 Comparative temperature profile for as received (15.96 % M.C.) and oven-dry (3.29% M.C.) crushed lignite.	59
Figure 3.10 SO ₂ emissions from co-firing lignite and peat/white pine pellets at 40% excess air versus fuel moisture content	61
Figure 3.11 NO _x emissions from co-firing lignite and peat/white pine pellets at 40% excess air versus fuel moisture content	61

Chapter Four - A Comparative Reactivity and Kinetic Study on the Combustion of Lignite, Woodwaste, Peat and Their Blends

- Figure 4.1** Distinct stages of a small biomass particle combustion 71
- Figure 4.2** Mass fraction of homogenous solid fuels as a function of temperature during the TGA analysis 76
- Figure 4.3:** Time derivative of mass fraction of chars as a function of temperature based on the data shown in **Figure 4.2**. 77
- Figure 4.4:** Displays the mass fraction of heterogeneous solid fuel-blends (the 50 wt% lignite-50 wt% peat and 50 wt% lignite-50 wt% pine sawdust fuel blends) as a function of temperature during the TGA analysis. 80
- Figure 4.5** Time derivative of mass fraction of solid fuel-blends as a function of temperature for 50% - 50% (by weight) lignite – peat blend and lignite – white pine blend. 82

CHAPTER 1

General Introduction

1.1 Background

Fossil fuels (oil, coal, and natural gas) represent around 80% of the world's primary energy supply, and global demand for fossil energy is expected to continue to grow. Coal currently accounts for approximately 40% of primary energy for the world electricity generation. In some provinces such as Alberta and Nova Scotia of Canada, coal contributes to over 70% of its electricity generation [1, 2]. The increasing awareness of the environmental impact of fossil fuels (mainly coal) combustion, which leads to high levels of CO₂, NO_x, SO₂, mercury and particulate emissions, has motivated research for potential alternatives such as switching from fossil fuels to biomass, or co-firing of both fuels.

About 28% of Ontario's electricity is generated from fossil fuels, which is mainly coal used at four Ontario Power Generation (OPG) plants (Atikokan, Lambton, Thunder Bay, Nanticoke), with a combined generation capacity of about 6,457 megawatts (MW). While these plants are significant contributors to Ontario's electricity grid, they are facing a great challenge as the Province has regulation in place to phase out the coal-fired electricity by 2014. In response, the OPG has turned to co-firing technology as a viable solution to continue operating, while reducing the net pollutant emissions from these coal-based power plants. The Ontario government (Ministry of Energy) together with Ontario Centers of Excellence initiated a major research project: Atikokan Bio-energy Research Center Program (ABRC) in 2007, and the present research is a part of this research program under its Theme-1 (Co-firing Biomass/Peat

and Coal for Power Generation) led by Dr. Charles Xu at Lakehead University in partnership with OPG and CanmetEnergy.

Co-firing has been successfully practiced on a commercial scale in more than 150 power plants in the USA and Northern Europe, which include pulverized coal boilers in large scale power plants (~ 700 MW) and bubbling or circulating fluidized beds boilers in smaller scale plants (~ 50 MW). Recent reviews of over 100 cofiring experiences have demonstrated successful field demonstrations of every major type of biomass (woody, herbaceous, and animal wastes) combined with every rank of coal and combusted in every major type of boiler (tangential, wall , and cyclone fired) [3].

Biomass resources include wood wastes (e.g. sawdust, planer shaving, chips, bark, and forestry residues), short rotation woody crops, and agricultural wastes (e.g. rice hulls, straws, orchard, and corn). Biomass fuels are advantageous due to their carbon neutral nature and renewability as well as low sulfur contents, although they are disadvantageous due to their low heating values and high moisture contents. For example, the amount of potential agricultural residues in Canada has been estimated at 29.3 Mt oven dried (OD) biomass per year, among which 17.8 Mt OD biomass/year may be available for energy and chemical production [4]. In addition, Canada contains some 40% of the world's peatlands – about 170 million hectares. Peat as the partially decayed vegetation matter may be regarded as a slowly renewable alternative fuel resource. Forestry/agricultural residues and peat can be thus used as an immense source of renewable energy for power generation by co-firing (co-combustion).

The major benefit of large scale utilization of biomass for energy and power generation is that it contributes to ZERO net CO₂ accumulations in the atmosphere, as the CO₂ released from combustion was absorbed by the biomass plant during its growth through photosynthesis.

Biomass fuels also tend to contain lower sulphur and nitrogen contents, decreasing the harmful SO₂ and NO_x emissions produced from combustion [5]. Biomass can be directly fired in coal dedicated boilers, although they tend to cause several technical challenges linked with storage, pre-treatment (drying and grinding), in-furnace problems (i.e., slagging, fouling, and corrosion), and ash deposition [6]. Several other biomass utilization technologies such as gasification, pyrolysis, liquefaction and supercritical fluid extraction, and bio-fuels have been highly examined in the last two decades, but none of these has been tested at the large scale. Co-firing biomass and coal in existing co-fired boilers could reduce the ash deposition and fouling problems encountered with biomass combustion. Co-firing proved to be a promising technology for large scale use of biomass for energy production, as it makes use of the extensive infrastructure associated with the existing coal-based power systems, and requires only relatively modest additional capital investment to achieve a significant CO₂ reduction.

Although environmentally beneficial (due to substitution of the fossil fuels and great reduction in CO₂ emission), co-firing biomass and coal also come with several major challenges such as the difficulty in fuel handling, the impacts on boiler operation with respects to slagging, fouling and corrosion resulting from the detrimental ash properties of some types of biomass that contains high concentrations of alkali metals and chloride. [7-10]. Moreover, co-firing biomass and coal might possibly have a negative influence on combustion efficiency and air emissions (e.g., particulate matters and NO_x). Co-firing biomass and coal for generating power and heat though appealing, is still challenging, and the co-firing processes are not yet completely understood and further investigation is still needed.

This research work explores the flue gas emissions of CO₂, SO_x, and NO_x resulting from combustion and co-combustion of woodwaste (white pine pellets/sawdust), peat and lignite in a

pilot-scale bubbling fluidized bed combustor. The effects of fuel types, different fuel blending ratios, moisture content of feedstock and excess air ratio on air emission rates were examined. The combustion efficiency and reactivity of the biomass, peat and lignite are also investigated.

1.2 Research objectives

The research objectives of the present work were to:

- (1) Investigate on combustion/cofiring lignite and woodwaste/peat in a pilot-scale fluidized-bed combustor, and effects of fuel-blending ratios, excess air, particle size and moisture contents on CO₂, CO, SO₂, and NO_x emissions in the combustion/co-combustion.
 - The lignite-biomass/peat blending ratios (based on heat input) were: 80%-20%, 50%-50%, and 20%-80%.
 - The excess airs tested were 40% and 60%.
 - Both pellet fuels and crushed fuels (or sawdust) were tested.
 - The moisture contents tested were as received or air-dried (approx. 20-25wt% M.C.) and oven dried (less than 5wt% M.C.).
- (2) Study the combustion reactivity of lignite, woodwaste, peat, and the blended fuels using thermogravimetric analysis (TGA).

1.3 Organization of the Thesis

This thesis is composed of five chapters.

Chapter 1 – General Introduction

This introductory chapter presented some background information about the present research project, benefits and the challenges of co-firing biomass and coal for power generation, and the research objectives.

Chapter 2 – Literature review

This chapter provided a comprehensive literature review on properties of solid fuels (coal, biomass fuels and peat fuel), solid fuel combustion technologies and combustors, co-firing technologies, and air emissions from co-firing biomass and coal.

Chapter 3 – Air Emissions from Co-firing Woodwaste/Peat and Lignite in a Bubbling Fluidized Bed Combustor

This chapter discussed the effects of particle size (pellets or crushed), the fuel blending ratios (0, 20%, 50%, 80% and 100% on a thermal basis), excess air, and moisture content on air emissions (CO_2 , CO , SO_2 and NO_x) from co-combustion of woodwaste or peat and lignite, examined in a pilot-scale bubbling fluidized bed combustor.

Chapter 4 – A Comparative Reactivity and Kinetic Study on the Combustion of Lignite, Woodwaste, Peat and Their Blends

This chapter presented the results on combustion/co-combustion behaviour and kinetics of lignite, peat and woodwaste (white pine sawdust) and their blends, investigated using thermogravimetric analysis (TGA) technique.

Chapter 5 – Conclusions and Recommended Future Work

The chapter summarized the main conclusions drawn from the project research on the behaviour and emissions from combustion/cofiring lignite and woodwaste/peat in a fluidized bed combustor, as well as the combustion reactivity of various types of feedstock. Recommendations for future work were also suggested.

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CHAPTER 2

Literature Review





This chapter provides a comprehensive literature review on (1) Properties of solid fuels (coal, biomass fuels and peat fuel); (2) Solid fuel combustion technologies and combustors; (3) Co-firing technologies; and (4) Air emissions from co-firing biomass and coal.

2.1 Properties of solid fuels (coal, biomass fuels and peat fuel)

2.1.1 Coal

Coal can be classified into four different ranks based on the fixed carbon (FC) contents as well as calorific values (CV): Anthracite Lignite, Bituminous coal, Sub-bituminous coal and Lignite, as shown in Table 2.1.

Table 2.1 Types and ranks of coal

	Class	% FC	Calorific Value (CV) (Btu/lb)	CV (MJ/kg)
	Anthracite	86-98	13000-16000	30-37
	Bituminous	50-86	11000-15000	26-35
	Sub- Bituminous	40-60	8000-12000	19-28
	Lignite (Brown Coal)	<40	5500-8000	13-19

1 Btu/lb = 2326 J/kg

The rank of the coal depends on the degree of maturation. Lignite and sub-bituminous coals are referred to as low rank coals, while bituminous coals and anthracites are high rank coals. Lignite, the lowest rank of coal, was formed from peat which was compacted and altered. Its color has become brown to black and it is composed of recognizable woody materials imbedded in pulverized (macerated) and partially decomposed vegetable matters. Lignite displays jointing, banding, high moisture content, and low fixed carbon ($FC < 40 \text{ wt}\%$) a lower heating value ($CV = 13\text{-}19 \text{ MJ/kg}$ on dry basis) when compared with the higher coals. Sub-bituminous coal is difficult to distinguish from bituminous and is dull, black colored, shows little woody material, is banded, and has developed bedding planes. It has relatively high moisture content and a relatively low heating value ($CV = 19\text{-}28 \text{ MJ/kg}$ on dry basis). Bituminous coal is dense, compacted, banded and brittle, and displays columnar cleavage and a dark black color. It is more resistant to reintegration in air than sub-bituminous and lignite coals. Its moisture content is low, and it has relatively lower volatile matter content or a higher FC ($50\text{-}86 \text{ wt}\%$) with a higher CV ($26\text{-}35 \text{ MJ/kg}$). Anthracite is the highly metamorphosed coal, is jet black in color, is hard and brittle, breaks with a conchoidal fracture, and displays a high luster. Its moisture content is low and its FC as well as the heating value are as high as $86\text{-}98 \text{ wt}\%$ and $30\text{-}37 \text{ MJ/kg}$, respectively.

World coal resources and reserves in terms of different ranks are provided in Table 2.2 [1]. Analyses of some typical coals are presented in Table 2.3.

Table 2.2 World coal resources and reserves [1]

Country	Coal rank	Proved in place (Mtonne)	Proved recoverable (Mtonne)	Additional in place (Mtonne)
North and Central America				
Canada	Bituminous	5,580	3,831	24,120
	Subbituminous	13,150	1,135	1,491
	Lignite	2,055	2,000	8,970
United States	Bituminous	225,943	112,972	469,885
	Subbituminous	163,516	81,758	276,934
	Lignite	41,023	20,511	392,730
Europe				
Britain	Bituminous	190,000	3,300	186,700
	Lignite	1,000	500	
France	Bituminous	790	213	200
	Subbituminous	151	45	
	Lignite	30	165	85
Germany	Bituminous	44,000	23,910	186,300
	Lignite	102,000	56,150	
Italy	Subbituminous	60	27	280
	Lignite	15	12	22
Soviet Union	Bituminous	130,000	104,000	2,100,000
	Subbituminous	47,000	37,000	1,900,000
	Lignite	110,000	100,000	1,200,000
Asia				
Japan	Bituminous	348	856	
	Lignite	175	17	
Turkey	Bituminous	593	175	
	Lignite	7,847	5,929	
Africa				
Morocco	Bituminous	134	46	
	Lignite	44		
South Africa	Bituminous	121,218	55,330	5,000
Oceania				
Australia	Bituminous	66,220	45,350	500,000
	Subbituminous	4,100	3,700	
	Lignite	46,500	41,900	204,000

Table 2.3 Typical Proximate and Ultimate Analysis of Coals [1]

Coal I.D. rank	Anthracite	Illinois coal bituminous	Kentucky bituminous	Wyoming subbituminous	North Dakota lignite
Moisture (%)	1.3	10.1	8.6	27.8	29.9
Proximate (wt%, d.b.)					
Volatiles	8.8	35.9	35.2	32.9	2.4
Fixed Carbon	71.8	46.7	41.5	34.3	76.1
Ash	18.1	7.3	23.3	5	20.6
Ultimate (wt%, d.b.)					
Carbon	73.2	68.3	61	76.3	69.7
Hydrogen	3.1	5	4.4	4.4	3.8
Nitrogen	0.9	1.3	1.4	1.1	1.9
Sulphur	0.9	3.5	4.3	0.5	1.1
Oxygen	3.8	13.8	5.6	10.8	13.2
Ash	18.1	8.1	23.3	6.9	10.3

As shown above in Table 2.3, the ultimate analysis of a solid fuel, commonly referred as elemental compositions, provides compositions of carbon (C), hydrogen (H), nitrogen (N), sulphur (S) and oxygen (O), while the O content (on a dry basis) is usually determined by difference as follows:

$$\%[O] = 100 - (\%[C] + \%[H] + \%[N] + \%[S]_{org} + \% Ash) \quad (\text{Eq. 2.1})$$

Compared with biomass and peat, coal (particularly the high rank anthracite) has much lower H/C and O/C atomic ratios, as is comparatively shown in Figure 2.1.

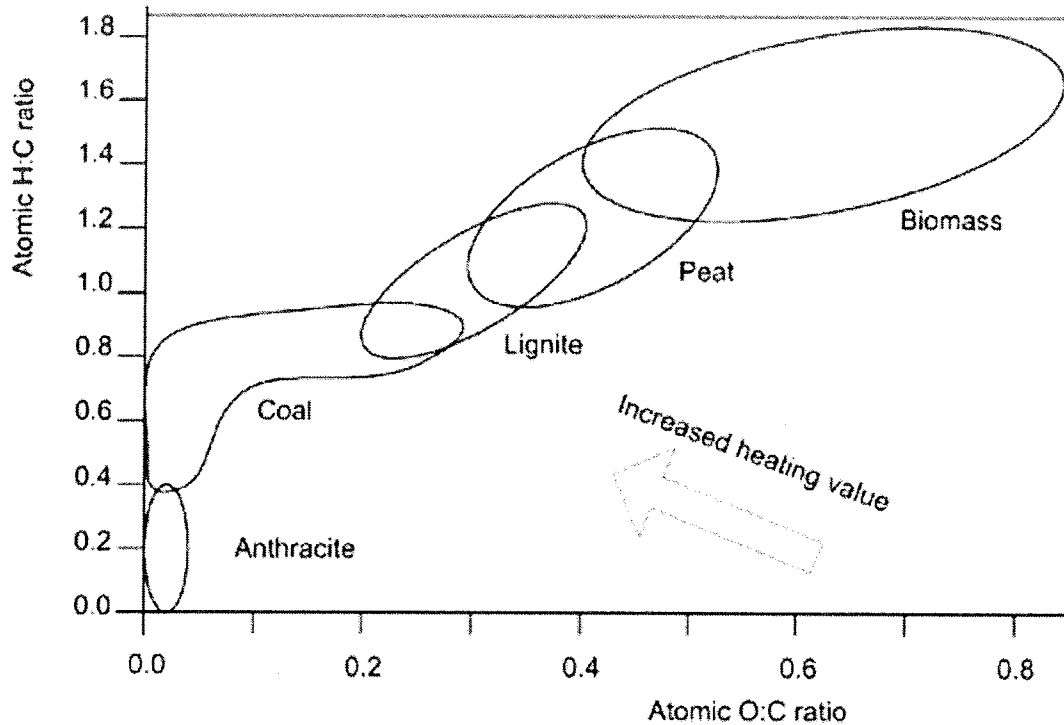


Figure 2.1 Hydrogen/carbon atomic ratio versus oxygen/carbon atomic ratio [2]

2.1.2 Biomass fuels

Biomass fuels include wood, short-rotation woody crops, agricultural wastes, short-rotation herbaceous species, wood wastes, bagasse, industrial residues, waste paper, municipal solid waste, sawdust, bio-solids, grass, waste from food processing, and animal wastes. Biomass combustion is advantageous due to the fuels' high reactivity and volatility; however biomass contains high amounts of alkali metals and chlorine which are the main contributors to slagging and unit corrosion. Biomass fuels also tend to have a lower heating value when compared with solid fossil fuels. In comparison with coal, biomass has less carbon, more oxygen, more silica and potassium, less aluminum and iron, lower heating value, higher moisture content, and lower density, as shown in Table 2.4 [3].

Table 2.4 Physical, chemical and fuel properties of biomass and coal fuels [3]

Property	Biomass	Coal
Fuel density (kg/m ³)	~ 500	~ 1300
C content (wt% of dry fuel)	42-54	65-85
O content (wt% of dry fuel)	35-45	2-15
S content (wt% of dry fuel)	Max 0.5	0.5-7.5
SiO ₂ content (wt% of dry ash)	23-49	40-60
K ₂ O content (wt% of dry ash)	4-48	2-6
Al ₂ O ₃ content (wt% of dry ash)	2.4-9.5	15-25
Fe ₂ O ₃ content (wt% of dry ash)	1.5-8.5	8-18
Ignition temperature (K)	418-426	490-595
Friability	Low	High
Dry calorific value (MJ/kg)	14-21	13-37

Although most biomass fuels share similar properties such as high volatility and reactivity, and low ash content, the chemical differences remain noticeable within the variety. Specifically, the nitrogen, sulfur, and chlorine contents tend to vary between different types of biomass, as can be seen in the following Figure 2.5. Straw has higher chlorine content, woody biomass has negligible Cl, and shells have higher nitrogen and sulfur contents.

Table 2.5 Ultimate analyses of typical biomass fuel samples (wt% dry basis) [3]

Fuel sample	C	H	N	S	Cl	O (by diff.)
Red oak wood	50	6	0.3	-	-	42.4
Wheat straw	41.8	5.5	0.7	-	1.5	35.5
Olive husk	49.9	6.2	1.6	0.05	0.2	42
Beech wood	49.5	6.2	0.4	-	-	41.2
Spruce wood	51.9	6.1	0.3	-	-	40.9
Corn cob	49	5.4	0.5	0.2	-	44.5
Tea waste	48	5.5	0.5	0.06	0.1	44
Walnut shell	53.5	6.6	1.5	0.1	0.1	45.4
Almond shell	47.8	6	1.1	0.06	0.1	41.5
Sunflower shell	47.4	5.8	1.4	0.05	0.1	41.3

2.1.3 Peat fuel

Peat forms in wetlands or peat lands, and it is an accumulation of partially decayed vegetation matter. Peat covers approximately 2% of the global land mass (3 million km²), containing 8 billion terajoules of energy [4]. The world peat land distribution is displayed in Table 2.6. As shown in the Table, Canada with 170 millions of hectares of peat land has a abundant peat fuel resource. Due to its slow renewability (hundreds to thousands of years), it can either be considered a fossil fuel or biomass. Under the proper geological conditions, peat could be converted into lignite coal over a geologic period of time, which explains the fuel characteristic similarities between peat and lignite.

Table 2.6 World peat lands distribution [5]

Country	millions of hectares
Canada	170.0
Russia	150.0
U.S.A.	40.0
Indonesia	26.0
Finland	10.0
Sweden	7.0
China	3.5
Ireland	1.2
Others	12.3
Total	420.0

Peat can be used as an alternative energy source to coal for heat power generation. For instance, Finland utilizes peat fuel to generate approximately 6.2% of their annual energy production [6]. According to the data published from the Ontario Ministry of

Energy, 8 million tonnes of peat fuel may be utilized for fuel to generate electrical power worth 3200 MW at 8 cents per kWh [5].

Compared with coal, peat has certain economic and environmental benefits such as [5]:

- low sulfur content
- minimal mercury content
- low ash content
- energy values equivalent to lignite
- less expensive than oil and natural gas and price competitive with other biofuels
- minor engineering retrofit needed when substituted for, or blended with coal
- source of local employment and regional development in areas disadvantaged by weakened forestry sector

2.2 Solid fuel combustion technologies and combustors

The most common commercial combustion technologies for thermal/power generation are as follows:

- Fixed bed combustion,
- Fluidized bed combustion, and
- Pulverized bed combustion.

Schematics of these three technologies are displayed in the Figure below.

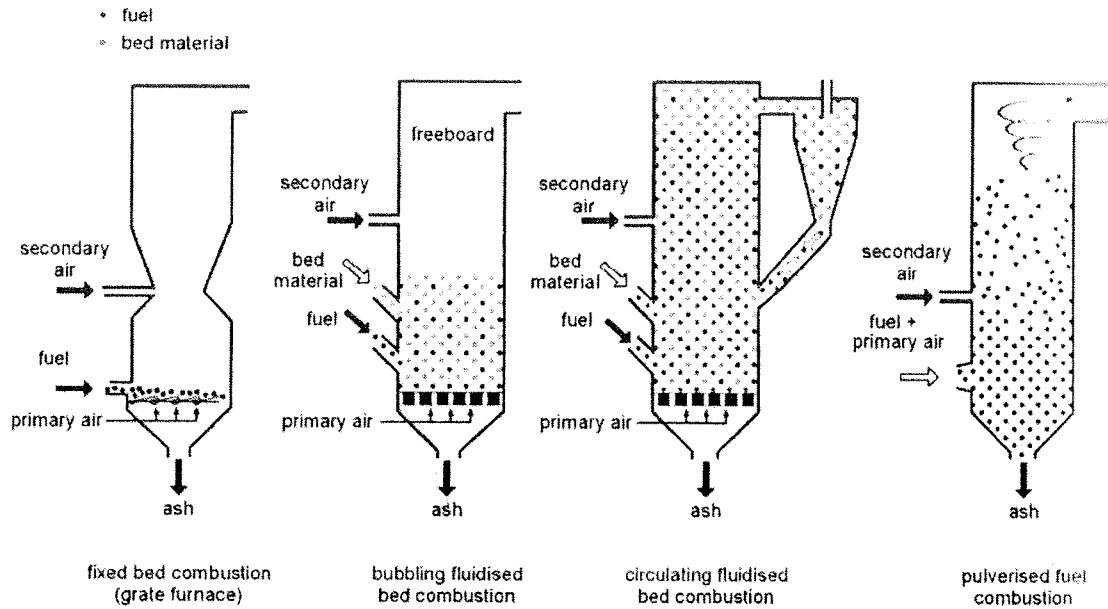


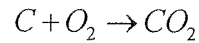
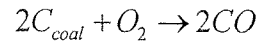
Figure 2.2 General schematics for various combustion/co-firing technologies [7]

2.2.1 Solid fuel combustion reactions

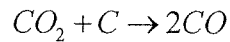
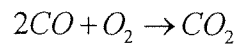
Combustion may be simply defined as the complete oxidation of a fuel, which produces hot gases that could be used for direct heating purposes. It is the follow up step to drying and pyrolysis/gasification when the temperature is high enough. Another by-product of combustion is ash, which varies in characteristics and composition depending on type and properties of the fuel.

The overall chemistry of solid fuel combustion begins with chemisorption of oxygen on active sites of the solid fuel particle surface, which decomposes the resultant surface oxides, continuously exposing fresh reaction sites, following the shrinking core model. The exact chemical reaction is difficult to predict due to the complex molecular structure of a solid fuel, but to simplify the process, an overall stoichiometry may be

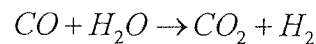
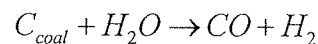
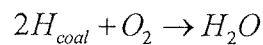
established. Typical reactions of solid fuel combustion may be represented by carbon reacting with oxygen to produce carbon monoxide and carbon dioxide:



The formed carbon monoxide is further oxidized in a gaseous boundary zone to generate carbon dioxide. The carbon dioxide either releases into the flue-gas stream or is reduced to carbon monoxide by hot char particles:



Indirect combustion of the hydrogen in the solid fuel (taking coal as the example) produces water, which could gasify the solid char to produce carbon monoxide and hydrogen gas. The steam reforming reaction between CO and H₂O also produce CO₂ and H₂, which is called a water-gas shift reaction. Steam reforming reactions are reactions between hydrocarbons and H₂O.



In general, the combustion of carbonaceous materials involves a large number of reactions between the reactants, intermediates, and products. Although the stoichiometry may be simple to conceive, the kinetics of coal combustion remains difficult. The rate of

carbon consumption is determined by the availability of oxygen and the particle surface area [6]. The overall combustion rate, R, may be expressed by:

$$R = k_s p_{o(s)} \quad (\text{Eq. 2.2})$$

Where:

k_s = The reaction rate constant of the primary reaction

$p_{o(s)}$ = Oxygen partial pressure at the particle surface

The rate constant of the overall combustion reaction is given as:

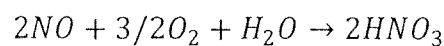
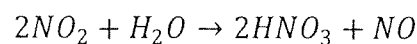
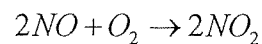
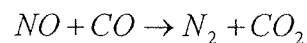
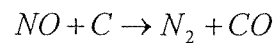
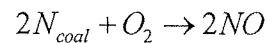
$$k_s = A e^{-E/RT} \quad (\text{Eq. 2.3})$$

Where:

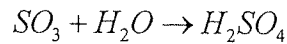
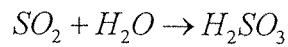
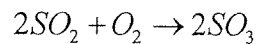
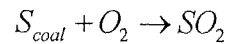
A = frequency factor

E = apparent activation energy

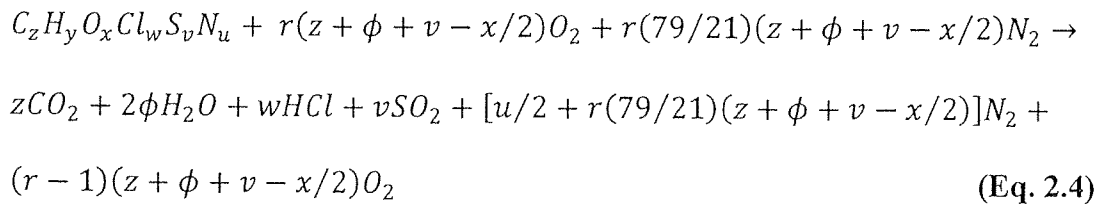
Both the solid fuel-bound nitrogen and the atmospheric nitrogen are involved in the combustion process, resulting in the formation of harmful nitrogen oxides as a major air pollutant contributing to acid rain and photochemical smog formation.



Sulphur contained in the solid fuel (e.g., coal-bound sulfur) can also be converted to sulphur oxides emission and sulphuric acids when reacting with water:



There are many overall combustion reactions developed to help predict the amount of air required and the stoichiometry of the gaseous products, depending on the amount of fuel incinerated. These equations rely on accurate elemental analysis (carbon, hydrogen, sulfur, nitrogen, chloride, oxygen, etc...) of the fuel. Considering the ash-free component of a solid fuel, represented by a general chemical formula of $C_zH_yO_xCl_wS_vN_u$ ($z + y + x + w + v + u = 1$), a general combustion reaction may be described [7] by:



where $\phi = (y - w)/4$ if $y > w$ or $\phi = 0$, as the chloride reacts with the hydrogen first to form hydrogen chloride, which is corrosive for the system. The $(r - 1)$ represents the excess air, where $r \geq 1$.

2.2.2 Fixed-bed combustion

The fixed bed combustors are also called grate furnaces including fixed grates, moving grates, traveling grates, rotating grates, and vibrating grates. Grate furnaces are ideal for the combustion of varying particle size biomass fuels with a high moisture and ash content. Fixed-bed combustors can be classified into two main types: updraft combustors and downdraft combustors. The basic method to achieving updraft combustion involves lumps of fuel supported on a grate bed. Primary air is supplied beneath the bed and secondary air above it, while a connection to a flue exit on the top of the reactor provides a draft. It is a simple technique which is used for domestic fire to the furnace. The ignition occurs at the base of the fuel bed, which spreads the flame upward till the whole bed is ignited. The ash drops beneath the grate to settle at the bottom of the reactor creating insulation. The downdraft combustion technology employs an inversion of the updraft combustion in order to control the emission of smoke. The air enters at the top of the container, passing through the fuel bed and exits from beneath the grate bed carrying the product gases. The flame travels opposite to the air, causing the volatile matter and NO_x to be reduced by hot char, therefore reducing the emissions of tar and air pollutants.

2.2.3 Fluidized bed combustion

Fluidized bed combustion (FBC) has been commonly used for combustion of solid fuel for heat generation or for incineration of industrial and municipal wastes since the 1960's due to its advantages of uniform temperature distribution inside the reactor and excellent heat/mass transfer efficiencies [7]. FBC plants are highly flexible with regards to the types of fuel mixtures which can be burned, although limited to the particle size and impurities within the fuel. Fluidized beds consist of a column with a gas distributor (porous or perforated) or sparger. In operation, a fluidized bed contains a suspension bed of inert granular material such as dolomite or silica sand, and the primary air enters through a distributor or sparger below the granular bed causing fluidization. The secondary air is introduced through various inlets in the freeboard section to ensure staged-air supply, which reduces NO_x emissions and increases the combustion efficiency. In order to avoid ash sintering in the bed, the combustion temperature is usually maintained within 650-900°C, ideal for fuels with low ash-melting temperatures. This can be achieved in various ways such as through internal heat exchangers, flue gas recirculation, or water injection. There are two types of FBC's that are commonly used commercially: (1) bubbling fluidized beds (BFB) and (2) circulating fluidized beds (CFB). BFB plants have been widely used for combustion or co-firing of various kinds of biomass mixtures, as the system is advantageous with respect to the particle size and moisture content of the fuel that it can handle. Circulating fluidized beds, as illustrated in Figure 2.3, utilizes a higher fluidizing velocity of 5-10 m/s, compared to 1.0 – 2.0 m/s for a BFB [8, 9]. Such high fluidizing velocity causes bed sand particles to be carried off

with the flue gas, then separated in a cyclone or a U-beam separator and fed back into the combustion chamber. The advantage of high turbulence produces a homogenous bed temperature distribution. The disadvantages of CFB furnaces are the large equipment dimension and the requirement for pre-treatment of the feedstock to reduce its particle size, and therefore the high infrastructure/operating costs.

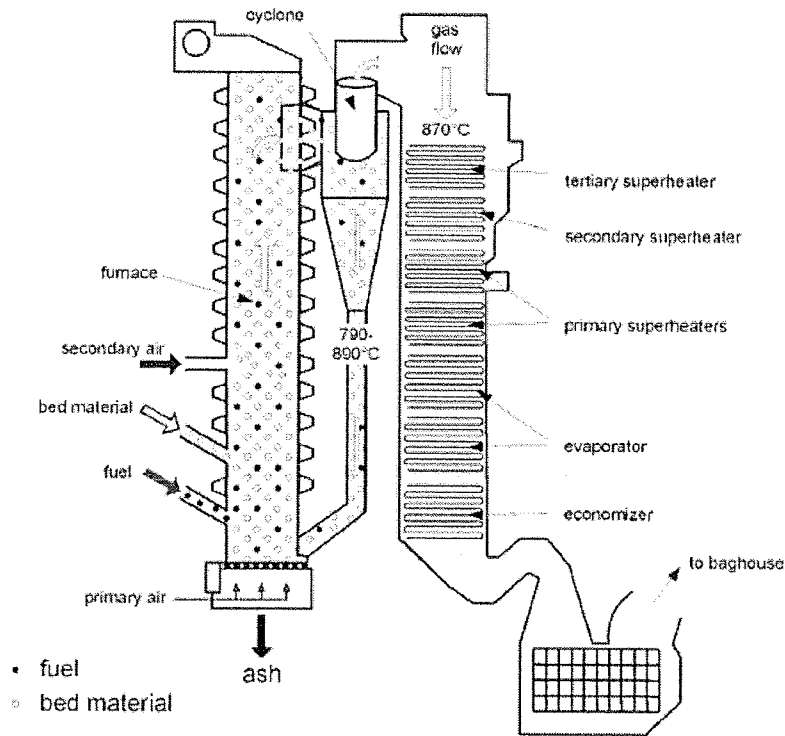


Figure 2.3 Schematic of a circulating fluidized bed (CFB) combustor [8]

2.2.4 Pulverized fuel combustion

Pulverized fuel combustion systems utilize pneumatic fuel injection of finely crushed fuel into the furnace, using the primary air for fuel transportation. The fuel/air mixture is injected tangentially for cylindrical muffle furnaces to establish a rotational flow. The start-up requires auxiliary burners until the desired temperature is achieved. Fuel pre-treatment is necessary to maintain a maximum fuel particle size of 10-20 mm

and moisture content below 20wt% [8]. Pulverized fuel systems usually attain temperatures up to 1600°C and a retention time of a few seconds. Due to the high temperature and small fuel particle size, fuel gasification and combustion occur at the same time, allowing for efficient load control. Pulverized fuel systems are the most widely used for coal-fired power generation.

2.3 Co-firing technologies

Co-firing technology, directly by burning biomass and coal or indirectly by gasifying biomass first to produce clean fuel gas that is then burnt with coal in a generation boiler, has proven to be a cost-effective technology to achieve the goal of increasing use of biomass-to-energy processes for power generation, thereby significantly reducing greenhouse gas emissions. Co-firing processes can be generally classified into three categories depending on the manner of introducing biomass into the combustion units: (1) biomass is simply blended with coal and then introduced into the boiler; (2) biomass is processed separately and injected into the boiler through dedicated lines; and (3) biomass is gasified before the subsequent co-firing process, also called indirect co-firing.

The remarkable advantages of biomass co-combustion as discussed above have broadened the applications of biomass co-firing technology in the energy production fields. Co-combustion has been commonly used in the USA, Finland, Denmark, Germany, Austria, Spain, and Sweden, The Netherlands, Poland and a number of other countries [10]. To date there are more than 150 coal-fired power plants (mainly 50-700MWe) in the world have adopted or tested co-firing of coals with woody biomass or waste materials [11]. Biomass systems can also be used for village-power applications in the 10–250 kW scale, for larger scale municipal electricity and heating applications [12], for

industrial application such as hog-fuel boilers and black-liquor recovery boilers, for agricultural applications such as electricity and steam generation in the sugar cane industry [13], and for utility-scale electricity generation on the 150 MW scale [14]. A variety of biomass including woodwaste, forestry/ agricultural residues and by-products, and herbaceous and energy crops materials have been co-combusted with essentially all types of commercially significant solid fossil fuels (e.g. lignites, sub-bituminous coals, bituminous coals, anthracites, and petroleum coke, etc.) at a co-firing ratio up to 15% [15-18]. Owing to their wide range of applicability to a diverse set of needs, biomass-based power generating systems are so far the only non-hydro renewable source of electricity that can be used for base-load electricity generation.

Co-firing has been successfully demonstrated in almost all types of coal boiler including pulverized fuel combustor (PFC), fixed bed and fluidized beds combustors, and grate boilers [19, 20]. For example, a very large-scale biomass co-firing plant, the Alholmens Kraft Combined Heat and Power (CHP) plant in Pietarsaari (Finland), has been in operation since 2001. This plant employs a circulating fluidized bed (CFB) boiler and has electricity output of 240 MW_e [21]. Although fluidized bed combustors, bubbling fluidized beds (BFB) and CFB are advantageous in terms of the fuel flexibility, being able to handle different types of fuels, solid, semi-solid, or liquid fuels, PFC is the most common technology used for co-firing biomass with coal. This is because less modification in equipment is required for co-firing biomass and coal in an existing large PFC boiler. There has been rapid progress over the past decade in development of the co-firing of biomass materials in pulverized coal-fired boiler plants worldwide, particularly in Europe, North America and Australia [22]. Worldwide approximately 41.5% of 135

coal-fired power plants that have experienced co-firing biomass use PFC boilers [23]. However, biomass co-firing in PFCs is limited due to both technical and non-technical problems. For example, co-firing ratio of biomass in most PFC boilers is no more than 10-15% on a thermal input basis due to the issues of increased ash deposition or accelerated corrosion rates for the boiler components.

Although co-firing technologies have been well developed and relatively widely applied in industries worldwide, co-firing processes are not yet completely understood and it is still challenging to increase the biomass co-firing ration to >20% [24]. Due to the inferior properties of biomass (e.g., higher moisture contents, low bulk densities, etc.), direct co-firing processes are normally limited to low co-firing ratios. The major technical challenges associated with co-firing biomass fuels are summarized as follows: (1) firing high-alkali herbaceous biomass fuels such as switch grass (containing potassium or sodium) would lead to increased slagging and fouling on boiler surfaces when; (2) chlorine compounds in volatile ash would result in corrosion of heat transfer surfaces inside the boiler; (3) biomass materials are generally moist and strongly hydrophilic as well as non-friable, which would pose difficulties in fuel preparation, storage, and delivery; (4) Depending on the quality of the biomass feedstock, co-firing might result in a reduced thermal efficiency and an increased emission (NO_x); (5) economic utilization of the fly ash from co-firing biomass and coal should be explored. Clearly one of the key challenges for direct co-firing processes is related to fly ash behaviours (deposition, fouling and corrosion, etc.) and air emission such as NO_x formation.

2.4 Air emissions from co-firing biomass and coal

Gaseous and gas-borne emissions of concern during co-combustion of coal and biomass/peat are: CO₂, CO, SO_x, NO_x, particulate matter, acid halides (HCl), organic compounds (VOCs and PAHs), chlorinated dioxins (PCDD), and trace metals. These emissions differ with the type of fuel used during the combustion and the method of combustion.

Although biomass and peat contain lower carbon content than coals, they also suffer from lower calorific values. In order to upkeep the same amount of heat input as coal, more peat/biomass is required, resulting in no significant changes to the CO₂ emissions. However, due to the carbon neutrality of biomass fuels, the CO₂ emitted from combustion of biomass does not contribute to the net increase in the CO₂ level of the atmosphere, hence does not impact on climate change. CO emissions tend to be mostly affected by other parameters such as: combustion efficiency and moisture content. Carbon tends to react with moisture released from the fuel to form carbon monoxide emissions. Low combustion efficiency resulting from incomplete combustion due to low retention time produces higher CO emissions.

Co-firing of biomass and coal has a great potential in reduction of emissions of greenhouse gas CO₂ (as discussed above) and other toxic gases such as SO_x and maybe NO_x [15, 16, 25-27]. The example environmental impacts of co-firing in power generation applications (vs. 100% coal) can be shown Table 2.7 [20]. A decrease in fuel bound sulfur and nitrogen results in the reduction of the corresponding gaseous sulfur dioxide (SO₂) (almost zero for most biomass) and nitrogen oxides (NO_x) formation [28].

Low sulphur content in most biomass fuels (usually less than 0.5 % db), as was given previously in Tables 2.4 and 2.5, would result in SO_x emissions reduction in line with the coal to biomass co-firing ratio. The reduction in SO_x emissions is not only ascribed to the lower sulfur content in the biomass feedstock, but also due to the retention of sulfur by alkali/alkaline earth elements present in the biomass [18, 26]. The alkali based compounds such as CaO and MgO in the ashes also cause retention of sulphur, although biomass and peat suffer from low ash content when compared to coals. The retention of sulphur by CaO and MgO, called sulfation, may be given by a general reaction as follows:

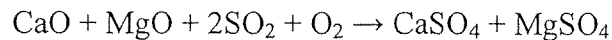


Table 2.7 Example environmental impacts of co-firing in power generation applications (vs. 100% coal) [20]

Boiler type	Plant size (MW)	Co-firing ratio	Reduced coal use (tons/yr)	Biomass used (tons/yr) ¹	Annual CO ₂ reduction (tons/yr) ²	Annual SO ₂ reduction (tons/yr)
Stoker (low cost)	15	20%	10,125	16,453	27,843	466
Stoker (high cost)	15	20%	10,125	16,453	27,843	466
Fluidized bed	15	15%	7,578	12,314	20,839	349
Pulverized coal	100	3%	7,429	12,072	20,430	342
Pulverized coal	100	15%	37,146	60,362	102,151	1,709

¹ Depending on the source of biomass, “biomass used” could be avoided landfilled material.

² Carbon reduction may further be calculated from the CO₂ reduction.

Nitrogen contents in biomass are less than 0.5% db, it is thus expected for coal and biomass co-firing to result in lower NO_x emissions. Unlike the SO_x emission, however, the level of NO_x emission in co-firing is not monotonous because NO_x can originate not only from fuel-bound nitrogen (fuel-N), but from the air-nitrogen through

the thermal NO_x mechanism depending on the operating conditions mainly combustion temperature and the state of air distribution within the high-temperature zones of the burner/combustor. For instance, Tsai *et al.* [29] observed reduced NO_x emission in co-firing, and it was attributed to the high moisture content in biomass, which lowered the combustion temperature and consequently resulted in lower NO_x emissions. In contrast, an increased amount of NO₂/N₂O was obtained in a bubbling fluidized combustor when co-firing coal and foot cake, a high moisture waste material from the olive oil industry [16].

Experimental studies on co-firing emissions of coal and biomass blends in a 18.68 MW traveling grate boiler have been conducted by K.V. Narayanan and E. Natarajan [30] where the biomass was co-fired at 20%, 40%, and 60% by mass with bituminous coal to generate 70 ton/h of steam. The fuels co-fired were bituminous coal (0.59 wt% S and 0.91 wt% N), lignite (0.5 wt% S and 0.28 wt% N) with wood chips (0 wt% S and 0 wt% N), sugarcane trash (0 wt% S and 0 wt% N), coconut shell (0.05 wt% S and 1.2 wt% N), and bagasse (0 wt% S and 0 wt% N). The emissions of SO₂ and NO_x from co-firing of bituminous coal with various fuels at different fuel mix ratio are shown in Figures 2.4 and 2.5, respectively. As a general result, both SO₂ and NO_x emissions were reduced in the co-firing due to the lower S and N contents in the co-fired fuels compared with the bituminous coal. The co-firing bituminous coal and coconut shell led to the lowest SO₂ and NO_x emissions at the 60:40 fuel mix ratio, but both increased at a higher mix ratio, suggesting the dependency of these emissions on the operating conditions (temperature, ash contents and compositions, etc.).

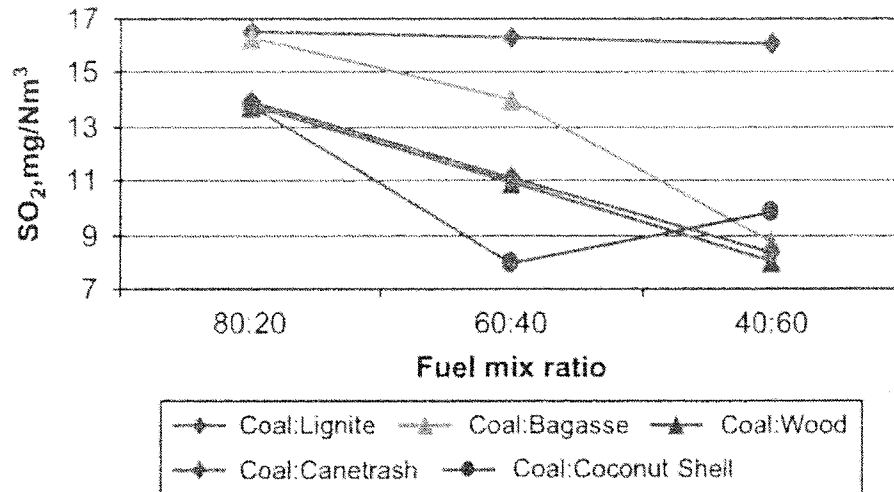


Figure 2.4 Variation of stack emission of SO₂ for different fuel mix ratio in co-firing of bituminous coal with various fuels [30]

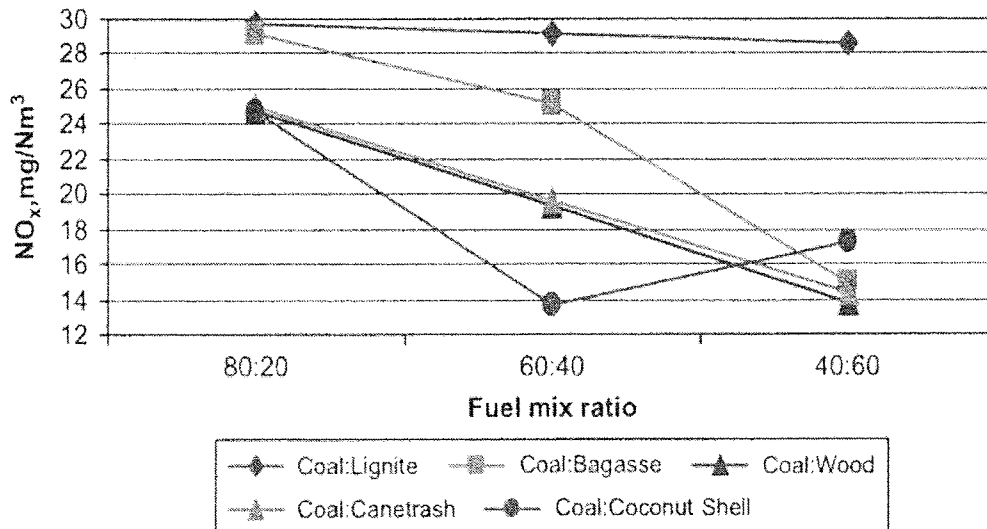


Figure 2.5 Variation of stack emission of NO_x for different fuel mix ratio in co-firing of bituminous coal with various fuels [30]

Operating conditions such as excess air, temperature, and the amount and location of secondary air for a co-firing facility are other major factors affecting air emissions. Excess air could substantially affect the air emissions in co-firing, as demonstrated in a study by Leckner and Lyngfelt [31] using a coal-fired 12 MW CFB. As demonstrated in the Figure 2.6 below, CO and SO₂ concentration in flue gas decreased monotonically with increasing the excess air ratio as expected, while the NO_x (NO and NO₂) and N₂O concentrations were the lowest at the air ratio of around 1.03, but increasing sharply as the air ratio increased further. The increased NO_x (NO and N₂O) concentrations were likely a result of the increased combustion temperature.

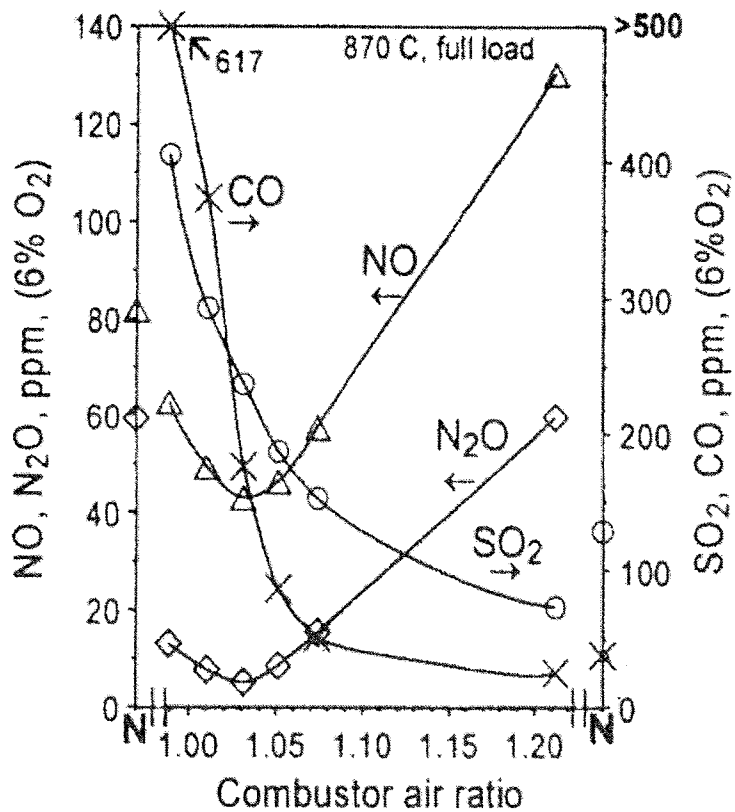


Figure 2.6 Concentrations of air pollutants in the flue gas versus combustor air ratio for a coal-fired combustor [31]

2.5 Summary of the literature review

- (1) Compared with biomass and peat, coal (particularly the high rank anthracite) has much lower H/C and O/C atomic ratios. Biomass fuels generally have lower contents of C, S, N and ash contents as well as calorific values, but a higher O content, compared to coal and peat fuel.
- (2) Co-firing technologies have been well developed and relatively widely applied in industries worldwide.
- (3) Co-firing has been successfully demonstrated in almost all types of coal boiler including pulverized fuel combustor (PFC), fixed bed and fluidized beds combustors, and grate boilers. Fluidized bed combustors, bubbling fluidized beds (BFB) and CFB are advantageous in terms of the fuel flexibility, being able to handle different types of fuels, solid, semi-solid, or liquid fuels, and PFC is the most common technology used for co-firing biomass with coal.
- (4) However, co-firing processes are not yet completely understood and it is still challenging to increase the biomass co-firing ratio to >20%, mainly due to the inferior properties of biomass (e.g., higher moisture contents, low bulk densities, etc.), and the major technical challenges associated with co-firing biomass fuels related to fly ash behaviors (deposition, fouling and corrosion, etc.).
- (5) Co-firing of biomass and coal has a great potential in reduction of emissions of greenhouse gas CO₂ (due to the carbon neutrality of biomass fuel) and other toxic gases such as SO_x. However, the NO_x (NO and NO₂) and N₂O emission in co-firing might be decreased or increased, depending on not only the fuel-N content

but the operating conditions (excess air ratio, temperature, etc.). More research in this respect is needed.

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Chapter 3

Air Emissions from Co-firing Woodwaste/Peat and Lignite in a Bubbling Fluidized Bed Combustor

The effects of particle size (pellets or crushed), the fuel blending ratios (0, 20%, 50%, 80% and 100% on a heat input basis), moisture content and excess air ratio on combustion efficiency and air emissions (CO_2 , CO, SO_2 and NO_x) from combustion/co-combustion of woodwaste or peat and lignite were examined in a pilot-scale bubbling fluidized bed combustor. The results showed that properly controlling the co-firing parameters could achieve increase in combustion efficiency and reduction of air emissions. Compared to solid fuels in fine particles ($< 4\text{mm}$), fluidized-bed combustion of solid fuels in the pellet form could obtain higher dense-phase temperatures and a more uniform temperature profile along the fluidized-bed column and achieve a much higher efficiency ($>94\%$), while yielding minimal effects on the emissions of SO_2 and NO_x . Co-firing of lignite and white pine pellets at an increasing blending ratio led to a proportional reduction in both SO_2 and NO_x emissions. Co-firing of peat and lignite led to an increase in SO_2 emission, but co-combustion of peat (0-100%) and lignite resulted in a reduction in NO_x emission. The presence of moisture in the fuels promotes the combustion of solid fuels by the steam gasification/reforming and gas-water shift reactions, leading to increases in combustion efficiency and CO emissions, and the combustion of fuels of a higher moisture content led to a decrease in SO_2 emission, but an increase in NO_x emission. To achieve higher combustion efficiency and lower air emissions for combustion/co-combustion in a fluidized bed combustor, a too high excess air ratio ($>40\%$) should be avoided.

Keywords: Co-firing; Biomass; Peat; Lignite; Fluidized bed; Air emissions.

3.1 Introduction

About 28% of Ontario's electrical energy production comes from fossil fuels, which is mainly coal used at four generating plants of Ontario Power Generation (OPG) in Atikokan, Lambton, Thunder Bay and Nanticoke with a combined generation capacity of about 6,457 megawatts (MW) [1]. While these plants are a significant proportion of the Province's generating capacity, they are at risk of being shut-down by 2014 due to Ontario government policy decision to decrease greenhouse gas emissions. In response, the OPG has turned to co-firing technology as a viable solution to continue operating of the coal-fired generation stations, while reducing the net pollutant emissions from these coal-based power plants. Co-firing makes use of the extensive infrastructure associated with the existing coal-based power systems, and requires only relatively modest additional capital investment for providing significant CO₂ reductions [2]. Co-firing is not a recent technology, but it has been remarkably progressing over the last 5-10 years, as it's presently being successfully practiced at commercial scales in more than 150 power plants all over the USA and Northern Europe [2, 3]. The majority of the large scale power plants (~ 700 MW) use pulverized fuel injection boilers, while smaller scale plants (~ 50 MW) tend to favor bubbling or circulating fluidized beds [4, 5].

Significant amounts of sulfur and nitrogen contained in coal fuel result in additional air pollutants such as oxides of sulfur (SO_x) and nitrogen (NO_x), which leads to acid rain and ozone depletion. Co-firing coal with biomass such as bagasse, wood chips, sugarcane trash, rice husk or coconut shells, proportionally reduces the SO_x and NO_x emissions due to the negligible amount of sulfur and nitrogen contained in biomass fuels [6]. Biomass and coal co-firing benefits in reducing air pollutants is noticeable [7]. However, it also poses some risks to operation, e.g., the reduced plant operational flexibility due to associated with biomass handling, and the possibly

higher maintenance and replacement costs and firing equipment due to the ash related issues of slagging, fouling, and corrosion. To convert an existing coal-fired combustion facility to a co-firing one, the following issues (as the major technical obstacles for co-firing) must be addressed: (1) fuel preparation, processing and handling issues; (2) combustion related issues such as flame stability, affecting plant operation and control; (3) ash related issues of slagging, fouling, and corrosion, where slag formation in the operation is believed to connect to the presence of iron, sulphur and alkaline and alkaline earth metals, and slagging is a crucial issue which can halt operation for maintenance; (4) and other environmental impacts such as NO_x and particulate matters [2].

As a clean biomass resource, woody wastes tend to have much lower nitrogen and ash content compared to agricultural wastes and coal, which would result in less NO_x and particulate matter emissions during combustion. It is thus preferable to incinerate biomass waste for energy recovery rather than disposing of it in landfills, as decomposition of biomass releases CH₄, which is a more harmful greenhouse gas than CO₂. Biomass consumes the same amount of CO₂ from the atmosphere during growth as is the released during combustion, and is therefore regarded as a carbon-neutral fuel, although biomass fuel is in fact not completely carbon neutral if taking into account the fossil fuel consumed in the harvesting and transportation processes. Although biomass offers important advantages as a combustion feedstock due to its high volatility and reactivity, it should be noticed that biomass contains much more oxygen and chlorine (for some waste materials), more silica and potassium, less iron and aluminum, higher moisture content, and a lower calorific value than coal [9]. High-temperature corrosion of super-heater tubes surfaces is an important concern due to the deposition of lower boiling alkaline compounds and the detrimental effects of the biomass containing chlorine [10]. Peat is an accumulation of

partially decayed vegetation matter, being the transition state from biomass into lignite. Although peat may not be regarded as a truly renewable fuel due to its much slower growth rate (the average re-growth time being 1,000 to 5,000 years) compared to biomass (tens to hundreds years) [11], it can still be a potential alternative fuel to coal, as it has several advantages as a fuel when compared to coal such as low contents of sulphur, ash, minimal mercury content, etc. [12]. Nevertheless, technical issues such as slagging are common for peat combustion, as the rich combination of iron, calcium, silicon, and aluminum, resulting in the formation of iron calcium aluminosilicate and iron calcium silicate glasses [13].

Although pulverized fuel boilers are remaining the most common facilities for power generation by combustion or co-combustion of coal with biomass or peat, the use of fluidized bed boilers is increasing because they provide increased overall efficiency, fuel flexibility and the economic use of low grade waste materials from agricultural/forestry residues and waste streams [14]. Fluidized bed technology with low-rank coals (brown coal or lignite) suffers from particle agglomeration and defluidization [15]. Lignite suffers from low heating value and higher moisture content when compared to higher rank coals. The main environmental advantage of some lignite coals is its low sulphur content, resulting in lower SO_x emissions. Calcium and MgO containing ash formations during combustion are known to absorb a significant amount of the SO_2 , forming CaSO_4 and MgSO_4 , accomplishing the sulfation step at moderate temperatures [16]. The above sulfation reaction is at maximum at temperatures around 850°C , as higher temperatures would cause either sintering or re-emission of SO_2 due to decomposition of the sulfates [17,18]. NO_x formation during combustion results from the oxidation of fuel-nitrogen (fuel- NO_x) and through thermal oxidation of nitrogen contained in the combustion air (thermal NO_x). The formation rate of thermal NO_x is primarily a function of temperature and the residence

time of nitrogen at that temperature. It becomes very significant at a very high temperature, usually above 1600°C. Depending on the operating conditions (e.g., feedstock compositions, and operating temperature) the effects of co-firing of biomass and coal on NO_x emission are normally less evident compared to SO₂ [19].

Canada is blessed with 10% of the world total forest resources. Woodwaste (harvest residue and sawmill residues, etc.) and peat are widely available resources in Ontario and Canada. Concerns regarding the environmental impacts of fossil fuels used in power generation have intensified the research interest in the use of these renewable fuels for energy. This research work investigate effects of fuel particle size, fuel types, different fuel blending ratios, moisture content of feedstock and excess air ratio on combustion efficiency and air emission of CO, CO₂, SO_x, and NO_x resulting from combustion and co-combustion of woodwaste (white pine pellets/sawdust), peat and lignite in a pilot-scale bubbling fluidized bed combustor.

3.2 Experimental

3.2.1 Fuel Characterization

The lignite fuel was provided by Ontario Power Generation from the Atikokan Generating Station. It is low sulfur lignite from Western Canada. The peat fuel was supplied by the Peat Resources Limited, which was in pellet form (10 mm OD x 30 mm long) to reduce the moisture and increase the bulk density. The woody biomass was white pine sawdust obtained from a local Sawmill in South Ontario.

The proximate and ultimate analyses and ash analysis for all the fuels were performed at CanmetENERGY Analytical Center. Before the analyses, the fuel samples were dried at 105°C in air for more than 12 h and grinded into particles <60 mesh (250 µm) using an electrical

grinder. Proximate analysis was determined with a thermogravimetric analyzer (TGA) using the ASTM D 5142 method, while the carbon, hydrogen and nitrogen are determined with an organic element analyzer, using the ASTM D 5373 method. Sulphur was determined using the alternative ISO 562 method, which has the ability to distinguish the organic from the inorganic sulphur content. The higher heating value was obtained using a bomb calorimeter. The proximate and ultimate analysis results of the three fuel feedstocks are shown in Table 3.1. As clearly shown, the lignite and peat are quite similar in compositions, distinguished mainly by the ash and oxygen contents. The lignite contains a much higher content of ash (22 wt% d.b.) than the peat (2 wt% d.b.), while the lignite has a much lower oxygen content than the peat (13.6 wt% d.b. vs. 35.2 wt% d.b.). Compared with the lignite and the peat, the white pine feedstock contains a much higher volatile matter (84.5 wt% db) and a much lower fixed carbon (15.1 wt% db) and ash (0.44 wt% db). In addition, the white pine is distinguished by its extremely lower sulfur (<0.05 wt% db) and nitrogen (0.1 wt% db), compared with the sulfur contents of 0.2-0.5 wt% db and the nitrogen contents of 0.8-0.9 wt% db for the lignite and peat fuels. All the three types of fuels are very close in HHV values (around 21 MJ/kg on a dry basis).

Table 3.1 Ultimate and proximate analysis of lignite, peat, and white pine

Fuel Type	Lignite	Peat	White Pine
Proximate analysis (wt%)			
Moisture (%)	30.0	35.8	38.0
Volatile matter (db)	54.0	68.6	84.5
Fixed carbon (db)	23.9	29.4	15.1
Ash (db)	22.0	2.00	0.44
HHV (MJ/kg)	23.5	21.4	20.6
Ultimate analysis (wt%, db)			
Carbon	58.8	56.1	52.5
Hydrogen	4.17	5.67	6.32
Sulphur	0.50	0.23	<0.05
Nitrogen	0.91	0.81	0.10
Oxygen (by diff.)	13.6	35.2	40.6

¹Calculated by difference (db: on a dry basis)

The ash compositions of these three fuels are given in Table 3.2. As also expected, the woody biomass and the peat contain significantly higher concentrations of alkali and alkaline-earth metals (K, Na, Ca and Mg) in their ashes than the lignite fuel. As shown in the Table, the peat fuel has a strikingly high chlorine content of 2008 $\mu\text{g/g}$, compared with only 25 $\mu\text{g/g}$ and 39 $\mu\text{g/g}$ for lignite and white pine, respectively.

Table 3.2 Ash Analysis for lignite, peat, and white pine

Fuel Type	Lignite	Peat Pellets	White Pine Pellets (Steam)
Ash Analysis (wt%, db)¹			
SiO ₂	49.76	28.05	6.70
Al ₂ O ₃	19.71	8.63	1.97
Fe ₂ O ₃	3.82	5.56	1.46
TiO ₂	0.86	0.48	0.09
P ₂ O ₅	0.30	1.31	3.52
CaO	9.91	12.65	31.10
MgO	2.11	17.72	4.34
SO ₃	6.09	12.73	2.80
Na ₂ O	4.2	2.84	0.36
K ₂ O	1.04	1.14	15.45
Halogens ($\mu\text{g/g}$, db)²			
Bromine	<21	153	<29
Chlorine	25	2008	39
Fluorine	100	<20	<29

¹X-ray fluorescence

²Pyrohydrolysis

3.2.2 Fuel Preparation

The as received fuels as shown in **Table 3.1** have a moisture (>30 wt%) and particle size and distribution that are suitable for the fluid bed combustor, so fuel preparation was necessary. For the lignite fuel, the moisture was reduced to below 25% by using a large rotary dryer at CanmetENERGY followed by sieving to 1- 4 mm diameter of particles for the combustion tests.

The peat fuel and white pine sawdust were air-dried to a moisture content of mainly below 25 wt% (except peat pellets: 30 wt% moisture). A small amount of peat pellets were crushed into particle sample (sieved into 1-4 mm) for the tests to study the effects of fuel particle size. The white pine sawdust, sieved into <4 mm particles for the combustion tests, while some white pine sawdust was pelletized into pellets (5 mm O.D., 40 mm length) mainly using steam or a small amount (<1 wt%) of binding agent ‘Ameribond 2x’ (ammonium lignosulfonate). The addition of the binding agent produced high quality pellets, but it also increased the sulphur content to 0.09 wt% (db) (compared to <0.05 wt% db for the original sawdust). As such, the pine pellets containing ‘Ameribond 2x’ were used only in two tests (#16 and #21) as indicated in the **Table 3.4**.

3.2.3 *CanmetENERGY Bubbling fluidized bed combustor*

The fluidized bed reactor at CanmetENERGY was originally designed as a circulating fluidized bed facility, but was used as a bubbling fluidized bed in this research. The schematic diagram of the facility is shown in **Figure 3.1**. The reactor system is composed of a 5in – ID stainless steel cylindrical column and 236 in-height. The feed rate can be adjusted within 5 - 25 kg/h, by controlling the conveyor belt speed. The primary air and secondary air were introduced at locations shown in **Figure 3.1**. The primary air was controlled through the computer control station, while the secondary air was manually adjusted using rotameters to minimize CO emissions and un-burnt carbon in the ash from incomplete combustion. The secondary air was injected to create a circular air motion to increase the particle retention time, as illustrated in **Figure 3.1**. 12 K-type thermocouples were installed on the fluidized bed column to monitor the temperature profile along the column height, among which three thermocouples (TC02, TC03

and TC04) monitored the fluidized bed dense phase zones (Zones 1, 2 and 3) temperatures. The flue gas compositions (CO, CO₂, O₂, SO₂, and NO₂) were analyzed online using the HORIBA 510 series flue gas analyzers whose details (model, measurement ranges) are described in **Table 3.3**.

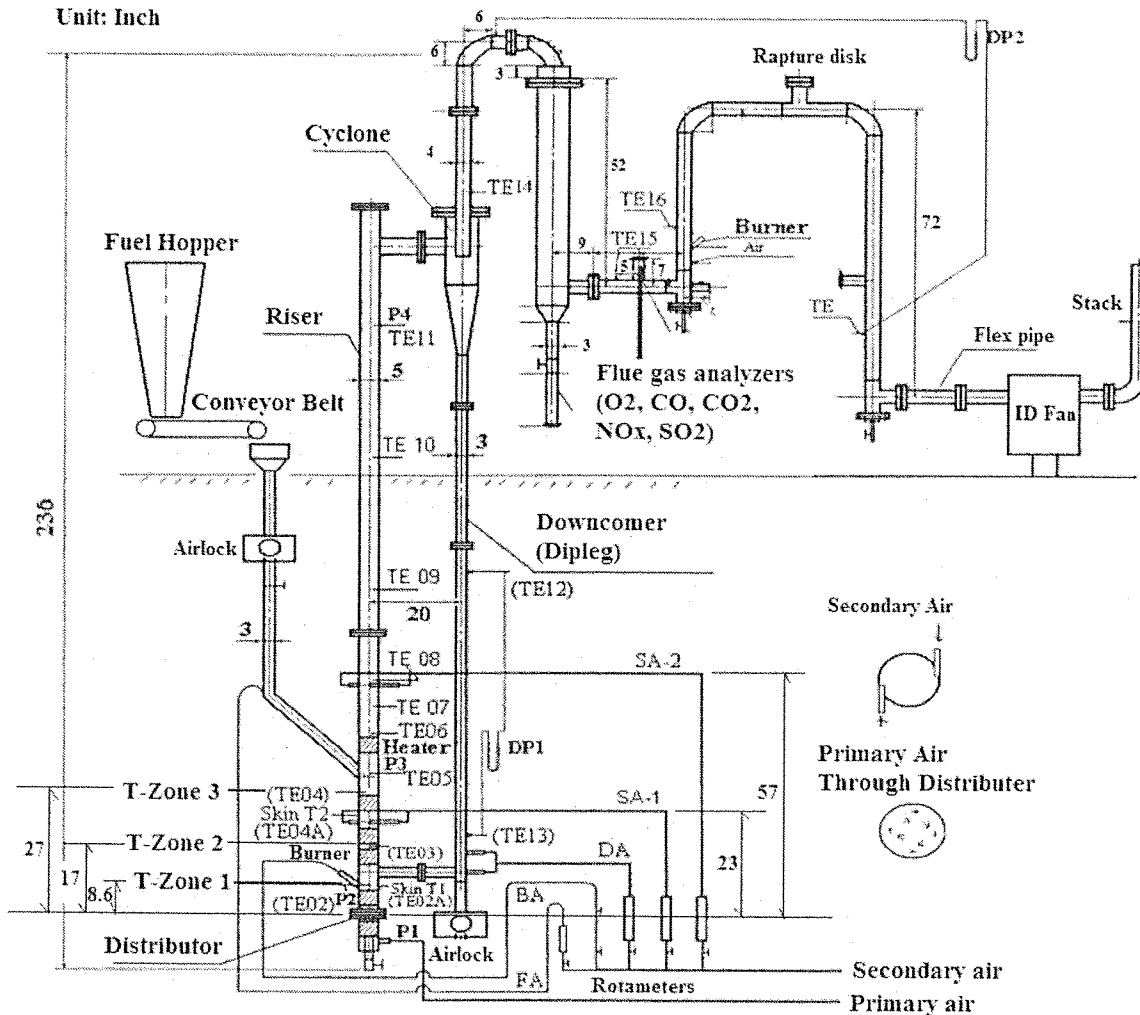


Figure 3.1 Schematic diagram of the CanmetENERGY fluidized bed combustor.

Table 3.3 Flue Gas Analyzers and Their Measurement Ranges

Gas	Model	Measurement Ranges	
		Minimum	Maximum
Carbon monoxide (CO)	Infrared analyzer	0 - 50 ppm	0 - 100 %
Carbon dioxide (CO ₂)	Infrared analyzer	0 - 50 ppm	0 - 100%
Nitric oxide (NO _x)	Chemi-NO _x analyzer	0 - 20 ppm	0 - 2000 ppm
Sulfur dioxide (SO ₂)	Infrared analyzer	0 - 50 ppm	0 - 100 %
Oxygen (O ₂)	Magnetropneumatic analyzer	0- 5 %	0- 50 %

3.2.4 Testing Methodology and Parameters

In each combustion/co-combustion test, 13 kg olivine sand as the bed material was fed into the combustor while using the primary air (250-300 L/min) to initiate the fluidization. The analyzers were zeroed/spanned using standard gas cylinders containing known concentrations of CO, CO₂, SO₂, NO₂, and O₂ gases. Fuel feeding began after the bed zone attained a temperature over 700°C using a propane burner. The fuel feed rate was adjusted to maintain a constant heat input of 58.3MJ/h and the air flow was adjusted to obtain a specific excess air ratio. In a steady operation for all the tests under 58.3 MJ/h heat input, the dense phase temperatures were in the range of 700-850°C and the maximum temperature in the column was at 850-950°C, which is the optimum temperature normally used for fluidized bed combustion for lowering the NO formation [20]. Steady-state was reached once the three bed zones (Zones 1 through 3) temperatures were steady within 20°C margin of one another. The flue gas compositions (CO, CO₂, O₂, SO₂, and NO₂) were analyzed online using the HORIBA 510 series flue gas analyzers. Hydrocarbon (HC) gas species in the flue gas such as CH₄ and C₂⁺ were confirmed to be negligible by GC, hence they were not monitored in the tests. The following equation (Eq. 3.1) was adopted to calculate the combustion efficiency based on the flue gas compositions of CO, CO₂ and HC where in this study [HC] ≈ 0.

$$\text{Combustion Efficiency } (\eta) = \frac{[CO_2] + [CO] \times 0.5}{[CO_2] + [CO] + \Sigma[HC]} \quad (\text{Eq. 3.1})$$

A minimum of 1.5h of steady state operation was ensured for collecting gaseous emissions data by the equipped computer system with a data logger. **Figure 3.2** displays an example of the steady state operation for a typical test (test #23 with 50% dried lignite and 50% dried white pine pellets at 40% excess air). More experimental data for other tests are provided in the Appendix of this thesis.

Several parameters were tested for their effects upon combustion efficiency, flue gas emissions resulting from combustion/co-combustion of lignite, peat, and white pine. They include particle size of peat and white pine fuels, fuel blending ratios of lignite with peat/white pine, moisture content of the fuels, and excess air. A summary of the testing parameters is provided in Table 3.3. To study the effects of particle size, the peat and white pine fuels were used in two different sizes: peat in the crushed (1-4 mm) and pellet (10 mm OD x 30 mm long) forms, and white pine in sawdust (sieved into < 4 mm) and pellet (5 mm OD x 40 mm long) forms. The main purpose of testing fuels of various particle sizes was to determine the effects of fuel particle size on combustion efficiency and emissions in the fluidized-bed combustion. The effects of moisture content on combustion/co-combustion and emissions were examined using pre-dried/air-dried fuels (of a moisture content of <25 wt%) in comparison to the 105°C oven dried fuels (moisture content < 5 wt%). Other operation parameters tested were fuel blending ratios (0, 20%, 50%, 80% and 100% on a thermal basis) and excess air (40% and 60%).

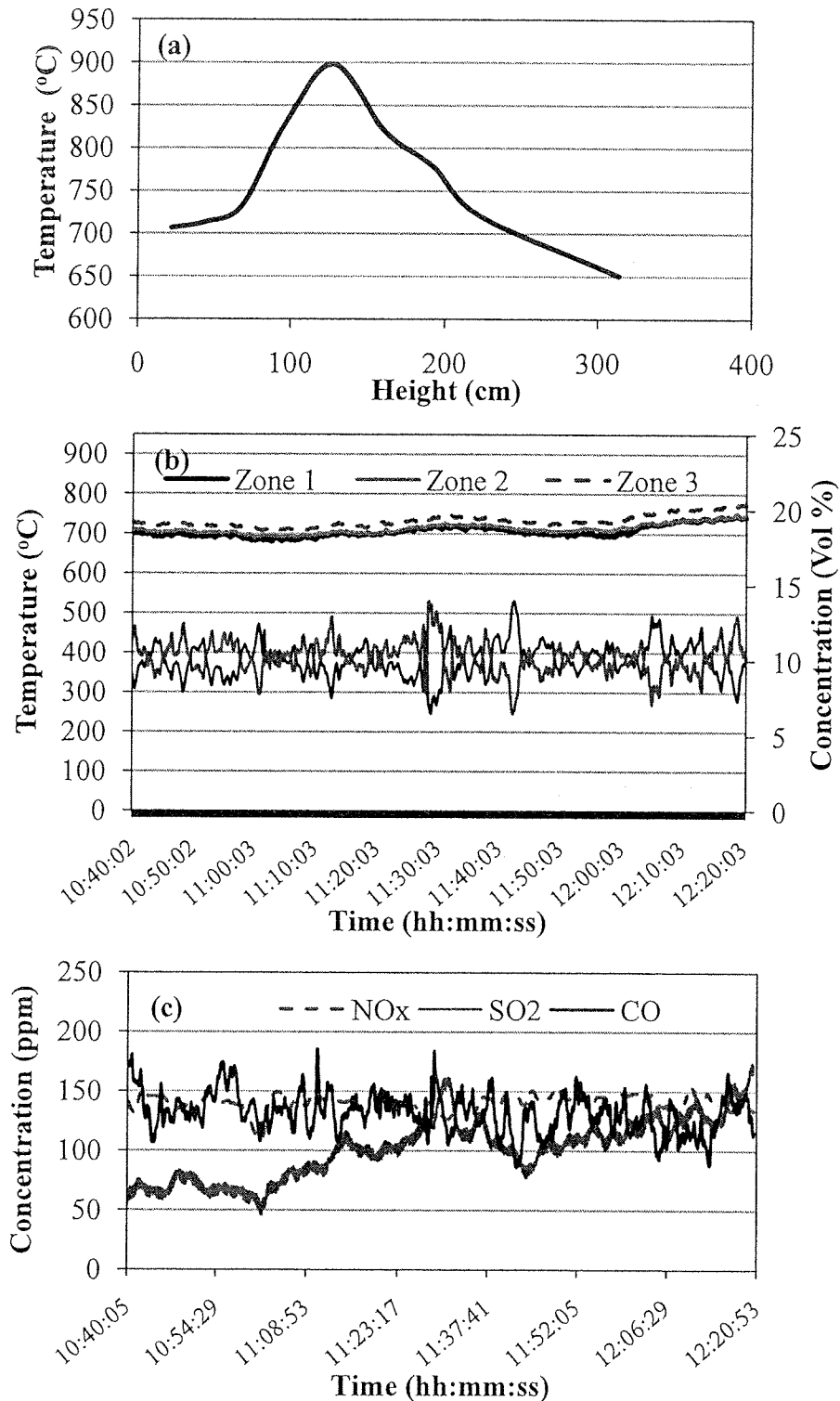


Figure 3.2 Example of the constant operation for the test #23 (50% dried lignite and 50% dried white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) - dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) - concentrations of CO, NO_x and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.73 kg/h (1.29 kg/h dried crushed lignite & 1.42 kg/h dried pine pellets); Air flow: 381.74 L/min (Primary air of 259.99 L/min and Secondary air: 118.66 L/min).

Table 3.4 Summary of the testing parameters

Combustion of individual fuel ^{1,2}						
Test #	Lignite	Peat	White Pine	Excess Air	Fuel feeding rate (kg/h)	Air flow rate (L/min)
1	100%	0%	0%	40%	2.49 (Lignite)	307 (Primary) + 97 (2 nd)
2	0%	100%, crushed	0%	40%	3.69 (Peat)	233 (Primary) + 134 (2 nd)
3	0%	100%, pellets	0%	40%	3.89 (Peat)	234 (Primary) + 135 (2 nd)
4	0%	0%	100%, sawdust	40%	3.64 (Pine)	227 (Primary) + 142 (2 nd)
5	0%	0%	100%, pellets	40%	3.24 (Pine)	260 (Primary) + 109 (2 nd)
Co-firing peat/pine and lignite ²						
6	80%	20%, pellets	0%	40%	2.33 (Lignite) + 0.77 (Peat)	262 (Primary) + 139 (2 nd)
7	80%	0%	20%, pellets	40%	2.33 (lignite) + 0.65 (Pine)	259 (Primary) + 136 (2 nd)
8	50%	50%, pellets	0%	40%	1.45 (Lignite) + 1.92 (Peat)	234 (Primary) + 159 (2 nd)
9	50%	0%	50%, pellets	40%	1.46 (Lignite) + 1.59 (Pine)	267 (Primary) + 114 (2 nd)
10	20%	80%, pellets	0%	40%	0.59 (Lignite) + 3.11 (Peat)	288 (Primary) + 112 (2 nd)
11	20%	0%	80%, pellets	40%	0.58 (Lignite) + 2.55 (Pine)	269 (Primary) + 118 (2 nd)
12	50%	25%, pellets	25%, pellets	40%	1.46(Lig)+0.80(Peat)+0.97(Pine)	255 (Primary) + 132 (2 nd)
13	20%	40%, pellets	40%, pellets	40%	0.58(Lig)+1.27(Peat)+1.56(Pine)	255 (Primary) + 117 (2 nd)
Combustion with a larger excess air ²						
14	100%	0%	0%	60%	2.94 (Lignite)	346 (Primary) + 118 (2 nd)
15	0%	100%, pellets	0%	60%	3.89 (Peat)	346 (Primary) + 118 (2 nd)
16 ⁴	0%	0%	100%, pellets	60%	3.18 (Pine)	245(Primary) + 163 (2 nd)
17	50%	50%, pellets	0%	60%	1.47 (Lignite) + 1.94 (Peat)	234 (Primary) + 210 (2 nd)
18	50%	0%	50%, pellets	60%	1.46 (Lignite) + 1.59 (Pine)	275 (Primary) + 162 (2 nd)
Effect of moisture content ³						
19	100%	0%	0%	40%	2.56 (Lignite)	254 (Primary) + 151 (2 nd)
20	0%	100%, pellets	0%	40%	2.84 (Peat)	255 (Primary) + 124 (2 nd)
21 ⁴	0%	0%	100%, pellets	40%	2.87 (Pine)	248 (Primary) + 114 (2 nd)
22	50%	50%, pellets	0%	40%	1.29 (Lignite) + 1.42 (Peat)	265 (Primary) + 123 (2 nd)
23	50%	0%	50%, pellets	40%	1.29 (Lignite) + 1.44 (Pine)	260 (Primary) + 119 (2 nd)

¹All the tests were operated at a constant heat input of 58.3 MJ/h; The lignite was crushed/sieved into 1-4 mm particles; Peat-crushed was crushed sample (1-4 mm) from peat pellets; White pine pellets (5 mm OD and 40 mm length) were pelletized using steam from sawdust (<4 mm).

²Fuels were as received;

³Fuels for this series of tests were oven dried (105°C for 12 hours to achieve <5 wt% moisture content).

⁴The pine pellets contained <1wt% ‘Ameribond 2x’.

3.3 Results and Discussion

3.3.1 *Effects of Fuel Particle Size*

The effects of fuel particle size on air emissions from fluidized bed combustion were examined using peat in both crushed (1-4 mm) and pellet forms and white pine in sawdust (sieved to <4 mm) and pellet forms, while the combustion was conducted at 40% excess air. **Figure 3.3** presents the emissions of CO₂, CO, SO₂ and NO_x for the four air-dried fuels of white pine (sawdust & pellets) and peat (crushed & pellets). As is clearly shown in the **Figures 3.3a** and **3.3b**, compared to fuels in fine particles combustion of solid fuels (peat and white pine) in pellet form led to a much higher CO₂ accompanied with reduced CO emissions, suggesting higher combustion efficiency. The combustion of pelletized white pine and peat increased the combustion efficiency from 83.3% to 93.7% and 85.1% to 94.6%, respectively, calculated by **Eq. 3.1**. Thus, compared to fine particles (1-4 mm for crushed peat fuel or <4 mm for the pine sawdust), fluidized-bed combustion of solid fuels in the pellet form could achieve a much higher efficiency, likely due to a longer retention time for the pellet fuels within the dense phase of the bubbling fluidized bed combustor. In contrast, in a bubbling fluidized bed fine and light fuel particles could be easily entrained by the fluidizing gas (air), decreasing combustion efficiency due to lowered fuel retention time. The longer retention time of solid fuel in the dense-phase zones (Zones 1, 2 and 3) also means less entrained particles and combustion in the freeboard zones above the dense zones. Accordingly, higher dense-phase temperatures and a more uniform temperature profile along the fluidized-bed column may be predicted for the combustion of pellet fuels, in comparison to the combustion of solid fuels in the finer-particle form. This was actually evidenced by the temperature profiles as shown in **Figure 3.4**. The combustion efficiency of a

solid fuel in a fluidized bed depends on various operating parameters (fuels size, density, moisture content), excess air and configuration of secondary air injection, etc. With proper combination of these parameters ensuring favourable fuel retention and mixing in the dense phase without greatly reducing the combustion temperature, a higher combustion efficiency may be expected.

From **Figures 3.3c** and **3.3d**, the effects of fuel particle sizes on the emissions of SO₂ and NO_x are minimal.

In summary, for fluidized bed combustion solid fuels in pellet form are more advantageous over the fuels in the particle form with respect to combustion efficiency. As a matter of fact, production of briquettes and pellets from biofuels is a growing business in the consumer market, as biomass pellets have several advantages over conventional biomass: easy storage and transport of pellets; higher burning efficiency; lower pollution and dust; and higher volumetric heat values. Therefore, pellet fuels were used in most of the tests in this study, as discussed below.

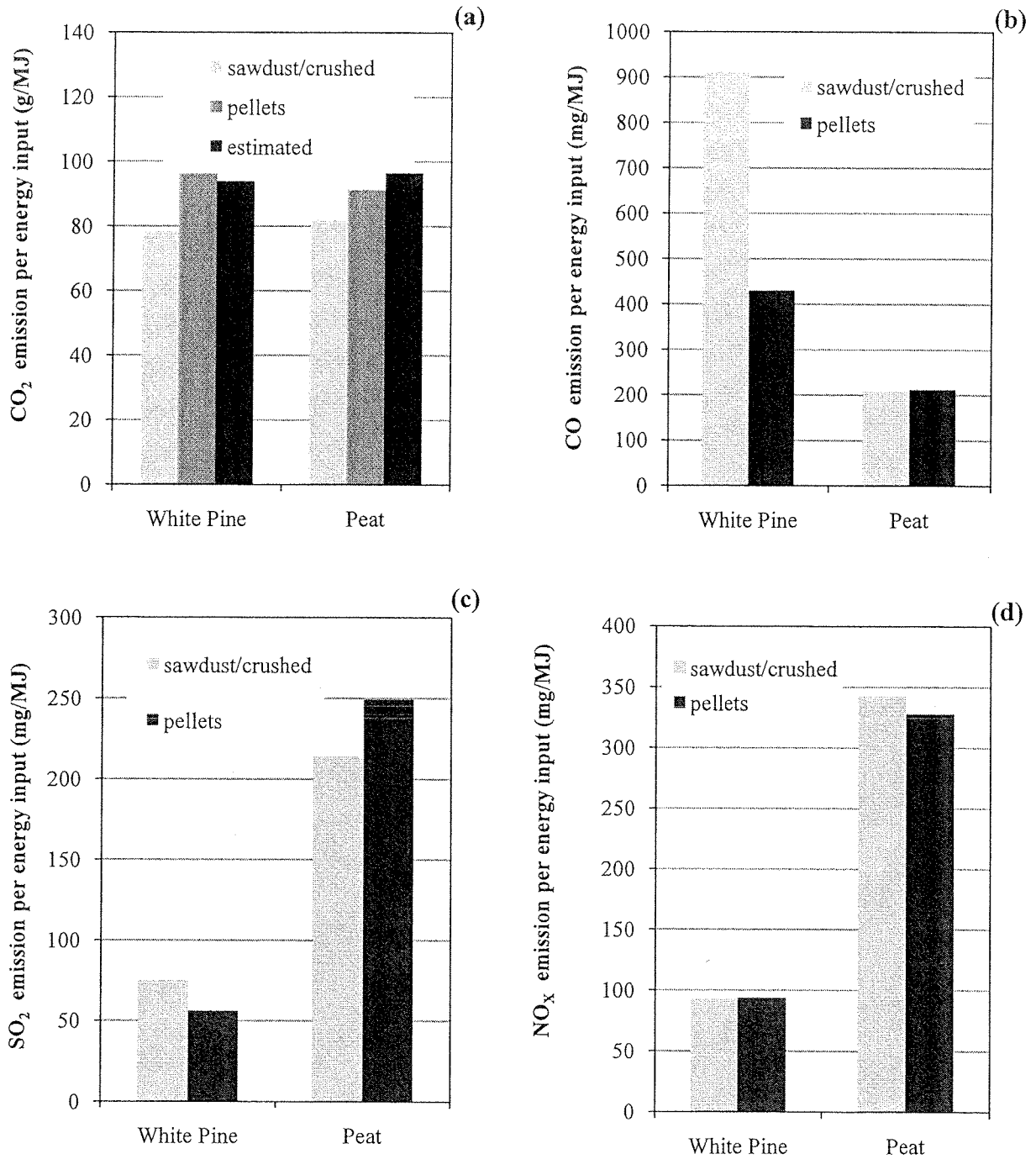


Figure 3.3 Emissions of CO₂ (a), CO (b), SO₂ (c) and NO_x (d) for the as-received/air-dried white pine (sawdust & pellets) and peat (crushed & pellets) at 40% excess air.

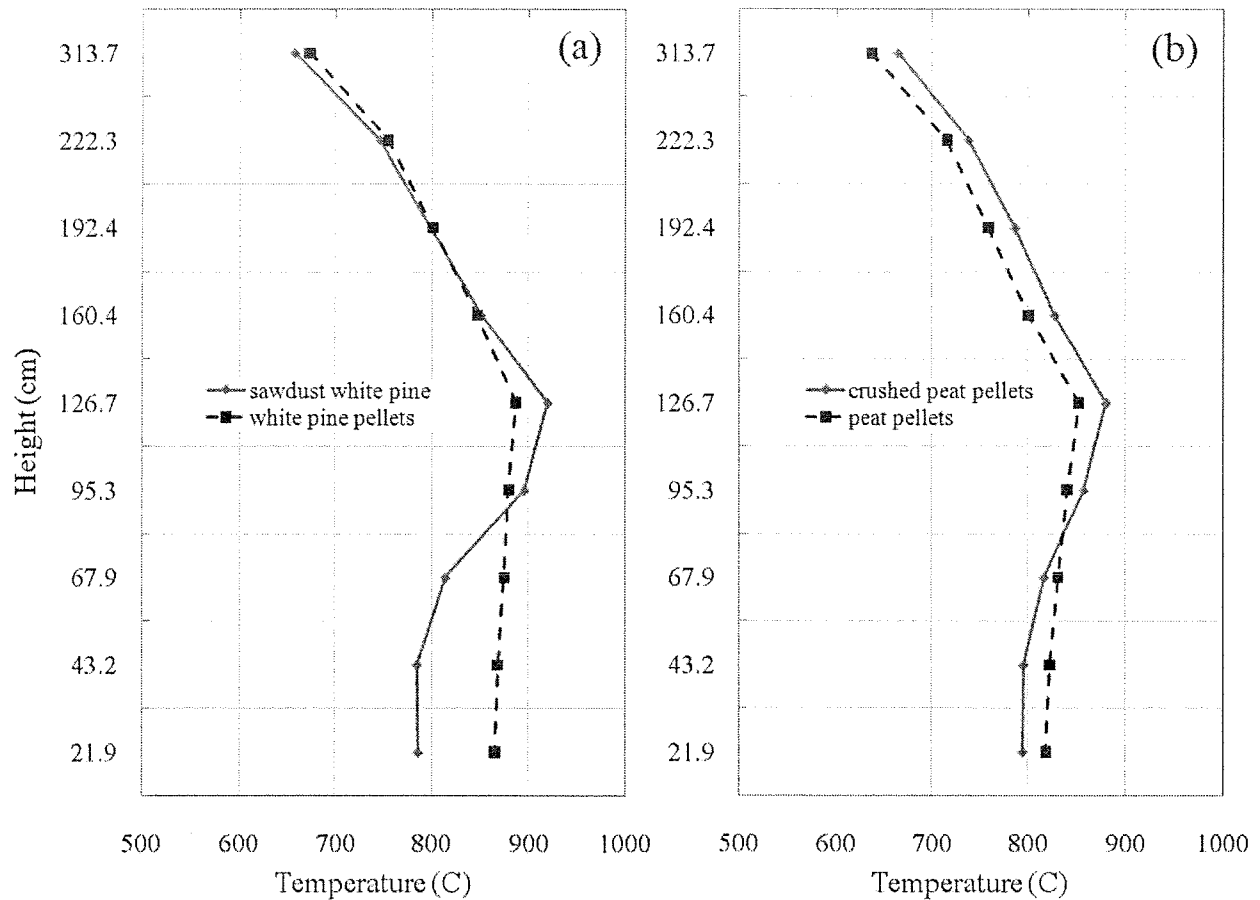


Figure 3.4 Fuel particle size comparative temperature profiles for white pine (a) and peat (b)

3.3.2 Effects of Fuel Blending Ratio

Effects of the ratios (0%, 20%, 50%, 80% and 100% on a thermal basis) of blending white pine or peat pellets with crushed lignite on emissions of CO₂, SO₂ and NO_x are summarized in **Table 3.4**. As shown in the Table, when co-firing lignite with the pine or peat pellets, CO₂ emissions were in a narrow range of 90-99 g/MJ against the blending ratio as the three types of fuels were very similar in the gross heating value (i.e. HHV ~ 21 MJ/kg) and carbon content (~53-59 wt% db), as shown previously in **Table 3.1**. However, the formation of CO from the co-firing varied with varying blend ratios, particularly when co-firing of lignite and white pine pellets. Generally CO emissions increased with increasing the blending ratios (from 0

to 80%) for both the lignite-white pine and lignite-peat blend fuels, leading to slightly reduced combustion efficiencies. We believe this may be accounted for by the higher volatile matters in both white pine (84.5 wt%) and peat (68.6 wt%) fuels, compared to the base fuel of lignite (51.4 wt%) as given previously in **Table 3.1**. In solid fuel combustion, volatile matters would release quickly when being heated up approximately $>300^{\circ}\text{C}$, and be entrained by the air/flue gas stream into the freeboard zones (at reduced temperatures). Thus combustion of a high volatile-containing fuel in a bubbling fluidized bed might lead to a decreased efficiency, as evidenced by the results in **Table 3.5**. Provided optimized configuration of the primary/secondary air ratio and an enough freeboard volume with well insulation, complete combustion of volatile matters is achievable.

Table 3.5: Summary of emissions from co-firing of lignite and white pine or peat at various blending ratios at 40% excess air

Fuel blends	Emissions				η (%)
	CO ₂ (g/MJ)	CO (mg/MJ)	SO ₂ (mg/MJ)	NO _x (mg/MJ)	
100% lignite	99.38	152.57	120.26	353.67	96.9
80% lignite+20% Pine	101.86	115.55	104.15	286.98	96.2
50% lignite+50% Pine	96.28	342.41	85.34	205.93	96.5
20% pine+80% Pine	100.62	528.74	67.35	148.28	94.1
100% pine	99.28	443.85	57.87	96.77	93.7
100% lignite	99.38	152.57	120.26	353.67	96.9
80% lignite+20% peat	101.65	151.90	133.31	350.69	95.7
50% lignite+50% peat	96.90	309.26	142.87	339.63	95.9
20% lignite+80% peat	93.19	651.51	172.56	324.28	93.05
100% peat	94.14	218.70	257.29	338.35	94.57

Although the emissions of SO₂ and NO_x are given in **Table 3.4**, we plotted these emissions versus the fuel blending ratios in **Figures 3.5** and **3.6**. As is clearly shown in **Figures 3.5** and **3.6**, co-firing of lignite and white pine pellets at an increasing blending ratio led to a proportional reduction in both SO₂ and NO_x emissions, which may be explained by the lower S/N-content in the white pine feedstock as previously shown in the fuel analysis (**Table 3.1**). The reduction of SO₂ in co-firing white pine and lignite might also be related to the relatively high concentration of CaO (31.1 wt% db) in the pine ash, as the CaO could react with SO₂ and O₂, or with SO₃ to form CaSO₄ [21]. This result confirms the findings of many previous studies in that co-firing biomass and coal demonstrated a significant decrease in SO₂ emissions [22]. On the contrary, co-firing of peat and lignite resulted in an increase in SO₂ emission (**Figure 3.5**), which was unexpected as the peat contained a lower sulfur content (0.23 wt% db) than that of lignite (0.5 wt% db). The increase in SO₂ emission with increasing the peat blending ratio might be resulted from the much lower ash content for the peat: 2 wt% db for the peat versus 22 wt% for the lignite. As some alkaline ash components such as CaO, MgO, Na₂O, and K₂O could have functioned as the SO₂ absorbents during combustion [21], the lower ash content of the peat fuel might thus account for the higher SO₂ emissions as observed in **Figure 3.5**. As shown in **Figure 3.6**, in co-firing either the white pine or peat pellets and the crushed lignite, the NO_x emission decreased with an increase in the blending ratio, likely due to the lower N contents in white pine (0.1 wt%) and peat (0.81 wt%) than that of lignite (0.91 wt%). These results may suggest that NO_x emissions were directly proportional to the nitrogen contained in the fuels. As discussed before, the NO_x formation during combustion results from the oxidation of fuel-nitrogen (fuel-NO_x) and through thermal oxidation of nitrogen contained in the combustion air (thermal NO_x).

The formation of thermal NO_x is only significant at a very high temperature, usually above 1600°C . Under current experimental conditions (with the maximum combustor temperature of $850\text{-}950^\circ\text{C}$), the formation of thermal NO_x is thus negligible. Namely, the NO_x emissions from the present tests mainly resulted from the fuel-N. As shown in Table 1, the peat and the white pine contain a much lower nitrogen content (0.81 wt% and 0.1 wt%, respectively) than the lignite (0.91 wt%). Consequently, reduction in NO_x emissions was expected when co-firing either the peat or white pine and coal.

Figures 3.7 and **3.8** display the percent reduction in SO_2 and NO_x emissions (lignite baseline level) versus blending ratio of white pine pellets or peat in co-firing air-dried lignite and these alternative fuels. The lignite and white pine pellet blend at 80%-20%, 50%-50%, and 20%-80% resulted in an 13.4%, 29.0%, 44.0% and 18.9%, 41.8%, 58.1% emission reduction for SO_2 and NO_x , respectively. The lignite and peat pellet blend at 80%-20%, 50%-50%, and 20%-80% resulted in an 10.9%, 18.8%, 43.5% emission increase and 0.84%, 3.97%, 8.31% emission reduction for SO_2 and NO_x , respectively.

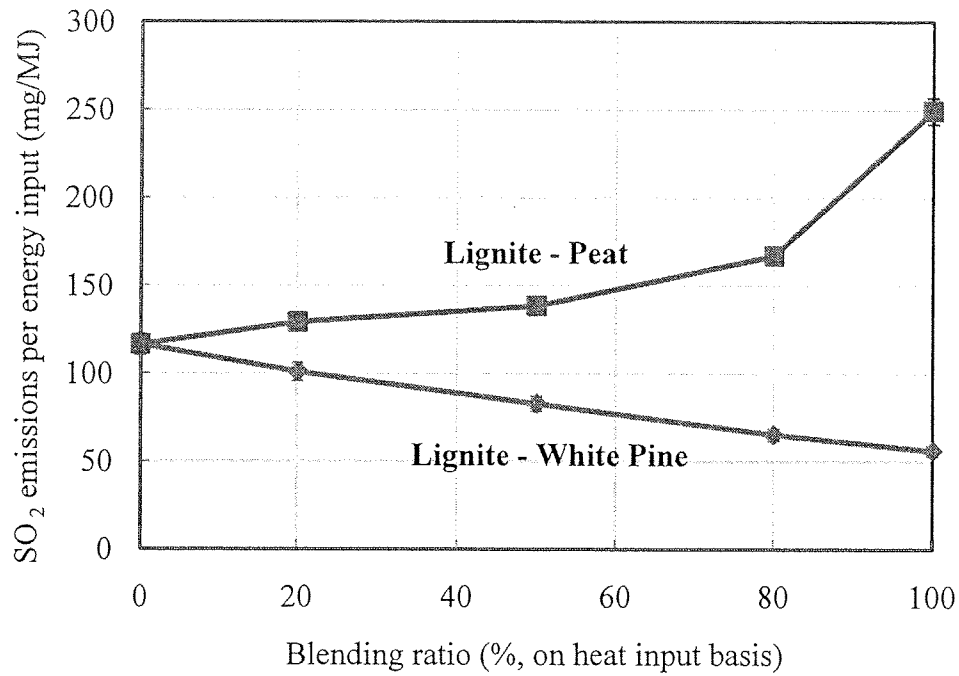


Figure 3.5 - SO₂ emissions per energy input during co-combustion (at 40% excess air) of air-dried crushed lignite blended with white pine pellets or peat pellets at 0%, 20%, 50%, 80%, and 100% on a thermal basis.

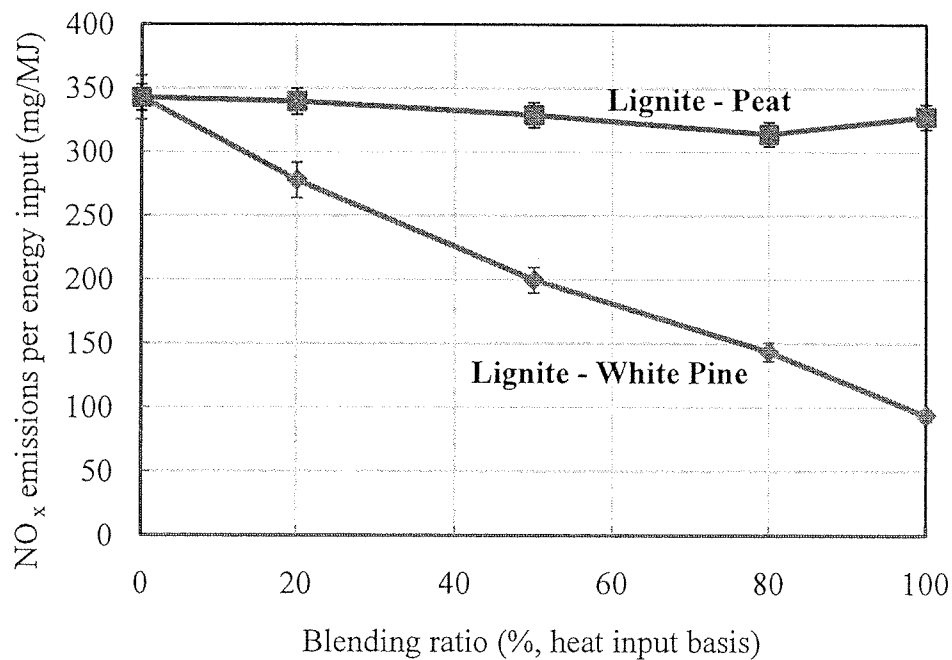


Figure 3.6 - NO_x emissions per energy input during co-combustion (at 40% excess air) of air-dried crushed lignite blended with white pine pellets or peat pellets at 0%, 20%, 50%, 80%, and 100% on a thermal basis.

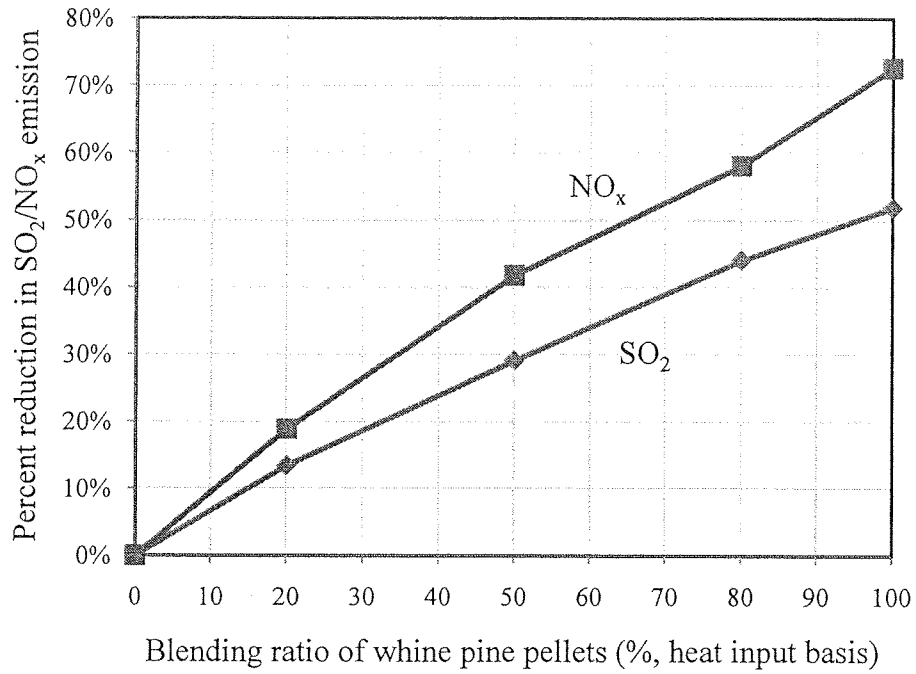


Figure 3.7 – Percent reduction in SO₂ and NO_x emissions (lignite baseline level) versus blending ratio of white pine pellets in co-firing air-dried lignite and white pine pellets.

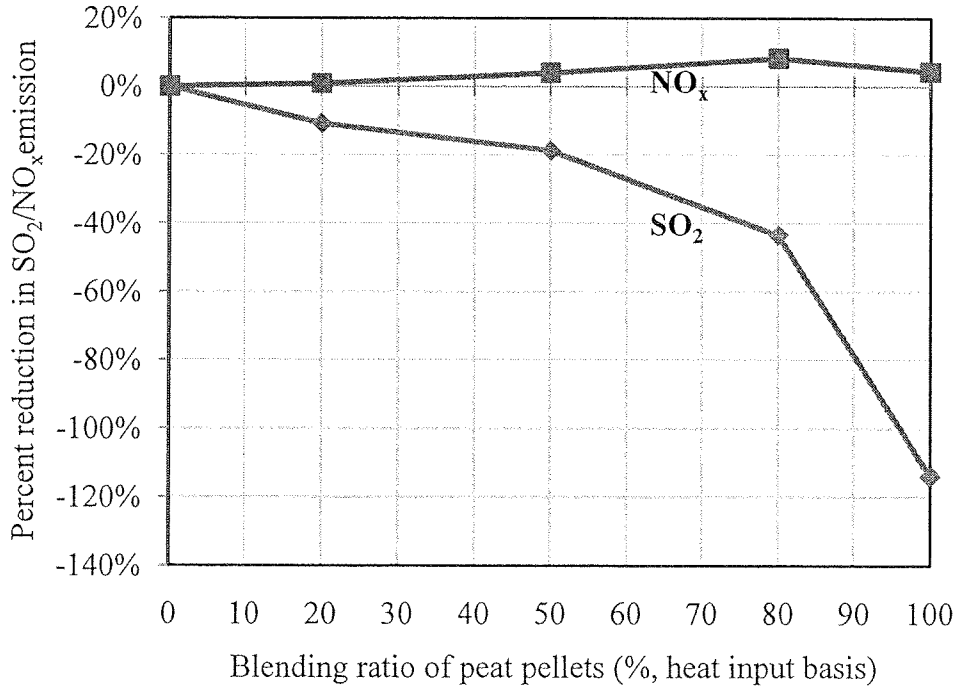


Figure 3.8 – Percent reduction in SO₂ and NO_x emissions (lignite baseline level) versus blending ratio of peat pellets in co-firing air-dried lignite and peat pellets.

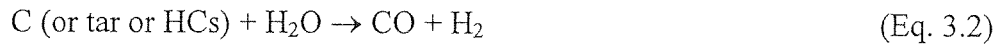
3.3.3 Effects of Fuel Moisture Content

Table 3.6 Effects of fuel moisture content on combustion/co-combustion of crushed lignite and pine/peat pellets at 40% excess air

	Oven dried fuels			Air-dried fuels		
	CO ₂ (g/MJ)	CO (mg/MJ)	η (%)	CO ₂ (g/MJ)	CO (mg/MJ)	η (%)
100% lignite	99.27	145.48	95.3	99.38	152.57	96.9
100% Pine pellets	93.91	80.26	83.7	102.67	459.01	93.7
100% Peat pellets	116.56	117.96	94.2	96.41	224.02	94.6
50% lignite-50% Pine pellets	96.60	60.33	91.2	96.68	343.83	96.5
50% lignite-50% Peat pellets	97.87	82.09	94.1	97.91	312.48	95.9

From the available literature, there is less research work reported so far on the effects of fuel moisture contents on combustion and air emissions in co-firing lignite and wood/peat pellets. In this study, we performed comparative combustion tests with fuels as received (or air-dried fuels) of a moisture content mainly <25 wt% (except peat pellets: 30 wt% moisture content) and the oven-dried fuels (<5 wt% moisture content), in order to examine the influence of moisture content in the fuel or fuel blends on the air emissions. Table 3.6 displays the effects of fuel moisture content on CO₂/CO and combustion efficiency in combustion/co-combustion of crushed lignite and pine/peat pellets at 40% excess air. As a general observation, both CO₂ and CO emissions as well as the combustion efficiency (η) were higher for the air-dried fuels compared to the oven dried fuels. For example, when co-firing 50% lignite-50% Pine pellets, the CO₂, CO emissions and the combustion efficiency (η) were 88.1 g/MJ, 55.02 mg/MJ and 91.2% for the oven-dried fuels, in comparison to the 93.3 g/MJ, 331.80 mg/MJ and 96.5% for the air-dried fuels the CO. The presence of moisture in the fuels thus promotes the combustion of solid

fuels and the CO formation, which may be explained by the following steam gasification/reforming and gas-water shift reactions:



Both reactions are highly endothermic reactions, resulting in lower bed temperatures. This was evidenced by the temperature measurements showing that the freeboard bed temperatures from the combustion of the as-received/air-dried fuels were about 50°C lower than those of the oven dried counterpart, as shown in Figure 3.9. However, the fuel moisture content has minimal influence on the dense-phase bed temperatures, suggesting that the above reactions mainly took place in the freeboard zones.

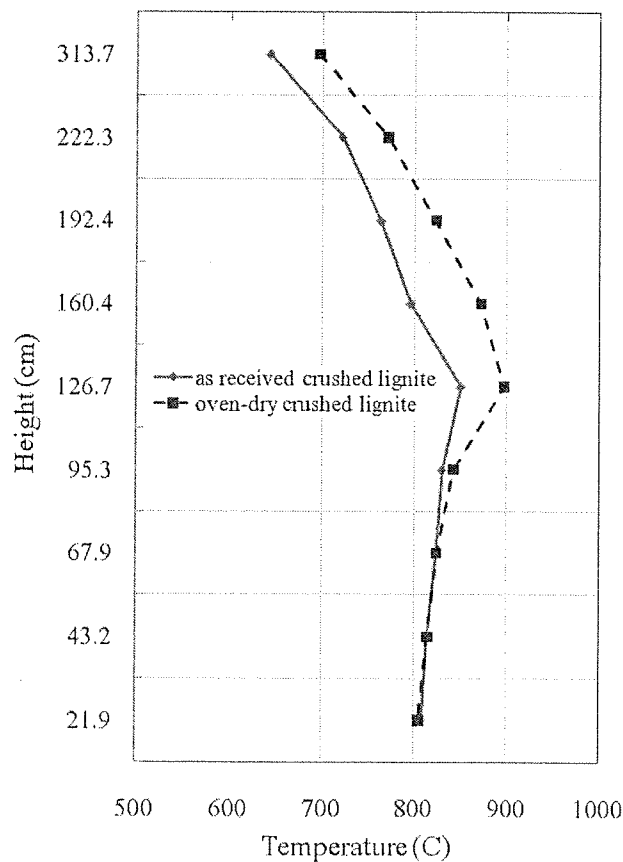


Figure 3.9 – Comparative temperature profile for as received (15.96 % M.C.) and oven-dry (3.29% M.C.) crushed lignite.

Emissions of SO₂ and NO_x per energy input during combustion/co-combustion of crushed lignite and pine/peat pellets with various moisture contents at 40% excess air) are shown in Figures 3.10 and 3.11, respectively. Generally, the combustion of fuels of a higher moisture content led to a decrease in SO₂ emission, but an increase in NO_x emission. With the high-moisture fuels, the present of moisture and the lower bed temperature would favour the formation of H₂S while suppressing the conversion of H₂S into SO₂, hence reducing the SO₂ emissions. The predicted higher formation of H₂S could be verified in our future study by online analysis of the flue gas H₂S composition. On the contrary, the present of moisture and the lower bed temperature would restrict the reduction of NO by hot char particles and CO (both being exothermic reactions, as shown below), hence leading to increased NO_x emissions.



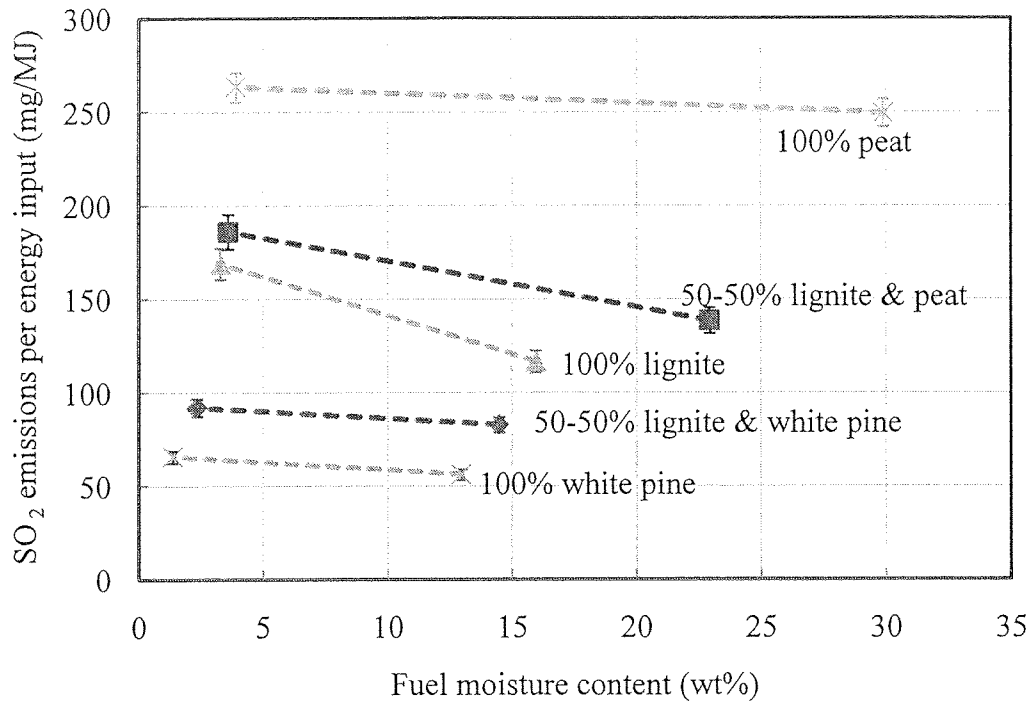


Figure 3.10 SO₂ emissions from co-firing lignite and peat/white pine pellets at 40% excess air versus fuel moisture content

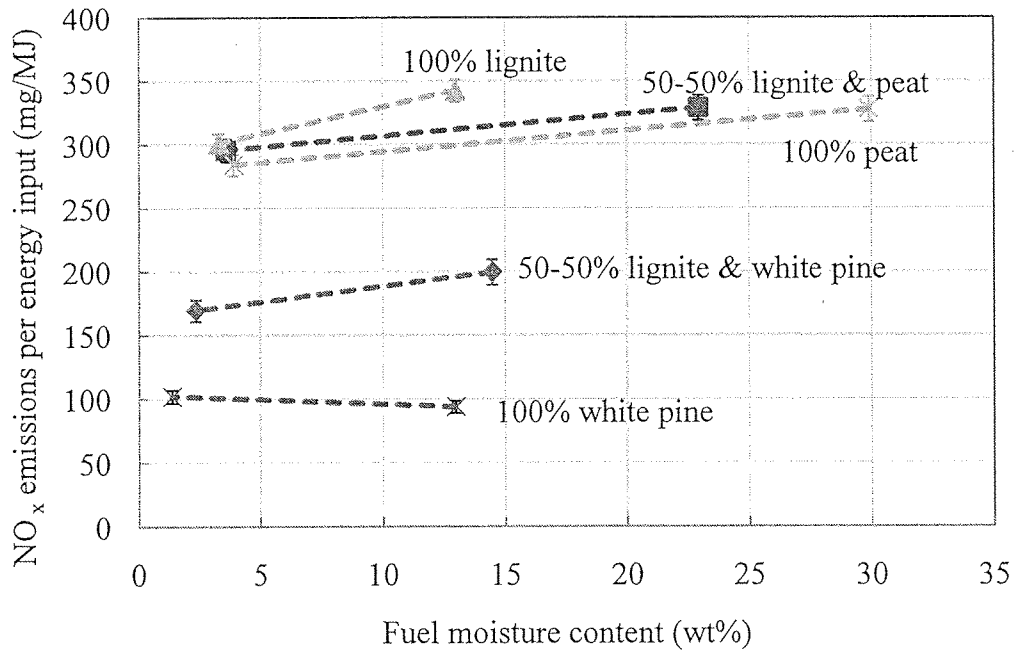


Figure 3.11 NO_x emissions from co-firing lignite and peat/white pine pellets at 40% excess air versus fuel moisture content

3.3.4 *Effects of Excess Air*

Table 3.7 presents the combustion efficiency and emissions of CO₂, CO, SO₂ and NO_x from combustion/co-combustion of crushed lignite and pine/peat pellets at 40% and 60% excess air ratios. The excess air showed evident effects on the emissions of CO₂, CO, SO₂ and NO_x. Generally, the CO₂ and CO emissions and the combustion efficiency were all reduced at a higher excess air ratio. The reduction of CO₂ emission and combustion efficiency were likely due to the decreased retention time of the fuel particles in the fluidized bed reactor and the reduced bed temperatures caused by the larger heat loss at a higher excess air ratio. At a high excess air, the concentration of combustible gases in flue gas (such as CO and HCs) decreased while a considerably increased char may be expected in the exit ash. A higher excess air resulted in an increase in SO₂ emissions for all type of the feedstocks, which might be due to the lower bed temperature and the shorter residence time of SO₂-containing gas in the reaction column, both unfavorable to the desulphurization reactions between SO₂ and the CaO and MgO components in the coal-ash. As the excess air increased from 40% to 60%, NO_x emission increased, as similarly reported by Leckner and Lyngfelt [20]. This might also be due to the lower bed temperature and the shorter residence time of NO_x-containing gas in the high-temperature zones, both unfavorable to the reduction of NO by CO or C at high temperatures. In summary, although excess air is important in achieving combustion efficiency, a too high ratio would lead to reduction in combustion efficiency and increased emissions of SO₂ and NO_x.

Table 3.7 Effects of excess air ratio on the combustion efficiency and emissions from combustion/co-combustion of crushed lignite and pine/peat pellets

Fuel/fuel blends	40% Excess air					60% Excess air				
	CO ₂ (g/MJ)	CO (mg/MJ)	η (%)	SO ₂ (mg/MJ)	NO _x (mg/MJ)	CO ₂ (g/MJ)	CO (mg/MJ)	η (%)	SO ₂ (mg/MJ)	NO _x (mg/MJ)
100% Lignite	99.38	152.57	96.90	120.23	353.66	99.36	126.41	93.30	138.59	441.59
100% Peat	96.41	224.02	94.60	263.53	346.62	105.38	169.77	94.80	267.93	419.41
100% White pine	102.67	459.01	93.70	59.85	100.07	93.91	75.60	85.40	78.45	209.13
50% Lignite-50% Peat	97.91	312.48	95.90	144.32	343.17	97.90	1018.52	95.20	154.52	411.87
50% Lignite-50% white pine	96.68	343.83	96.50	85.69	206.84	97.59	741.78	91.40	107.22	304.38

3.4 Conclusions

Combustion efficiency and air emission from co-firing lignite with biomass or peat in a pilot-scale fluidized bed combustor were studied extensively at varying parameters including particle size of peat and white pine fuels, fuel blending ratios of lignite with peat/white pine, moisture content of the fuels, and excess air. Increase in combustion efficiency and reduction in air emissions could be achieved by properly controlling the co-firing parameters, as summarized below.

- (1) Compared to fine particles (1-4 mm for crushed peat fuel or <4 mm for the pine sawdust), fluidized-bed combustion of solid fuels in the pellet form could achieve a much higher efficiency, likely due to a longer retention time for the pellet fuels within the dense phase of the bubbling fluidized bed combustor. Combustion of crushed lignite and white pine or peat fuels in the pellet form achieved the combustion efficiency of >94%. Moreover, higher dense-phase temperatures and a more uniform temperature profile along the fluidized-bed column were obtained in the combustion of pellet fuels, in comparison to the combustion of solid fuels in the finer-particle form. On the other hand, the effects of fuel particle sizes on the emissions of SO₂ and NO_x were minimal.
- (2) Although increasing the blending ratios (from 0 to 80%) for both the lignite-pine and lignite-peat blend fuels in the co-firing increased CO emissions and reduced slightly the combustion efficiencies, co-firing of lignite and white pine pellets at an increasing blending ratio led to a proportional reduction in both SO₂ and NO_x emissions, which may be explained by the lower

S/N-content in the white pine feedstock. Co-firing of peat and lignite led to an increase in SO₂ emission which is believed due to the lower ash content in the peat fuel compared to that of the lignite, but co-combustion of peat (0-100%) and lignite resulted in reduction in NO_x emission.

- (3) The presence of moisture in the fuels promotes the combustion of solid fuels by the steam gasification/reforming and gas-water shift reactions, leading to increases in combustion efficiency and CO emissions. The overall reaction is endothermic; the freeboard bed temperatures from the combustion of the as-received/air-dried fuels were about 50°C lower than those of the oven dried counterpart. The combustion of fuels of a higher moisture content led to a decrease in SO₂ emission, but an increase in NO_x emission.
- (4) The excess air showed evident effects on combustion efficiency and the emissions of CO₂, CO, SO₂ and NO_x in a fluidized bed combustor. Generally, the CO₂ and CO emissions and the combustion efficiency were all reduced, accompanied by increased emissions of SO₂ and NO_x emissions at a higher excess air ratio (>40%) due to the shorter retention time of the solid fuel and vapour products and lower bed temperatures. To achieve higher combustion efficiency and lower air emissions for combustion/co-combustion in a fluidized bed combustor, a too high excess air ratio should be avoided.

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CHAPTER 4

A Comparative Reactivity and Kinetic Study on the Combustion of Lignite, Woodwaste, Peat and Their Blends

The combustion/co-combustion behaviour and kinetics of lignite, peat and woodwaste (white pine sawdust) and their blends were investigated using non-isothermal thermogravimetric analysis (TGA) technique. The TGA experiments were performed for pure fuels and compared to blended fuels with respect to their performance in air over a temperature range of 25-700°C and at a heating rate of 20°C/min. The overall kinetic de-volatilization-combustion reactions for these fuels and their blends were evaluated using the power law model. Using the DTA data and applying the least square multi-linear regression method, kinetic parameters for the overall devolatilization/combustion reactions including the apparent activation energy (E_a), reaction order (n) and the pre-exponential (A) factor were calculated for each homogeneous fuel and the lignite-peat or lignite-pine sawdust blended fuels (50 wt%-50 wt%%). The wood waste and peat demonstrated a higher reactivity when compared to lignite. The activation energies for lignite, peat, and white pine were determined to be 124.10 kJ/mol, 83.95 kJ/mol, and 98.23 kJ/mol, respectively. Compared with the devolatilization/combustion of homogenous solid fuels, blending peat/white pine with lignite resulted in synergistic effects, enhancing the combustion reactivity of each component fuel.

Keywords: Co-firing; Biomass; Peat; Lignite, Reactivity; Activation Energy.

4.1 Introduction

Biomass is considered carbon-neutral due to its renewability, and increasing the combustion efficiency can significantly reduce the greenhouse gas emissions and extends the resources lifetime. As such, partial substitution of coal with renewable and inexpensive biomass significantly reduces the consumption of fossil fuels and its resulting emissions. Ontario government's regulation to reduce the net CO₂ emissions from fossil fuel power plants has instigated the introduction of co-firing technology. Power plants are increasingly utilizing coal and biomass blends to improve combustion performance and reduce emissions while maintaining production capacities [1]. Although co-firing of coal and biomass is most notably praised for its impact on lowering net CO₂ and SO₂, the formation of NO_x is still strongly dependent on the combustion conditions [2].

Achieving effective operation of combustors, boilers or other thermochemical conversion units requires a thorough knowledge of the thermal behaviour and reactivity of the fuels [3]. Several challenges appear using some biomass fuels, due to the rich alkali and chlorine content present (with the exception of wood biomass), causing operational problems related to low melting temperature of deposits and corrosion [4]. Co-combustion of biomass fuels with peat (may be viewed as a semi-fossil fuel or slowly renewable fuel) and coal may also achieve better control and less deposition and fouling problems when compared with the high ash-containing agricultural residues [5, 6]. Knowledge of the combustion reactivity of the coal-biomass and coal-peat blends is necessary to successfully design new boilers and adapt existing coal boilers to the introduction of biomass/peat fuels.

Combustion reactivity is heavily dependent upon the chemical and physical properties of the fuel, and the behaviour of the inorganic compounds present within fuel, which are of substantial concern due to their catalytic effects [7]. There are three distinct stages of combustion that can be seen in a TGA analysis, as shown in **Figure 4.1**: Drying, devolatilization, and char oxidation [8]. Drying is the process where moisture evaporates at low temperatures (below 100 °C), and vaporization of water consumes the heat released from the combustion process, causing a temperature drop. Devolatilization, also referred to as gasification, is achieved starting at a temperature of approximately 200-300°C. The reactivity and thermal behaviour of a fuel during volatilization is heavily influenced by the amount of volatile matter present. High reactivity is noticed when a fuel contains higher volatile content, which is usually common for biomass fuels. Biomass volatilization creates two main areas of weight loss; a lower temperature shoulder representing the hemicelluloses decomposition and a higher temperature peak representing cellulose decomposition [8]. Softwoods (white pine, white spruce, larch, and hemlock) contain less hemicellulose than hardwoods (birch, beech white, and acacia) resulting in a lower 'hemicellulose shoulder'. A rapid volatilization rate decrease occurs at a 400 °C to 500 °C temperature range, caused by lignin decomposition. The char combustion process follows at temperatures above 500 °C, resulting in a complete oxidation of the fuel. Physical properties such as high porosity and active surface area and low fuel size are determinant factors in increasing homogeneity and reactivity, while enabling better process control.

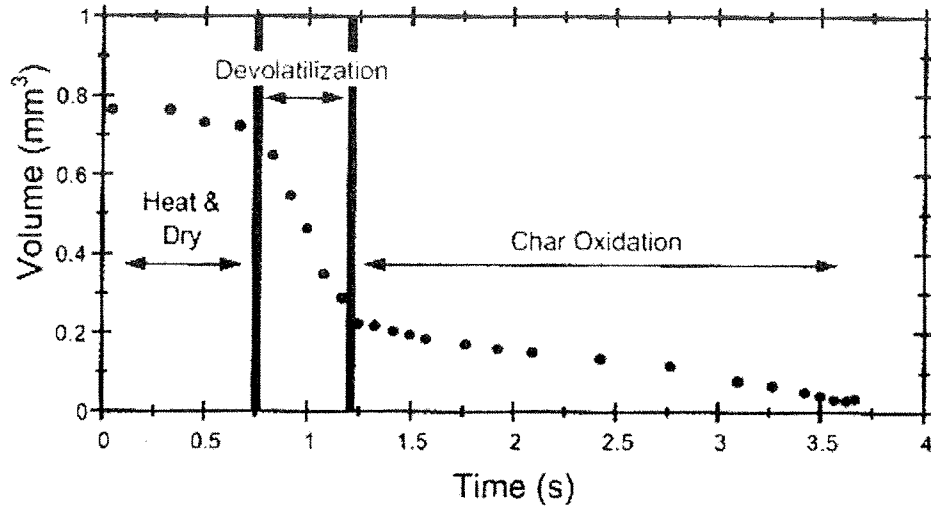


Figure 4.1: Distinct stages of a small biomass particle combustion [8]

Fuel reactivity experimentation is commonly applied using thermo gravimetric analysis, which produces a burning profile by exposing a weighed fuel sample to air at a constantly increasing temperature until it is fully oxidized. The most important characteristic temperatures that result from a burning profile are the ignition/devolatilization and peak temperatures. The ignition/devolatilization temperature is the temperature where the burning profile undergoes a sudden and significant rise after the drying process. The peak temperature is point where the maximum rate of weight loss occurs due to combustion. In previous research by H. Haykiri-Acma et al [9], the TGA burning profile of peat and lignite indicates ignition temperature of 443 °C and 458 °C respectively, demonstrating that the ignition temperature is highly affected by the carbonization degree of the fuel. Based on the TGA/DTG data, the kinetic models have been evaluated using a power law model [9-14], based upon two assumptions: (1) chars are composed of parts with different properties (heterogeneous) and (2) reactivity of a unit surface may vary as the sample is burning [14]. The combustion behaviour of coals and biomass blends is greatly

influenced by the rank of coal and the proportion of biomass in the blend. The influence of biomass is more substantial with lower rank coals such as lignite.

The present work is to investigate the combustion reactivity of lignite and peat or white pine and their blends, by operating an experimental investigation of the combustion behaviour of the individual and blended fuels using non-isothermal thermogravimetric analysis (TGA) technique. In this study, we also compared the experimental results with the simulated results from mathematical models developed in previous work on heterogeneous combustion TGA analysis.

4.2 Experimental

Three different fuels were studied: lignite, peat, and white pine. The lignite was supplied by Ontario Power Generation, and it known for its low sulphur content of 0.50 % wt (db). Peat was provided in a pellet form by Peat Resources Limited, an Ontario based company that is exploring the possibility of the usage of peat as a reliable energy source. The white pine was obtained as sawdust residue produced by a local sawmill in Ontario. All samples were crushed and sieved to obtain a mean size ranging from 70~100 μm . Mixtures of lignite with peat or white pine sawdust were prepared at 50 wt% - 50 wt% blending ratio and analyzed. The proximate/ultimate analyses of the fuels are provided in **Table 4.1**.

The thermogravimetric analysis was performed using a TGA *i* 1000 analyzer. The samples were contained in crucibles that held 35-55 mg for each test. The oxidizing gas used was air, fixed at a flow rate of 30 cc/min flow rate. The sample was heated from 25 °C to 700 °C, at

20 °C/min. Once the temperature had reach 700°C, it was maintained at that temperature for 15 minutes to ensure complete combustion.

Table 4.1 Proximate and ultimate analysis of lignite, peat, and white pine

Fuel Type	Lignite	Peat	White Pine
Proximate analysis (wt%)			
Moisture (%)	30.0	35.8	38.0
Volatile matter (db)	54.0	68.6	84.5
Fixed carbon (db)	23.9	29.4	15.1
Ash (db)	22.0	2.00	0.44
HHV (MJ kg ⁻¹)	23.5	21.4	20.6
Ultimate analysis (wt%, db)			
Carbon	58.8	56.1	52.5
Hydrogen	4.17	5.67	6.32
Sulphur	0.50	0.23	<0.05
Nitrogen	0.91	0.81	0.10
Oxygen (by diff.)	13.6	35.2	40.6

The moisture content does not affect the thermogravimetric analysis as it is evaporated during the early temperature stage (25 – 105 °C) of the analysis. Usually, the higher the fixed carbon content and lower the volatile matter, the less combustion reactivity [9]. Biomass white pine generally contains a high volatile matter content and low ash content in comparison with lignite and peat, as shown in **Table 4.1** which makes white pine a highly reactive fuel.

4.3 Kinetic Model

Thermal decomposition of carbonaceous materials is complicated, involving several parallel and series of reactions described by the independent parallel first-order reactions' model [12-13]. The overall rate of conversion of the N parallel reactions and thermal decomposition for i components can be modelled by:

$$-\frac{dm}{dt} = \sum_i c_i \frac{da_i}{dt} \quad i = 1,2,3 \dots N \quad (\text{Eq. 4.1 [3]})$$

$$\frac{da_i}{dt} = A_i \exp\left(-\frac{E_i}{RT}\right) (1 - a_i) \quad (\text{Eq. 4.2 [3]})$$

$$\left(\frac{dm}{dt}\right)_{sum} = x_1 \left(\frac{dm}{dt}\right)_{lignite} + x_2 \left(\frac{dm}{dt}\right)_{peat/biomass} \quad (\text{Eq. 4.3 [14]})$$

where: m is the sample mass (M) normalized by the initial sample mass (M_0), dm/dt is the mass loss rate; A_i is the pre-exponential factor; i is the component; E_i is the activation energy; da_i/dt is the conversion rate; R is the gas constant; c_i is the contribution of the partial process to the overall mass loss ($m_0 - m_{char}$); T is the temperature; and x is the mass fraction of the fuel.

The fuel samples heterogeneity was included into the model, assuming that chars may be composed of different fractions with different properties and that the reactivity of a unit surface changes during the particle combustion [14]. A char heterogeneity model assuming a char sample could be a mixture of components with varying reactivities is expressed as:

$$m(t) = \sum_{j=1}^n c_j [1 - a_j(t)] + m_{\infty} \quad [m(0) = 1] \quad (\text{Eq. 4.4 [3]})$$

where: m is the sample mass normalized by the initial sample mass; n is the number of components; c_j is the fraction of combustibles in component j ; $a_j(t) = -m = -(M/M_0)$ is the reacted fraction of component j in time t and m_{∞} is the normalized residual mass at the end of the TGA analysis [13].

The model power law model describes the dependence of the reaction rate on the temperature. The fractional burn-off for each component is modelled by the following equation:

$$\frac{da_j}{dt} = A_j \exp\left(-\frac{E_j}{RT}\right) g(P_{O_2}) f(a_j) \quad (\text{Eq. 4.5 [3]})$$

$$f(a_j) = (1 - a_j)^{n_j} \quad (\text{Eq. 4.6 [3]})$$

where A_j is the pre-exponential factor of component j ; E_j is the activation energy of component j ; $g(P_{O_2})$ (0.21 atm) is the partial pressure of oxygen in air; f is the change of surface reactivity as a function of fractional burn-off; and n_j is the reaction order [14].

The determination of the fuel activation energy (E_j), pre-exponential factor (A_j), and reaction order (n) was accomplished using the least squares method for multi-linear regression, as described below:

$$\ln\left[\frac{-d(M/M_0)}{dt}\right] = \ln[A_j \cdot g(P_{O_2})] + \left(-\frac{E_j}{R}\right) \cdot \frac{1}{T} + n \cdot \ln\left(\frac{M}{M_0}\right) \quad (\text{Eq. 4.7})$$

We defined: $Y = a_0 + a_1X_1 + a_2X_2$ (Eq. 4.8)

where $Y = \ln \left[\frac{-d(M/M_0)}{dt} \right]$, $a_0 = \ln[A_j \cdot g(P_{O_2})]$, $a_1 = -\frac{E_j}{R}$, $X_1 = \frac{1}{T}$, $a_2 = n$, and $X_2 = \ln \left(\frac{M}{M_0} \right)$.

Using the experimental values of $\frac{-d(M/M_0)}{dt}$ from the DTA data and applying the least square multi-linear regression method, we could obtain the apparent activation energy (E_j), pre-exponential factor (A_j), and reaction order (n) for each fuel and blend.

4.4 Results and Discussion

4.4.1 Thermal decomposition and modeling of homogenous samples

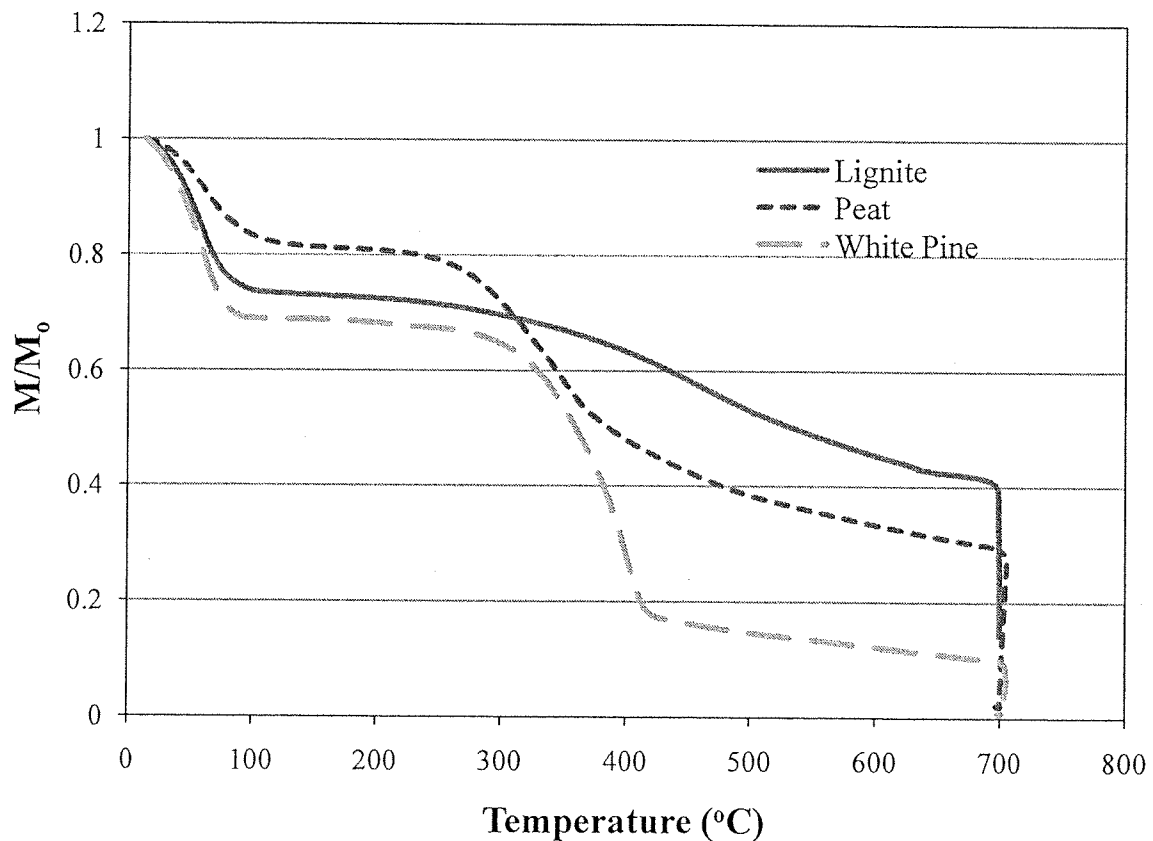


Figure 4.2: Mass fraction of homogenous solid fuels as a function of temperature during the TGA analysis

The thermogravimetric analyses of the homogeneous solid fuels used in this work are demonstrated in **Figure 4.2**. The moisture is evaporated in the drying stage at temperatures lower than 105°C, and then the de-volatilization stage begins at temperatures of approximately 250-350°C, depending on the fuel type, followed by char combustion. The de-volatilization-combustion temperatures are lower for peat and white pine due to their higher reactivity, than that of the lignite.

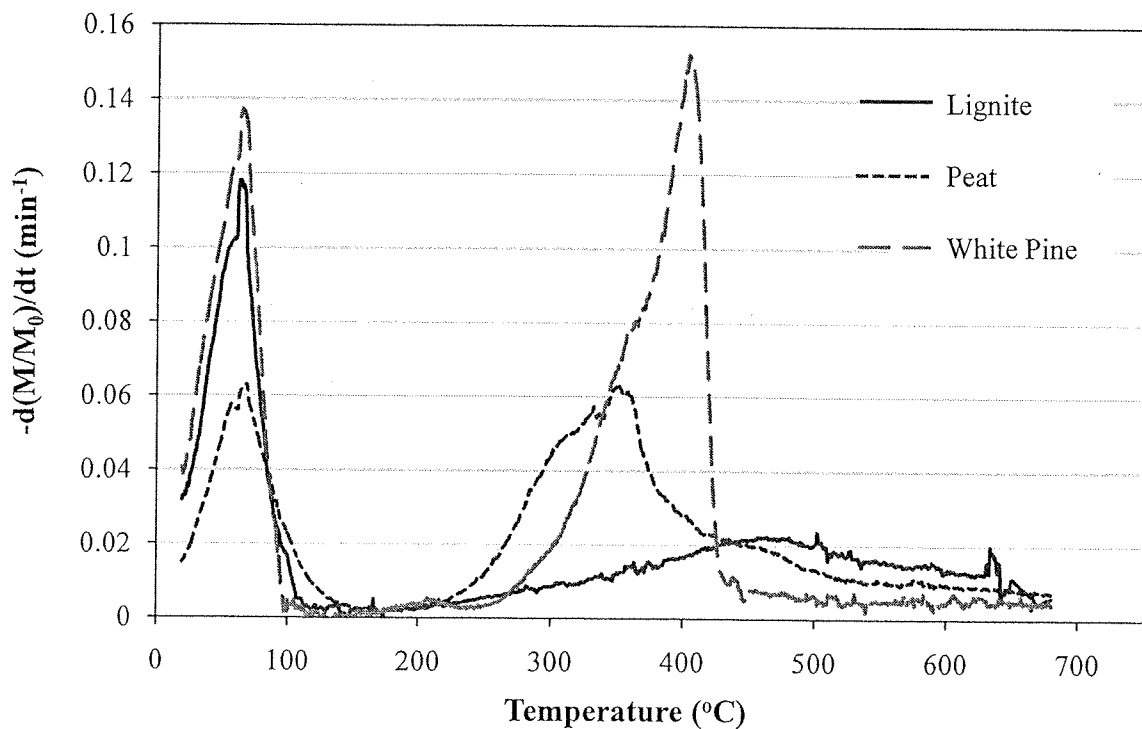


Figure 4.3: Time derivative of mass fraction of solid fuel as a function of temperature based on the data shown in **Figure 4.2**.

Figure 4.3 displays the time derivative of mass fraction of chars ($-d(M/M_0)/dt$) as a function of temperature based on the data shown in **Figure 4.2**. The devolatilization-combustion

peaks are clearly shown in **Figure 4.3**, while the first strong peak in each profile was a result of moisture evaporation. The devolatilization-combustion of peat peaked at the lowest temperature (~ 367 °C), while the devolatilization-combustion of lignite peaked at the highest temperature (~ 496 °C). White pine showed the highest peak-reaction rate ($6.58 \times 10^{-2} \text{ min}^{-1}$), followed by peat ($2.52 \times 10^{-2} \text{ min}^{-1}$), while lignite exhibited a lower peak-reaction rate ($1.01 \times 10^{-2} \text{ min}^{-1}$), as was commonly demonstrated for coal fuels [14].

Table 4.2 – Representative temperatures for devolatilization/combustion of homogenous solid fuels

Sample	Initial temperature T_i (°C)	Temperature at max. rate T_{max} (°C)	Final temperature T_f (°C)
Lignite	308	496	637
Peat	256	367	559
White pine	295	424	463

The temperature at the maximum rate (T_{max}) may be considered as a measure of fuel reactivity, i.e., the lower the (T_{max}) peak temperature, the more reactive the fuel [15]. In this case, the devolatilization/combustion representative temperatures are summarized in **Table 4.2**, which indicates that peat is likely the most reactive fuel, while lignite seems to be the least reactive with the highest T_{max} and lowest reaction rate. The burn-out time, calculated from the devolatilization/combustion peak time-span, showed that it was the shortest for white pine (8.4 min) when compared to that of peat (15.2 min) and lignite (16.5 min). Previous research suggested that for lignite containing a high content of ash (22 wt% db in this study), the last phase of weight loss (above 600-700°C) should be ignored, because it could result from the decomposition of calcium carbonates inherently presented in the coal ash [16].

Using the DTA data and applying the least square multi-linear regression method as described previously in **Eqs. 4.7 & 4.8**, kinetic parameters for the overall devolatilization/combustion reactions including the apparent activation energy (E_a), reaction order (n) and the pre-exponential (A) factor were calculated and are listed in **Table 4.3**. The activation energies for lignite, peat, and white pine were determined to be 124.10 kJ/mol, 83.95 kJ/mol, and 98.23 kJ/mol, respectively. The overall reaction orders were determined to be 2.6, ~2.0 and ~1.0 for the lignite, peat and white pine sawdust, respectively. Similarly as discussed previously on the devolatilization-combustion peak temperatures (Table 4.2), the activation energies calculation also suggests the following order of the reactivity: peat > white wine > lignite. The activity energy values obtained in this study are in the range that has been reported in the literature, e.g., the activation energy of woody biomass was within the 80-150 kJ/mol range [17], and 47 – 139 kJ/mol for various lignite coals [18, 19]. Figure 4.4 compares the experimental and calculated combustion rates for lignite, peat and white pine. The calculated peaks were obtained by applying the experimental kinetic parameters (A , E_a , and n) into Eq. 4.5, and calculating the mass conversion rate with respect to temperature.

Table 4.3 – Calculated kinetic parameters for devolatilization-combustion of homogeneous fuels

Sample	<i>Primary Peak</i>			<i>Secondary Peak</i>		
	A (atm ⁻¹ min ⁻¹)	E_a (kJ/mol)	n	A (atm ⁻¹ min ⁻¹)	E_a (kJ/mol)	n
Lignite	1.35	124.10	2.6	-	-	-
Peat	1.88	83.95	~2.0	1.51	71.18	1.2
White pine	8.70	98.23	~1.0	5.21	85.65	1.1

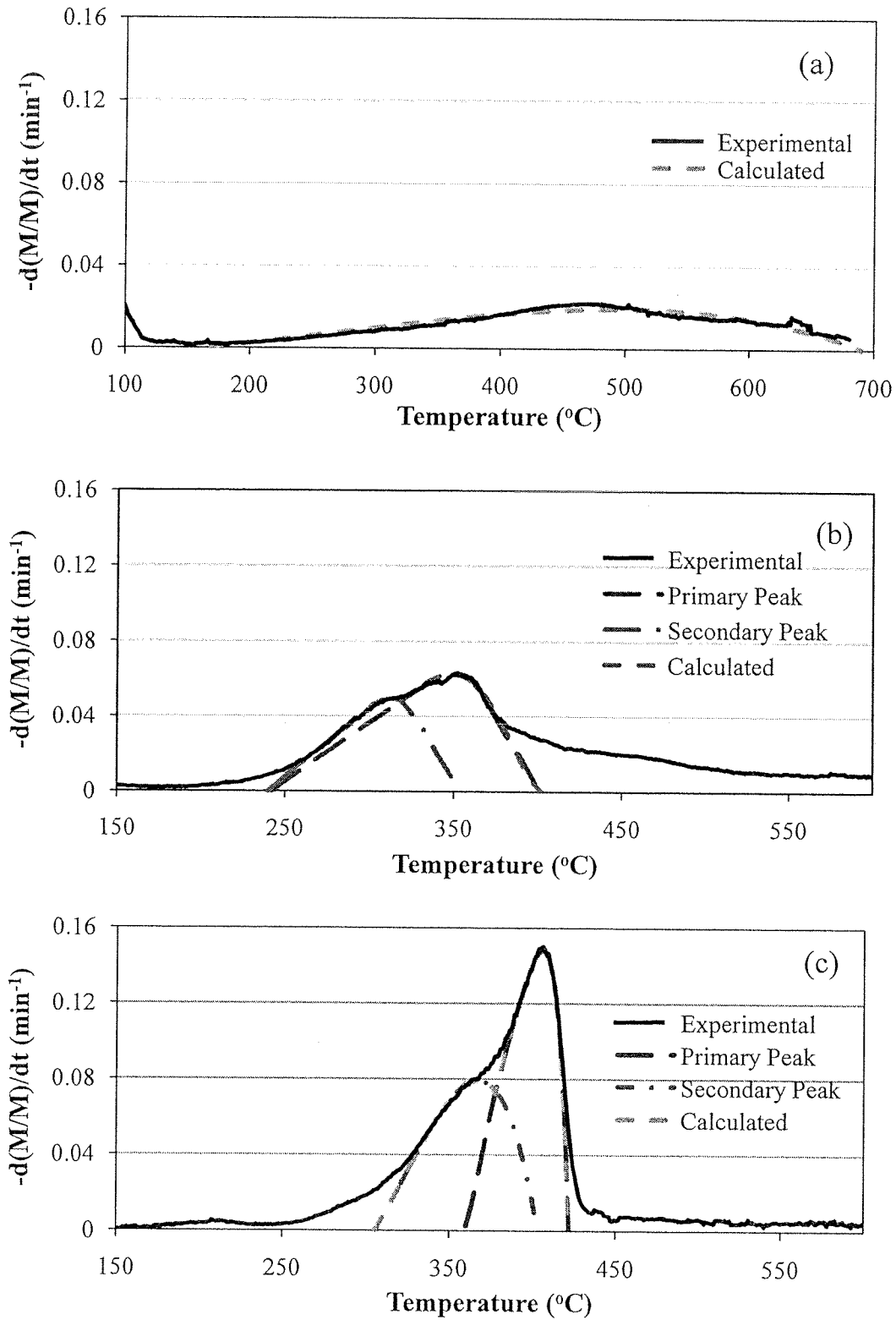


Figure 4.4: Calculated time derivative of mass fraction of solid fuel as a function of temperature based on the data shown in **Table 4.3** for (a) lignite, (b) peat, and (c) white pine.

4.4.2 Thermal decomposition and modeling of heterogeneous samples

The TGA analysis for 50/50 lignite-peat and 50/50 lignite-white pine blends is shown in Figure 4.5. Time derivative of mass fraction of chars as a function of temperature for these two heterogeneous fuel blends are shown in **Figure 4.5**. As clearly displayed in Figure 4.5, the combustion of the fuel mixtures resulted in two distinct peaks, likely resulting from the devolatilization-combustion reactions of each fuel component. The representative temperatures for the devolatilization/combustion of these two fuel blends (50% Lignite-50% Peat and 50% Lignite-50% Pine sawdust) are summarized in **Table 4.4**.

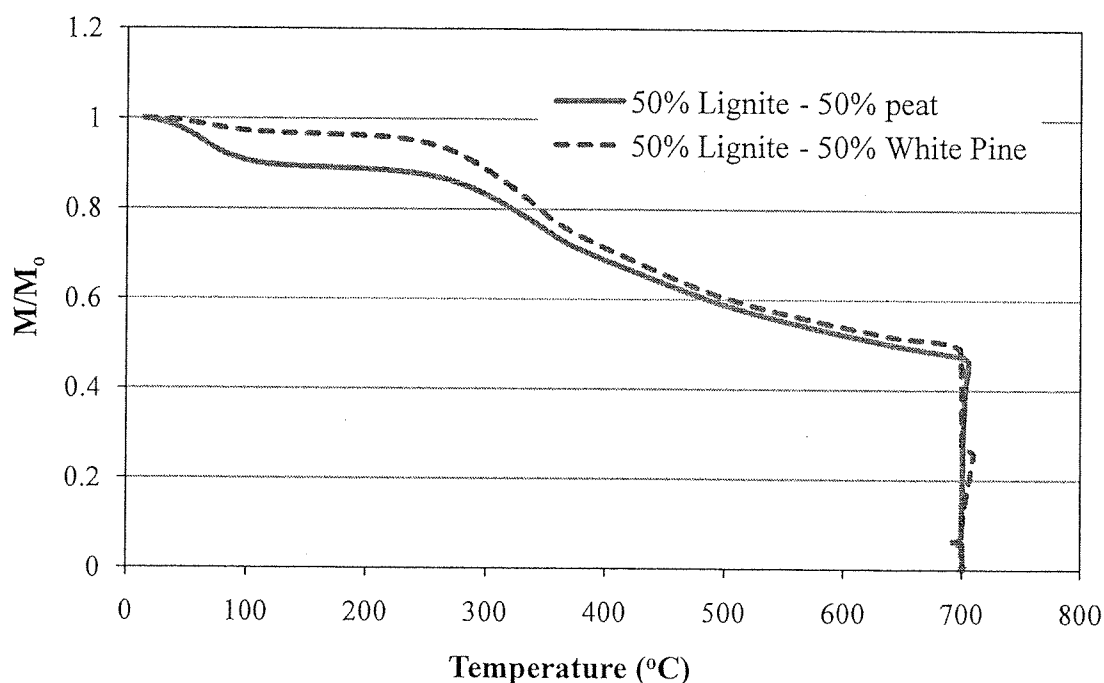


Figure 4.5: Displays the mass fraction of heterogeneous solid fuel-blends (the 50 wt% lignite-50 wt% peat and 50 wt% lignite-50 wt% pine sawdust fuel blends) as a function of temperature during the TGA analysis.

Table 4.4 – The representative temperatures for devolatilization/combustion of heterogeneous fuel-blends

Sample	Initial temp T_i (°C)	First peak $T_{1,max}$ (°C)	Second peak $T_{2,max}$ (°C)	Final temp T_f (°C)
50% lignite - 50% peat	249	352	453	597
50% lignite - 50% white pine	288	359	442	578

Compared with the representative temperatures for devolatilization/combustion of homogenous solid fuels as shown previously in **Table 4.2**, the blending peat/white pine with lignite led to decreases in the peak temperatures of each component fuel, particularly for the lignite. For example with the 50% lignite - 50% peat, the first peak temperature was 352°C (ascribed to peat devolatilization/combustion), slightly lower than that of the homogeneous peat fuel (367 °C), while the second peak temperature was 453°C (ascribed to lignite devolatilization/combustion), significantly lower than that of the homogeneous lignite fuel (496 °C). Similarly with the 50% lignite - 50% peat, the first peak temperature was 359°C (ascribed to white pine devolatilization/combustion), much lower than that of the homogeneous white pine fuel (424°C), while the second peak temperature was 442°C (ascribed to lignite devolatilization/combustion), over 50°C lower than that of the homogeneous lignite fuel (496 °C). The above results might suggest that blending lignite with peat or woody biomass resulted in synergistic effects, enhancing the combustion reactivity of each component fuel.

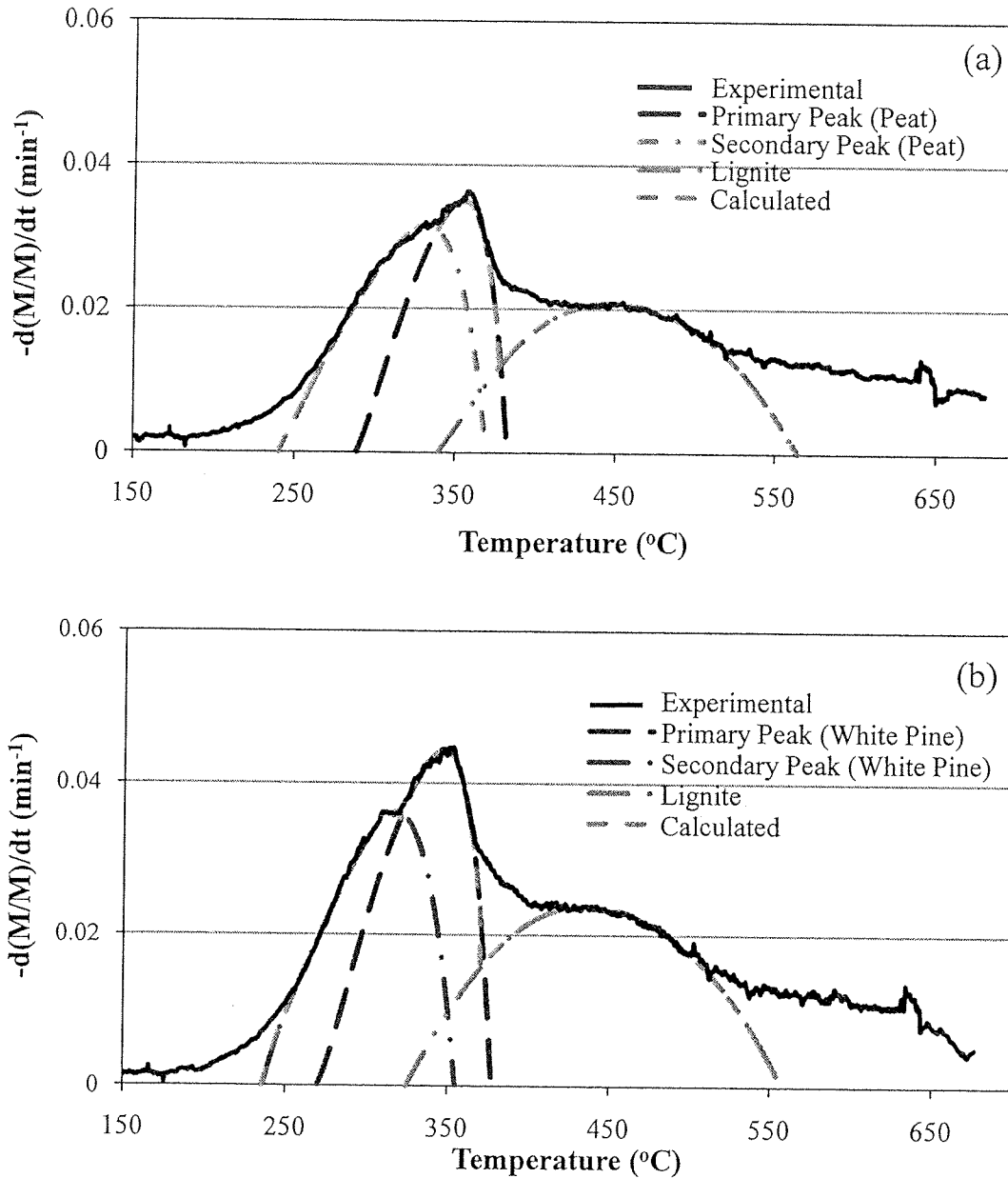


Figure 4.6: Time derivative of mass fraction of solid fuel-blends as a function of temperature for 50% - 50% (by weight) lignite – peat blend (a) and lignite – white pine blend (b).

Using the DTA data (**Figure 4.5**) and applying the least square multi-linear regression method as described previously in **Eqs. 4.7 & 4.8**, the two component peaks were modelled and the modelled component peaks are shown comparatively with the experimental data in **Figure 4.6**

too. The kinetic parameters, including the apparent activation energy (E_a), reaction order (n) and the pre-exponential (A) factor, for the overall devolatilization/combustion reactions for each component peak were calculated and are listed in **Table 4.5**.

Table 4.5 - Kinetic parameters for combustion of heterogeneous fuel blends

Sample	Component 1 (Peat/White Pine)						Component 2 (Lignite)		
	<i>Primary Peak</i>			<i>Secondary Peak</i>			A_2	E_2	n
	A_1	E_1	n	A_1	E_1	n			
	($\text{atm}^{-1} \text{min}^{-1}$)	(kJ/mol)		($\text{atm}^{-1} \text{min}^{-1}$)	(kJ/mol)		($\text{atm}^{-1} \text{min}^{-1}$)	(kJ/mol)	
50% lignite - 50% peat	2.37	80.78	2.9	1.97	70.97	1.5	1.72	114.52	1.3
50% lignite - 50% white pine	3.92	94.55	1.1	2.72	83.75	1.2	1.66	115.03	1.1

Compared with the kinetic parameters for devolatilization/combustion of homogenous solid fuels as shown previously in **Table 4.3**, the blending peat/white pine with lignite led to decreases in the apparent activation energy of each component fuel, particularly for the lignite. For example with the 50% lignite - 50% peat, the activation energy calculated from the first peak ($T_{1,\text{max}} = 352^\circ\text{C}$, ascribed to peat devolatilization/combustion) was 80.78 kJ/mol, slightly lower than that of the homogeneous peat fuel (83.95 kJ/mol), while the activation energy calculated from the second peak ($T_{2,\text{max}} = 453^\circ\text{C}$, ascribed to lignite devolatilization/combustion) was 114.52 kJ/mol, significantly lower than that of the homogeneous lignite fuel (124.1 kJ/mol). Similarly synergistic effects were observed with the 50% lignite - 50% white pine fuel blend. These results

confirm previous coal-biomass blend reactivity research, revealing a significant increase in reactivity for some coal-biomass blends [14].

4.5 Conclusions

(1) The devolatilization-combustion of peat peaked at the lowest temperature (~ 367 °C), while the devolatilization-combustion of lignite peaked at the highest temperature (~ 496 °C). White pine showed the highest peak-reaction rate ($6.58 \times 10^{-2} \text{ min}^{-1}$) and shortest burn-out time (8.4 min), followed by peat ($2.52 \times 10^{-2} \text{ min}^{-1}$ and 15.2 min), while lignite exhibited a lower peak-reaction rate and longest burnout time ($1.01 \times 10^{-2} \text{ min}^{-1}$ and 16.5 min);

(2) The activation energies for lignite, peat, and white pine were determined to be 124.10 kJ/mol, 83.95 kJ/mol, and 98.23 kJ/mol, respectively. The overall reaction orders were determined to be 2.6, ~ 2.0 and ~ 1.0 for the lignite, peat and white pine sawdust, respectively. Activation energies calculation also suggests the following order of the reactivity: peat > white wine > lignite.

(3) Compared with the devolatilization/combustion of homogenous solid fuels, the blending peat/white pine with lignite led to decreases in the peak temperatures and activation energy for the of each component fuel, suggesting that blending lignite with peat or woody biomass resulted in synergistic effects, enhancing the combustion reactivity of each component fuel.

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CHAPTER 5

Conclusions and Recommended Future Work

5.1. Summary and Conclusions

This research work explores the combustion efficiency and flue gas emissions of CO₂, SO₂, and NO_x resulting from combustion and co-combustion of woodwaste (white pine pellets/sawdust), peat and lignite in a 16.19 kW pilot-scale bubbling fluidized bed combustor. The effects of fuel types, different fuel blending ratios, moisture content of feedstock and excess air ratio on air emission rates were examined. The combustion efficiency and reactivity of the biomass, peat and lignite are also investigated. The fuel's reactivity and kinetic parameters for homogeneous and heterogeneous fuels were also evaluated using thermogravimetric analysis (TGA). Some major conclusions are summarized below:

Part-I:

Air Emissions from Co-firing Woodwaste/Peat and Lignite in a Bubbling Fluidized Bed Combustor

Compared to fine particles (1-4 mm for crushed peat fuel or <4 mm for the pine sawdust), fluidized-bed combustion of solid fuels in the pellet form could achieve a much higher efficiency, likely due to a longer retention time for the pellet fuels within the dense phase of the bubbling fluidized bed combustor. Combustion of crushed lignite and white pine or peat fuels in the pellet form achieved the combustion efficiency of >94%. Moreover, higher dense-phase temperatures and a more uniform temperature profile along the fluidized-bed

column were obtained in the combustion of pellet fuels, in comparison to the combustion of solid fuels in the finer-particle form. On the other hand, the effects of fuel particle sizes on the emissions of SO₂ and NO_x were minimal.

Although increasing the blending ratios (from 0 to 80%) for both the lignite-pine and lignite-peat blend fuels in the co-firing increased CO emissions and reduced slightly the combustion efficiencies, co-firing of lignite and white pine pellets at an increasing blending ratio led to a proportional reduction in both SO₂ and NO_x emissions, which may be explained by the lower S/N-content in the white pine feedstock. Co-firing of peat and lignite led to an increase in SO₂ emission which is believed due to the lower ash content in the peat fuel compared to that of the lignite, but co-combustion of peat (0-100%) and lignite resulted in reduction in NO_x emission.

The presence of moisture in the fuels promotes the combustion of solid fuels by the steam gasification/reforming and gas-water shift reactions, leading to increases in combustion efficiency and CO emissions. As these reactions are highly endothermic, the freeboard bed temperatures from the combustion of the as-received/air-dried fuels were about 50°C lower than those of the oven dried counterpart. The combustion of fuels of a higher moisture content led to a decrease in SO₂ emission, but an increase in NO_x emission.

- (1) The excess air showed evident effects on combustion efficiency and the emissions of CO₂, CO, SO₂ and NO_x in a fluidized bed combustor. Generally, the CO₂ and CO emissions and the combustion efficiency were all reduced, accompanied by increased emissions of SO₂ and NO_x emissions at a higher excess air ratio (>40%) due to the shorter retention time of the

solid fuel and vapour products and lower bed temperatures. To achieve higher combustion efficiency and lower air emissions for combustion/co-combustion in a fluidized bed combustor, a too high excess air ratio should be avoided.

Part-II:

A Comparative Reactivity and Kinetic Study on the Combustion of Lignite, Woodwaste, Peat and Their Blends

- (1) The devolatilization-combustion of peat peaked at the lowest temperature (~ 367 °C), while the devolatilization-combustion of lignite peaked at the highest temperature (~ 496 °C). White pine showed the highest peak-reaction rate ($6.58 \times 10^{-2} \text{ min}^{-1}$) and shortest burn-out time (8.4 min), followed by peat ($2.52 \times 10^{-2} \text{ min}^{-1}$ and 15.2 min), while lignite exhibited a lower peak-reaction rate and longest burnout time ($1.01 \times 10^{-2} \text{ min}^{-1}$ and 16.5 min);
- (2) The activation energies for lignite, peat, and white pine were determined to be 124.10 kJ/mol, 83.95 kJ/mol, and 98.23 kJ/mol, respectively. The overall reaction orders were determined to be 2.6, ~ 2.0 and ~ 1.0 for the lignite, peat and white pine sawdust, respectively. Activation energies calculation also suggests the following order of the reactivity: peat > white wine > lignite.
- (3) Compared with the devolatilization/combustion of homogenous solid fuels, the blending peat/white pine with lignite led to decreases in the peak temperatures and activation energy for the of each component fuel, suggesting that blending lignite with peat or woody biomass resulted in synergistic effects, enhancing the combustion reactivity of each component fuel.

5.2. Recommendations for Future Work

The pilot scale co-combustion in a bubbling fluidized bed, which has shown promising low SO₂ and NO_x emission results for lignite and white pine blends. Co-firing with biomass also reduces fossil-CO₂ emission proportional to the biomass blend, assuming biomass-CO₂ is negligible. Even though the research results have demonstrated several positive benefits to co-firing biomass with lignite, several other factors need to be considered and researched to fully assess co-firing.

- Although biomass is advantageous in reducing air emissions, it would potentially cause unit corrosion and other ash-related problems (slagging, fouling, etc.) on long term usage due to high chlorine content and high contents of alkali and alkaline earth metals. It is important to run long term co-firing tests to assess the corrosion and fouling issues.
- In addition to olivine sand, other new bed material with catalytic effects on NO_x reduction or SO₂ absorbent materials (such as calcined lime stone) may be tested to further reduce the SO₂ and NO_x emissions.
- Combustion reactivity studies using TGA technique can be further explored at various blending ratios of coal/biomass or coal/peat to obtain the optimum blending ratios with respect to the lowest de-volatilization/combustion activation energy.

Appendix

Table 3.4 Summary of the testing parameters

Combustion of individual fuel^{1,2}

Test #	Lignite	Peat	White Pine	Excess Air	Fuel feeding rate (kg/h)	Air flow rate (L/min)
1	100%	0%	0%	40%	2.49 (Lignite)	307 (Primary) + 97 (2 nd)
2	0%	100%, crushed	0%	40%	3.69 (Peat)	233 (Primary) + 134 (2 nd)
3	0%	100%, pellets	0%	40%	3.89 (Peat)	234 (Primary) + 135 (2 nd)
4	0%	0%	100%, sawdust	40%	3.64 (Pine)	227 (Primary) + 142 (2 nd)
5	0%	0%	100%, pellets	40%	3.24 (Pine)	260 (Primary) + 109 (2 nd)

Co-firing peat/pine and lignite²

6	80%	20%, pellets	0%	40%	2.33 (Lignite) + 0.77 (Peat)	262 (Primary) + 139 (2 nd)
7	80%	0%	20%, pellets	40%	2.33 (lignite) + 0.65 (Pine)	259 (Primary) + 136 (2 nd)
8	50%	50%, pellets	0%	40%	1.45 (Lignite) + 1.92 (Peat)	234 (Primary) + 159 (2 nd)
9	50%	0%	50%, pellets	40%	1.46 (Lignite) + 1.59 (Pine)	267 (Primary) + 114 (2 nd)
10	20%	80%, pellets	0%	40%	0.59 (Lignite) + 3.11 (Peat)	288 (Primary) + 112 (2 nd)
11	20%	0%	80%, pellets	40%	0.58 (Lignite) + 2.55 (Pine)	219 (Primary) + 118 (2 nd)
12	50%	25%, pellets	25%, pellets	40%	1.46(Lig)+0.80(Peat)+0.97(Pine)	255 (Primary) + 132 (2 nd)
13	20%	40%, pellets	40%, pellets	40%	0.58(Lig)+1.27(Peat)+1.56(Pine)	255 (Primary) + 117 (2 nd)

Combustion with a larger excess air²

14	100%	0%	0%	60%	2.94 (Lignite)	346 (Primary) + 118 (2 nd)
15	0%	100%, pellets	0%	60%	3.89 (Peat)	346 (Primary) + 118 (2 nd)
16 ⁴	0%	0%	100%, pellets	60%	3.18 (Pine)	245(Primary) + 163 (2 nd)
17	50%	50%, pellets	0%	60%	1.47 (Lignite) + 1.94 (Peat)	234 (Primary) + 210 (2 nd)
18	50%	0%	50%, pellets	60%	1.46 (Lignite) + 1.59 (Pine)	275 (Primary) + 162 (2 nd)

Effect of moisture content³

19	100%	0%	0%	40%	2.56 (Lignite)	254 (Primary) + 151 (2 nd)
20	0%	100%, pellets	0%	40%	2.84 (Peat)	255 (Primary) + 124 (2 nd)
21 ⁴	0%	0%	100%, pellets	40%	2.87 (Pine)	248 (Primary) + 114 (2 nd)
22	50%	50%, pellets	0%	40%	1.29 (Lignite) + 1.42 (Peat)	265 (Primary) + 123 (2 nd)
23	50%	0%	50%, pellets	40%	1.29 (Lignite) + 1.44 (Pine)	260 (Primary) + 119 (2 nd)

¹All the tests were operated at a constant heat input of 58.3 MJ/h; The lignite was crushed/sieved into 1-4 mm particles; Peat-crushed was crushed sample (1-4 mm) from peat pellets; White pine pellets (5 mm OD and 40 mm length) were pelletized using steam from sawdust (<4 mm).

²Fuels were as received;

³Fuels for this series of tests were oven dried (105°C for 12 hours to achieve <5 wt% moisture content).

⁴The pine pellets contained <1wt% ‘Ameribond 2x’.

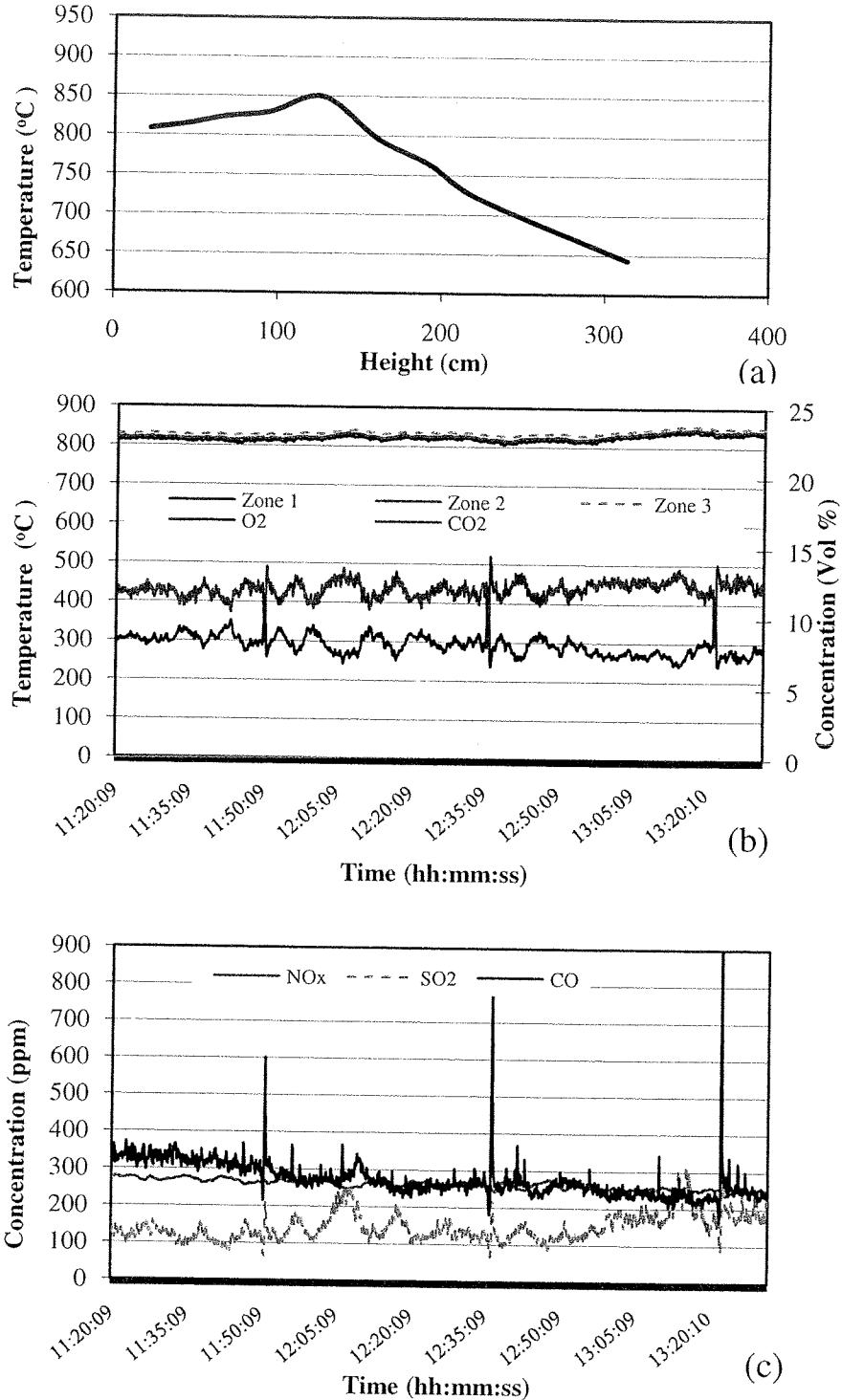


Figure A.1 – Test #1 (100% as received lignite at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.49 kg/h; air flow: 404 L/min (Primary air of 307 L/min and Secondary are: 97 L/min).

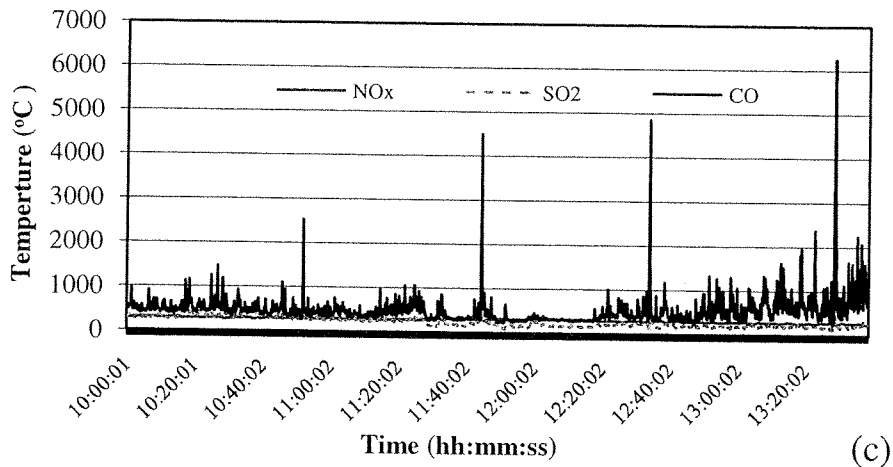
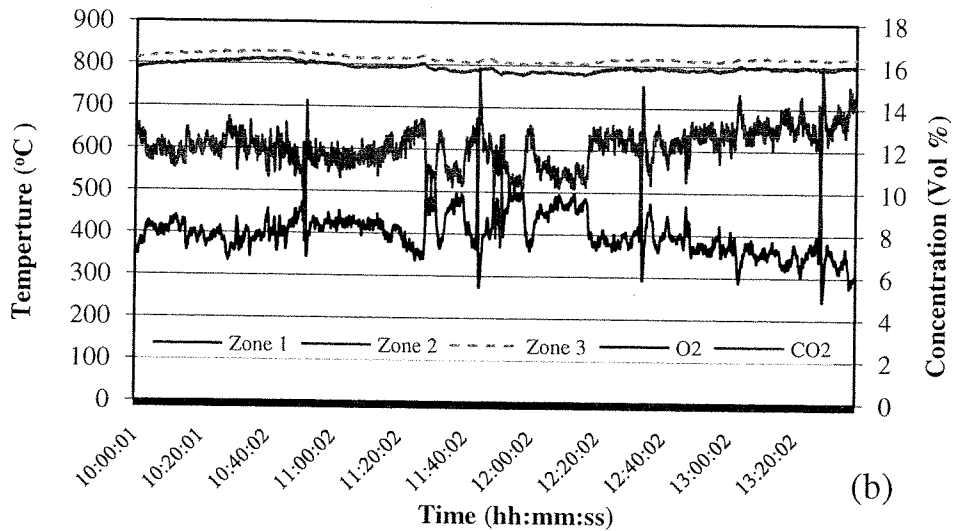
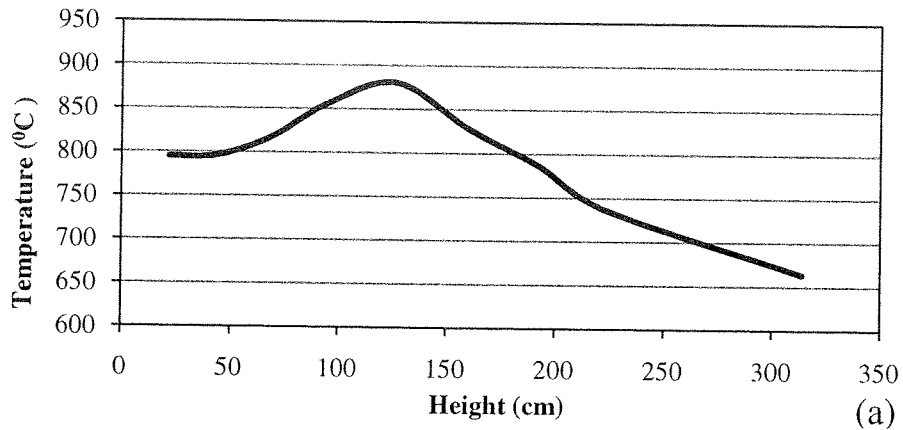


Figure A.2 – Test #2 (100% as received crushed peat at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.69 kg/h; air flow: 367 L/min (Primary air of 233 L/min and Secondary are: 134 L/min).

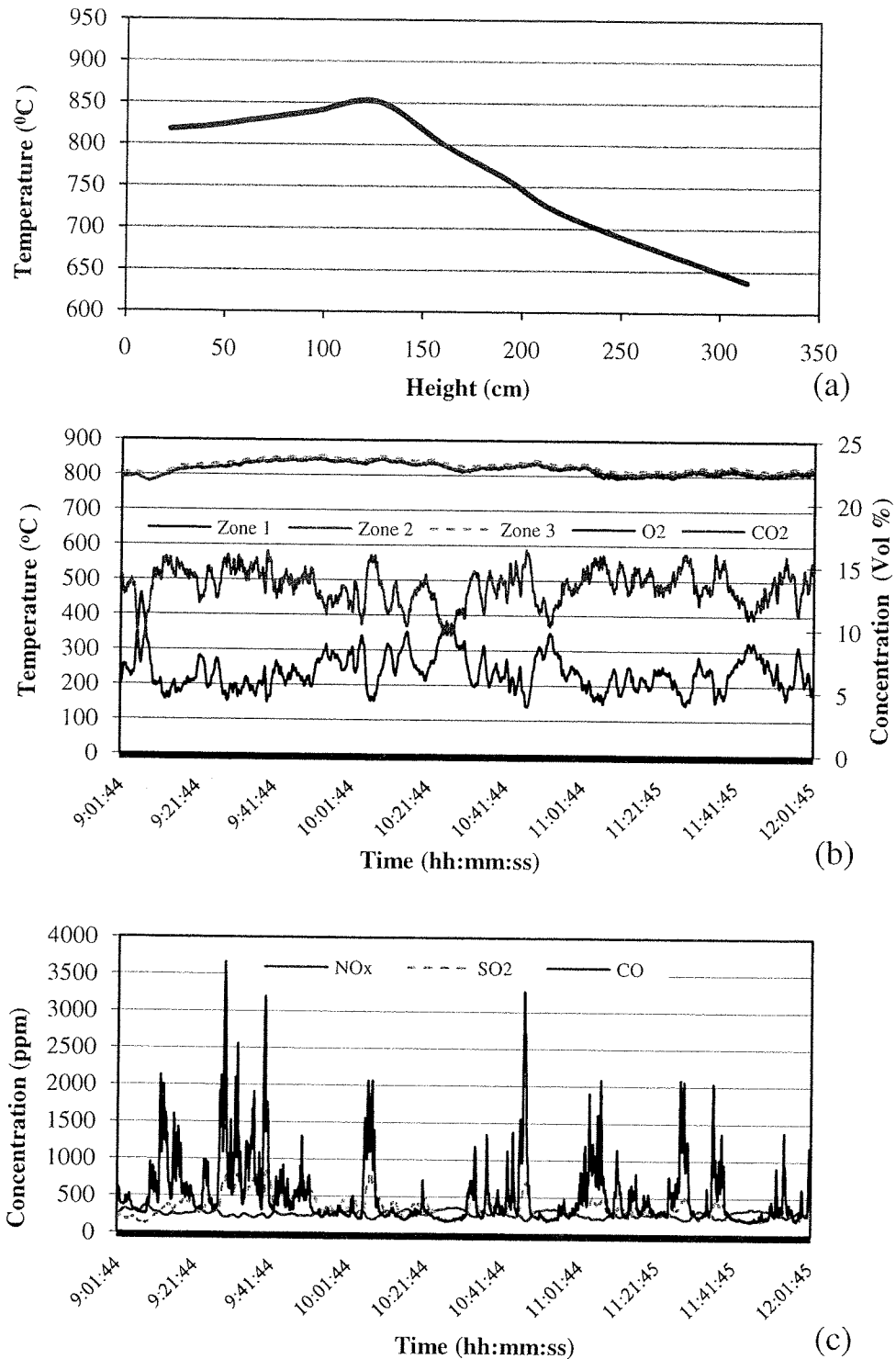


Figure A.3 – Test #3 (100% as received peat at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.89 kg/h; air flow: 369 L/min (Primary air of 234 L/min and Secondary are: 135 L/min).

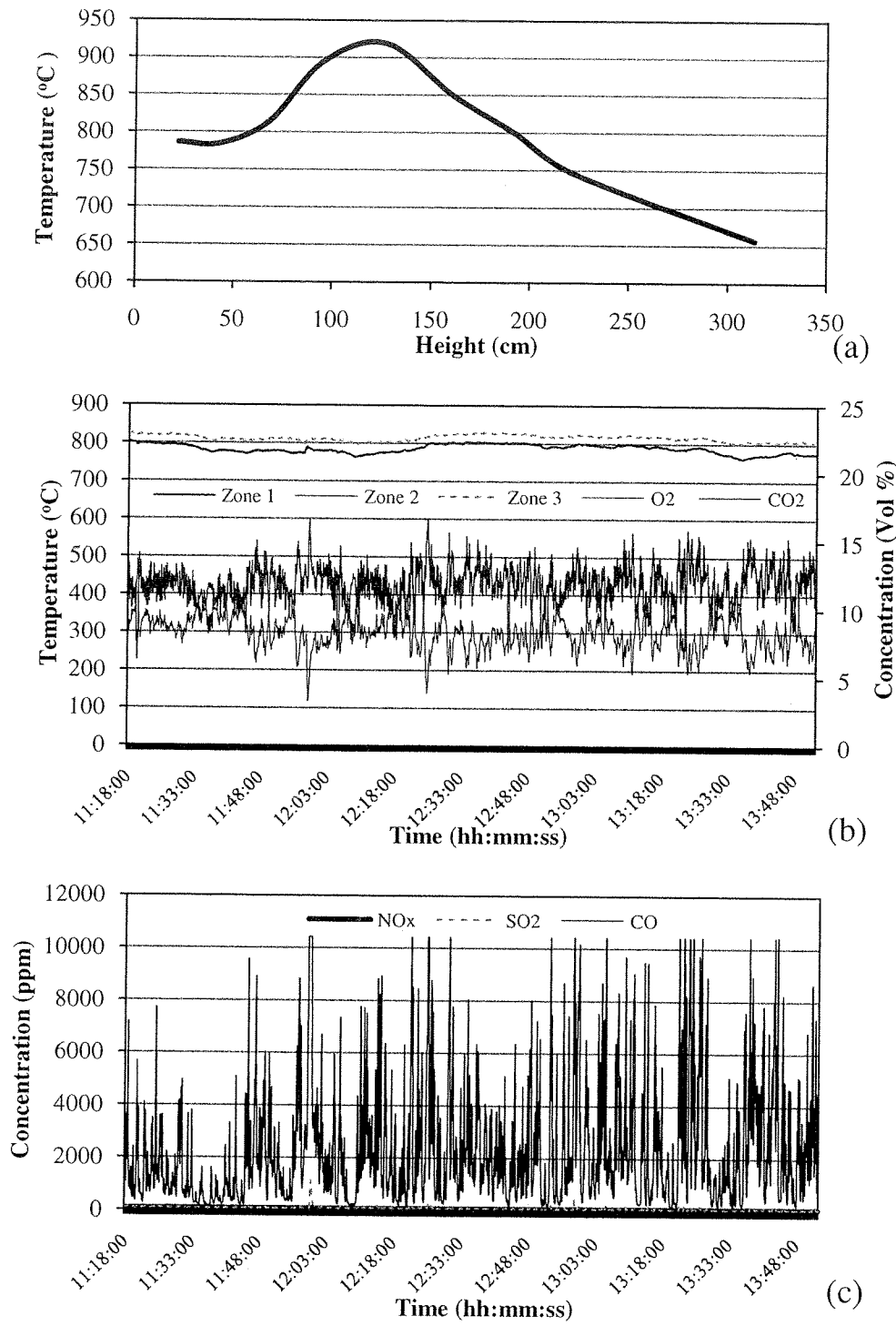


Figure A.4 – Test #4 (100% as received white pine sawdust at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.64 kg/h; air flow: 369 L/min (Primary air of 227 L/min and Secondary are: 142 L/min).

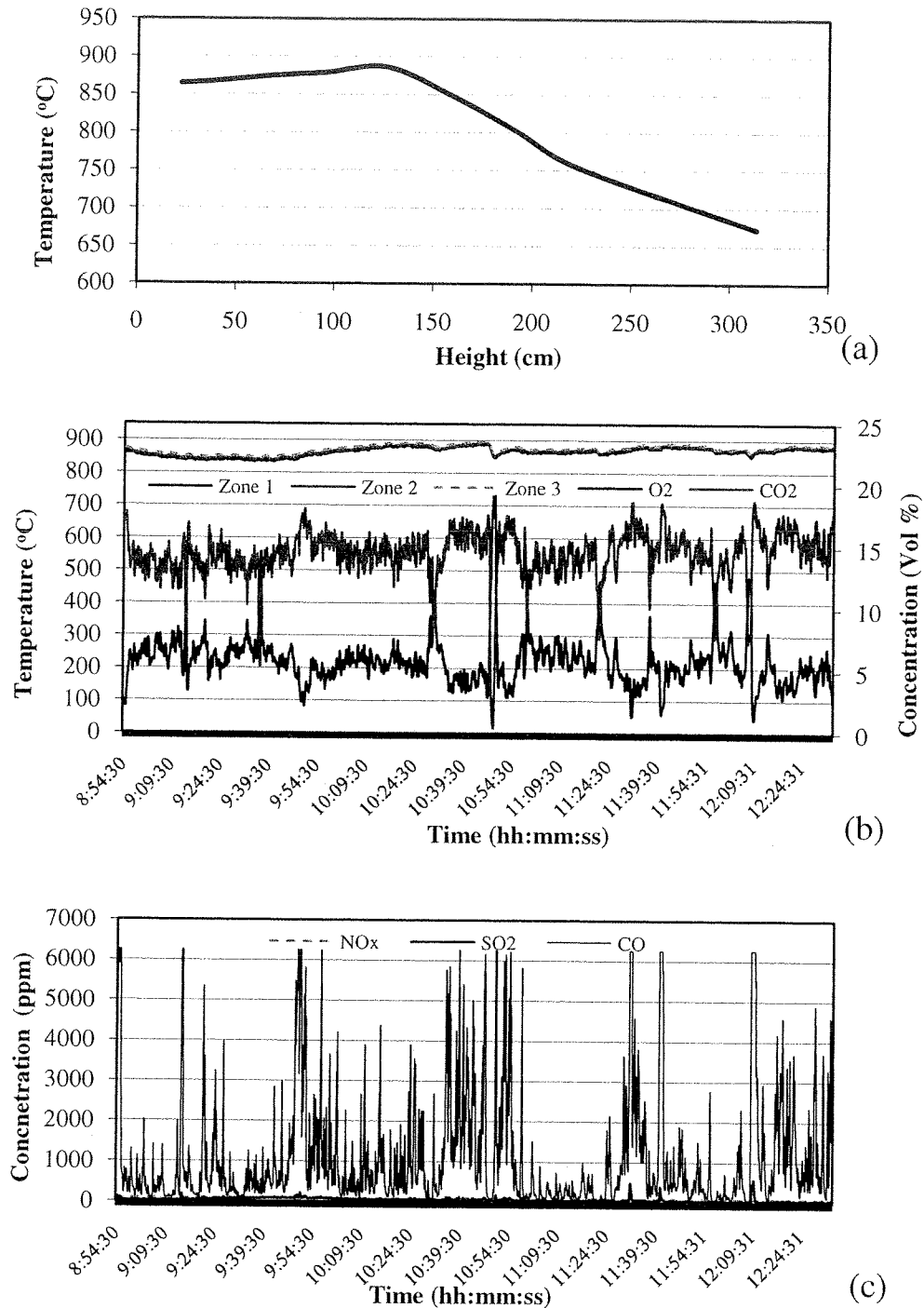


Figure A.5 – Test #5 (100% as received white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.24 kg/h; air flow: 369 L/min (Primary air of 260 L/min and Secondary are: 109 L/min).

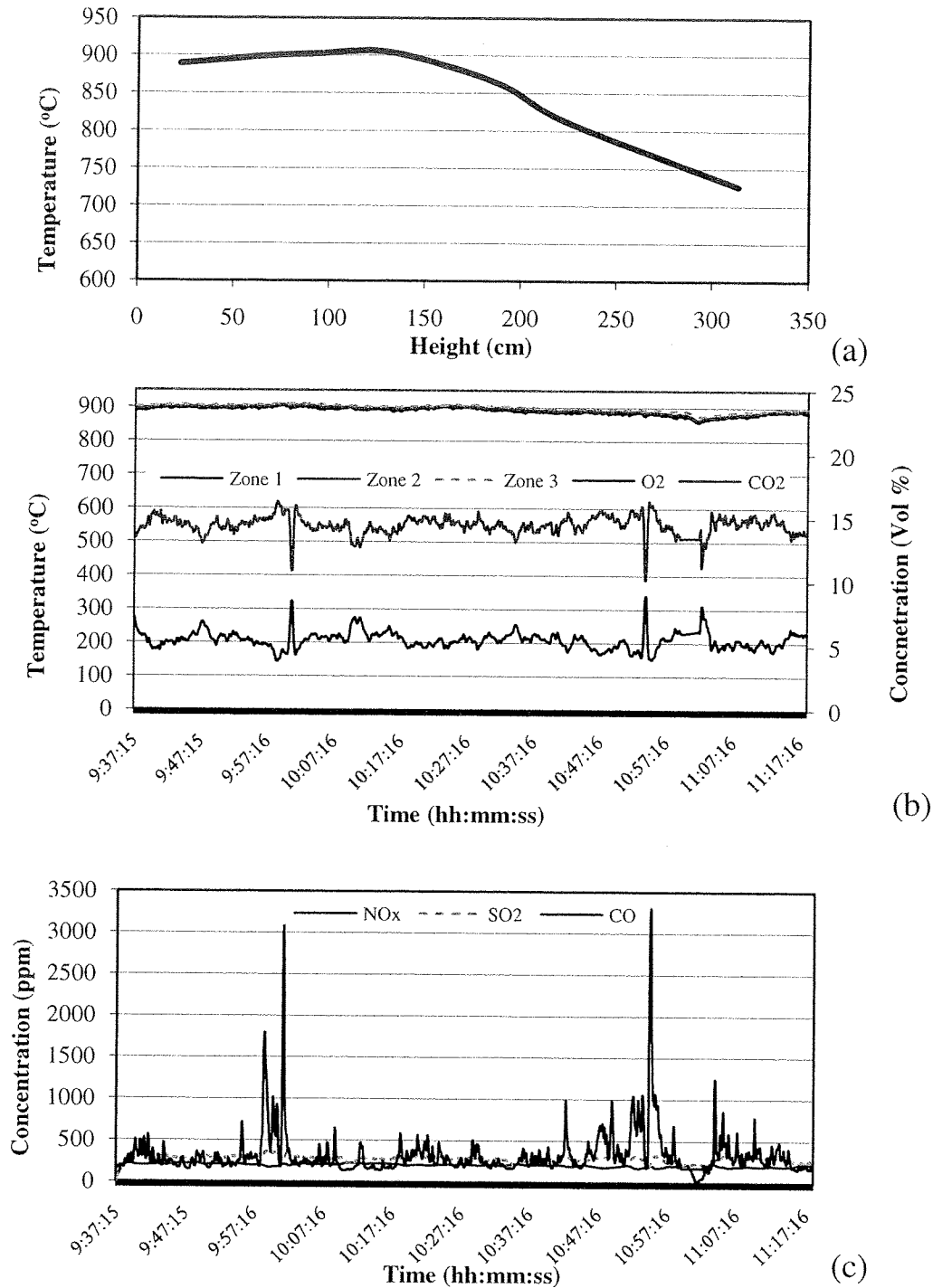


Figure A.6 – Test #6 (as received 80% lignite – 20% peat pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations of O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.10 kg/h (2.33 kg/h crushed lignite & 0.77 kg/h peat pellets); air flow: 401 L/min (Primary air of 262 L/min and Secondary are: 139 L/min).

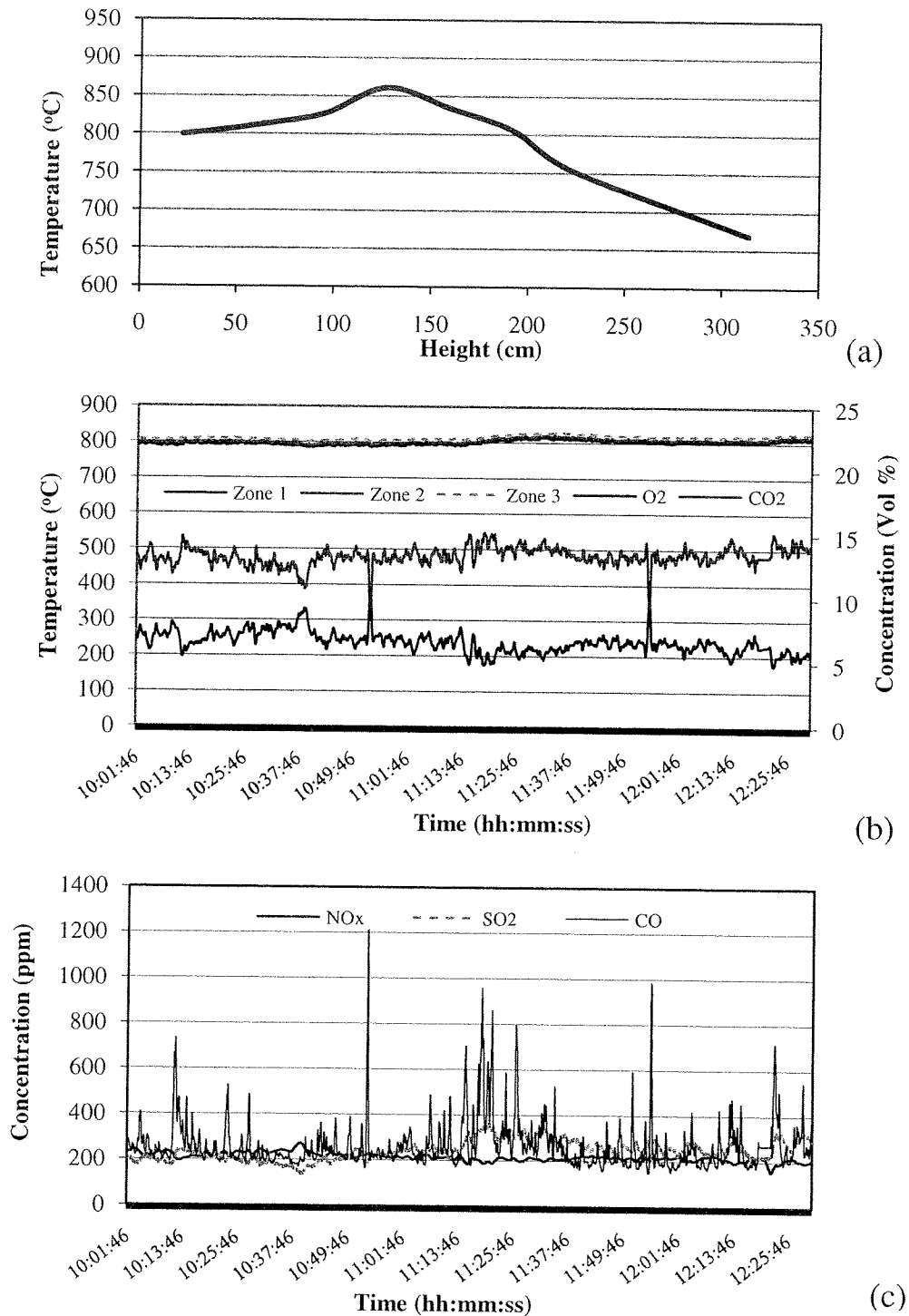


Figure A.7 – Test #7 (as received 80% lignite – 20% white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.98 kg/h (2.33 kg/h crushed lignite & 0.65 kg/h white pine pellets); air flow: 392 L/min (Primary air of 259 L/min and Secondary are: 136 L/min).

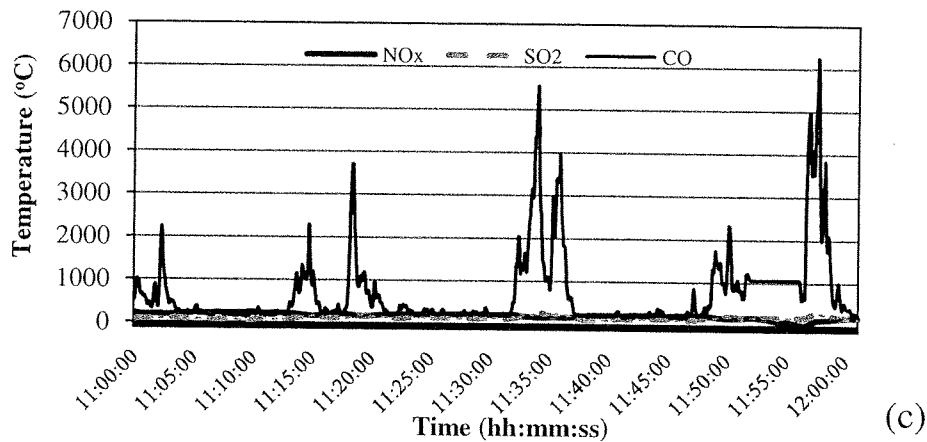
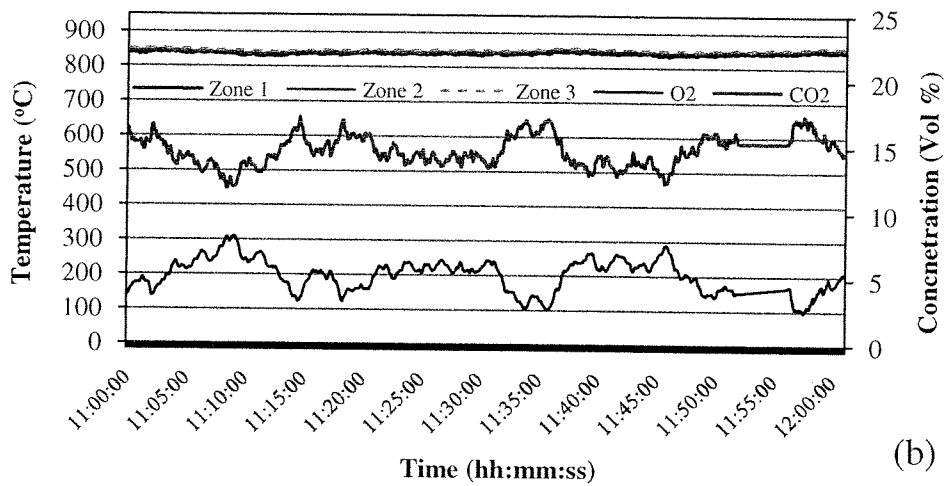
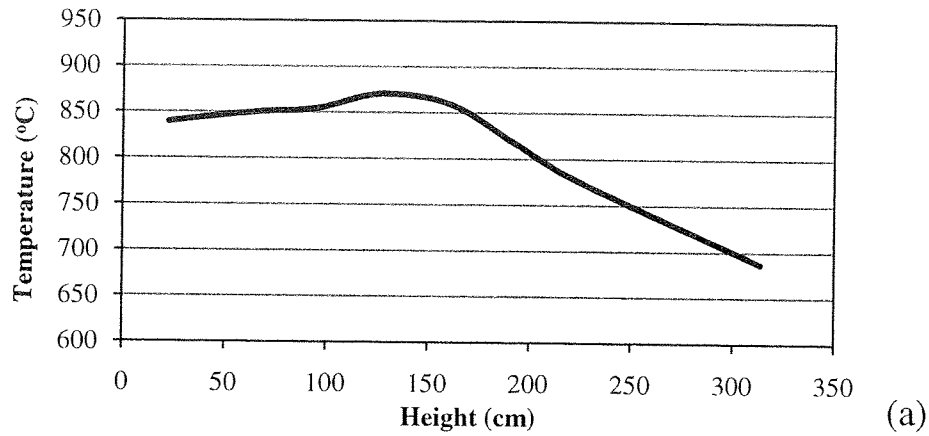
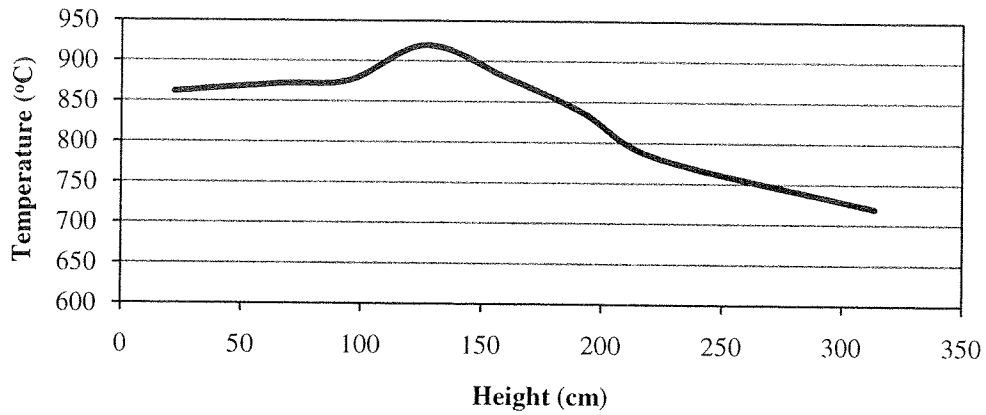
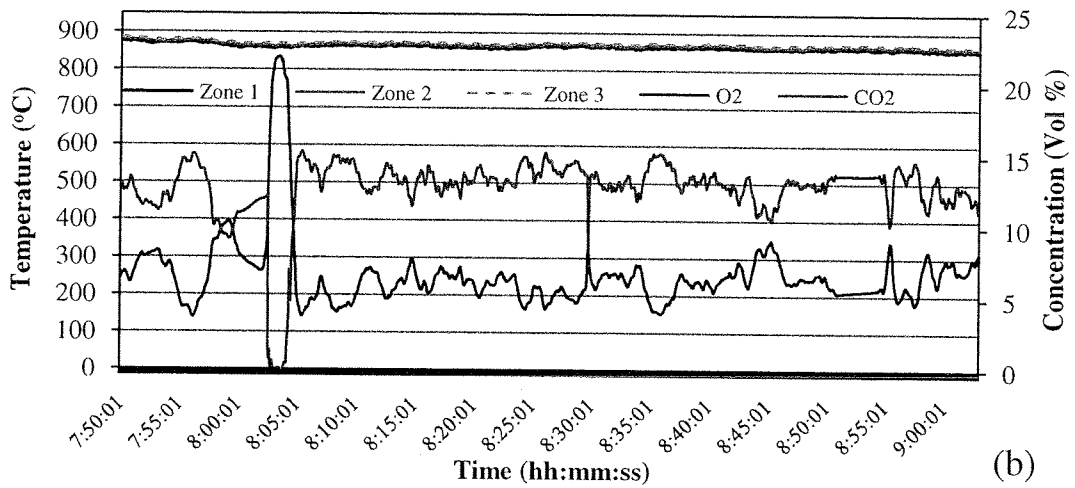


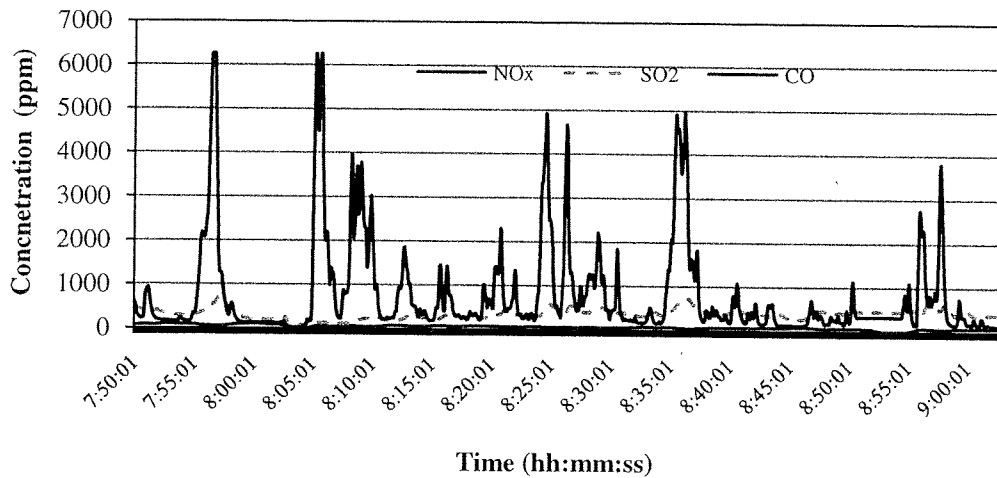
Figure A.8 – Test #8 (as received 50% lignite – 50% peat pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O_2 and CO_2 in flue gas; and (c) – concentrations of CO , NO_x , and SO_2 in flue gas. Other experimental conditions are: fuel feeding rate of 3.37 kg/h (1.45 kg/h crushed lignite & 1.92 kg/h peat pellets); air flow: 393 L/min (Primary air of 234 L/min and Secondary are: 159 L/min).



(a)



(b)



(c)

Figure A.9 – Test #9 (as received 50% lignite – 50% white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O_2 and CO_2 in flue gas; and (c) – concentrations of CO , NO_x , and SO_2 in flue gas. Other experimental conditions are: fuel feeding rate of 3.05 kg/h (1.46 kg/h crushed lignite & 1.59 kg/h peat pellets); air flow: 381 L/min (Primary air of 267 L/min and Secondary are: 114 L/min).

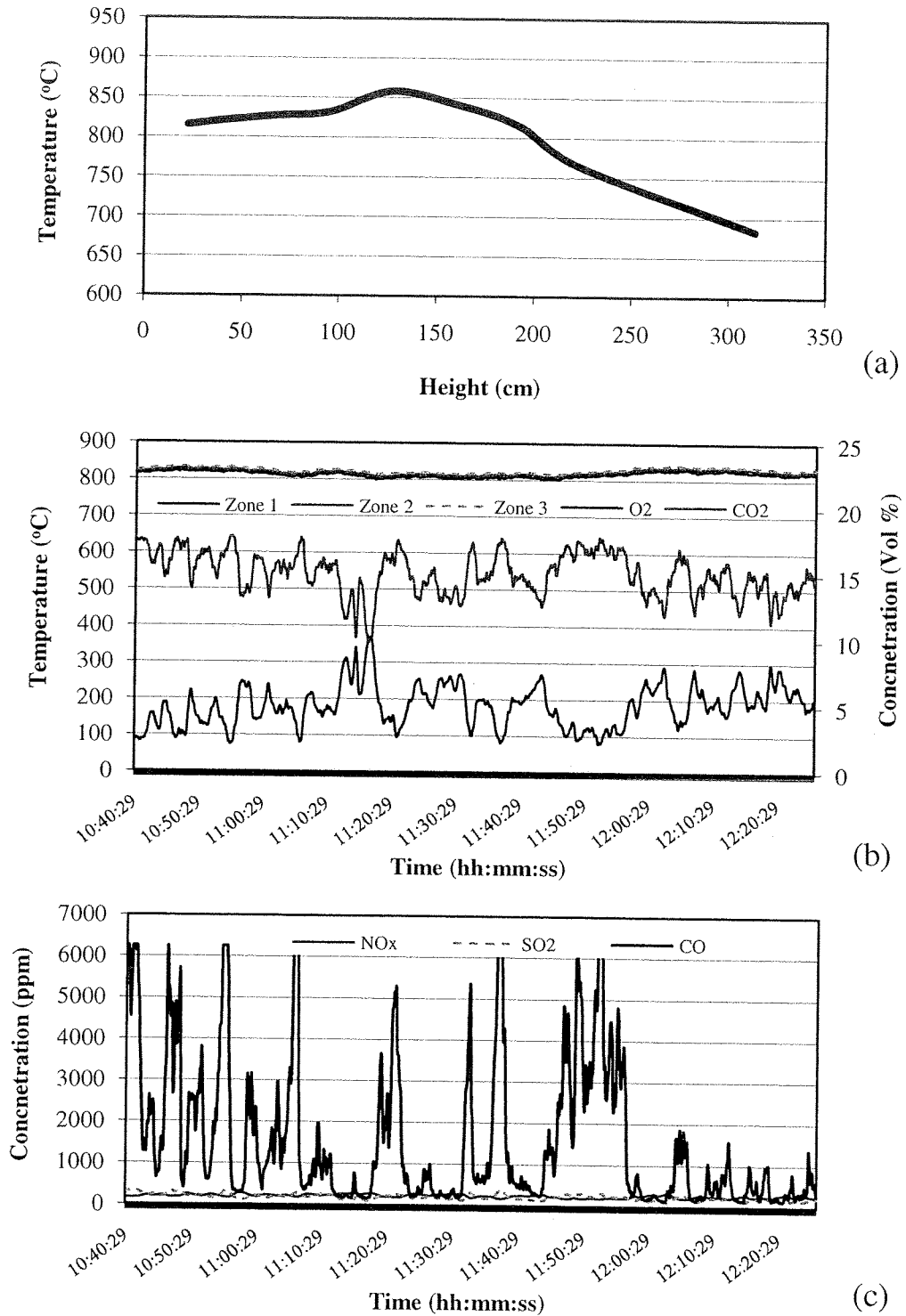


Figure A.10 – Test #10 (as received 20% lignite – 80% peat pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.70 kg/h (0.59 kg/h crushed lignite & 3.11 kg/h peat pellets); air flow: 400 L/min (Primary air of 288 L/min and Secondary are: 112 L/min).

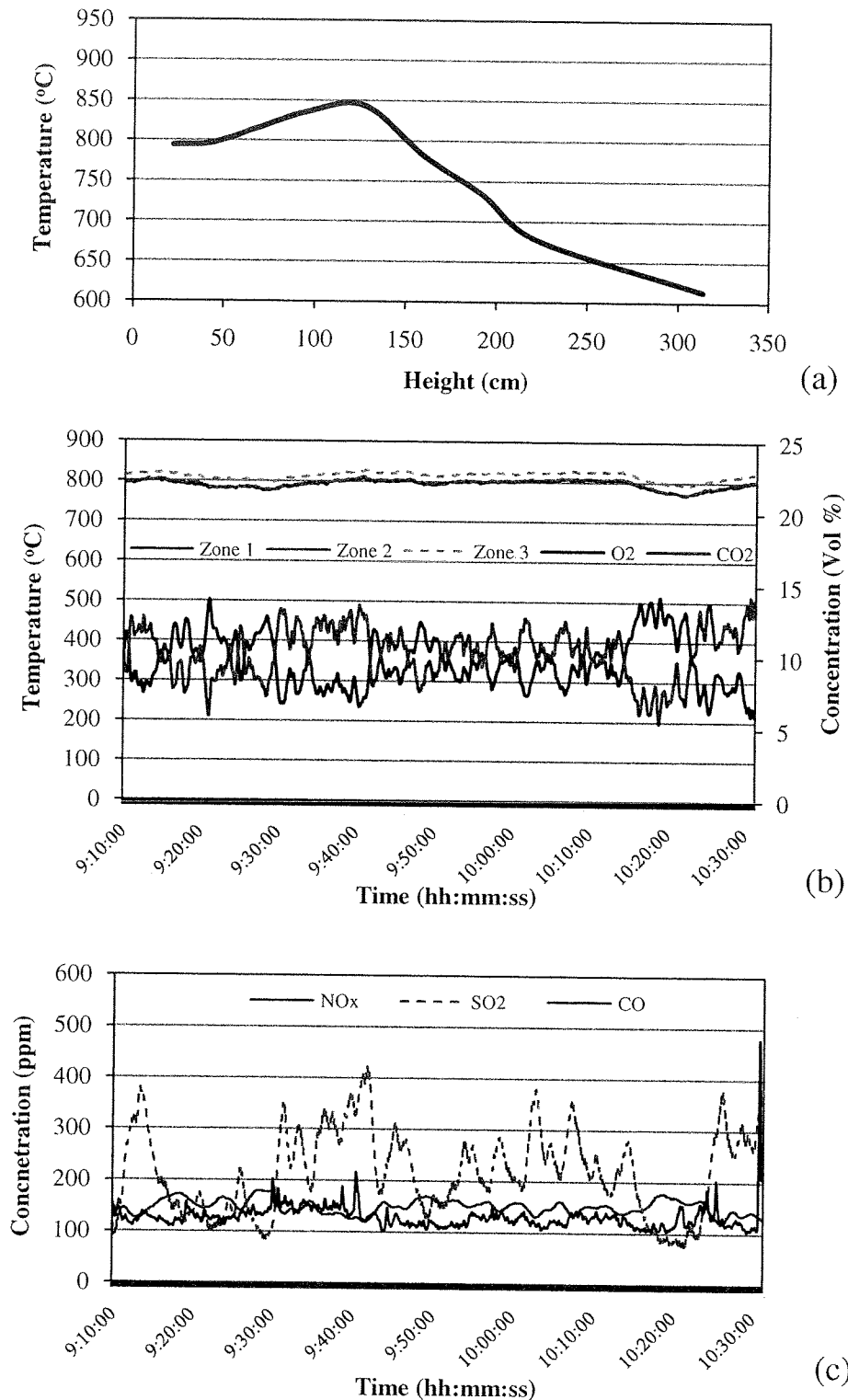


Figure A.11 – Test #11 (as received 20% lignite – 80% white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.13 kg/h (0.58 kg/h crushed lignite & 2.55 kg/h peat pellets); air flow: 387 L/min (Primary air of 269 L/min and Secondary are: 118 L/min).

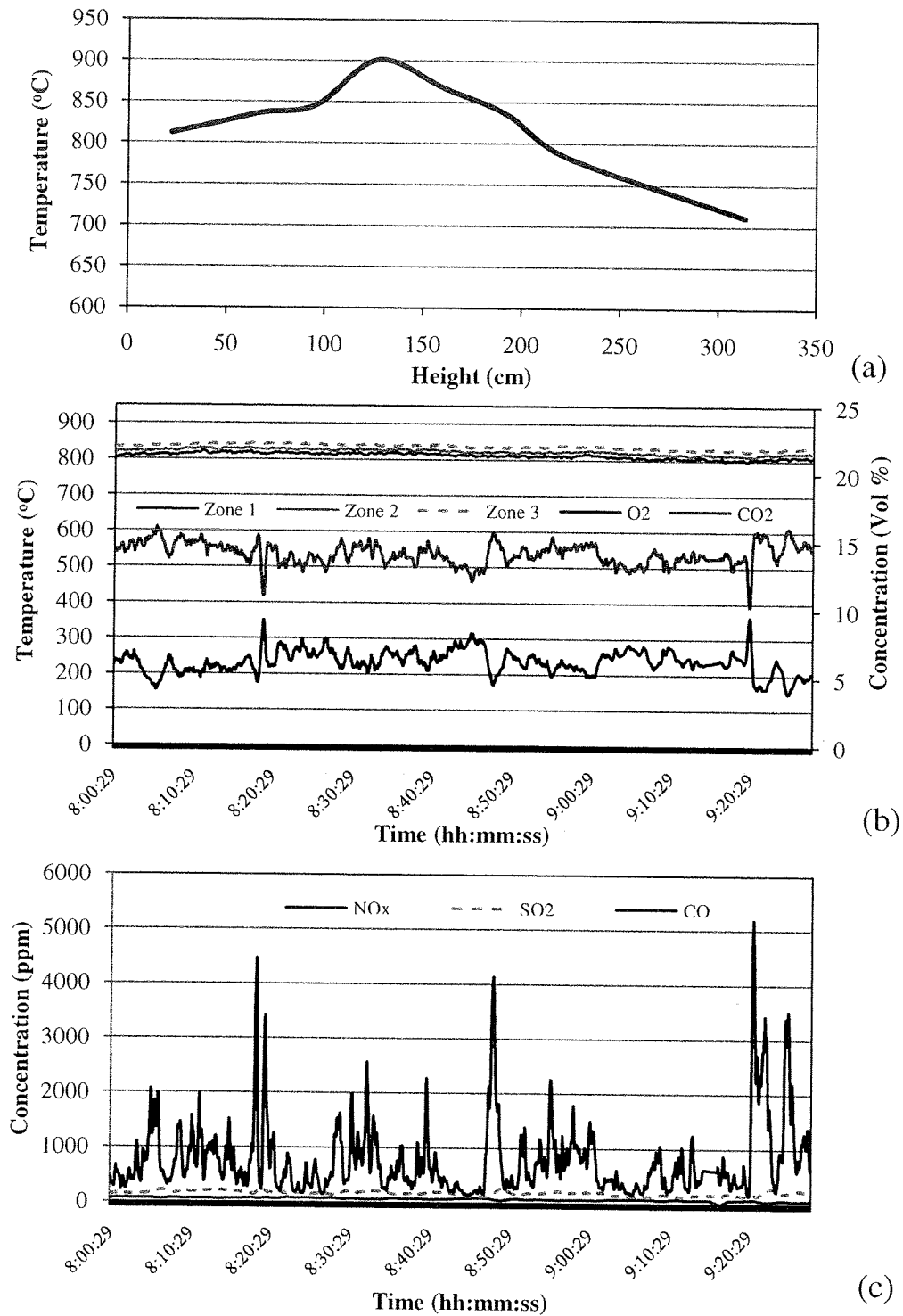


Figure A.12 – Test #12 (as received 50% lignite – 25% peat pellets - 25% white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.23 kg/h (1.46 kg/h crushed lignite & 0.80 kg/h peat pellets & 0.97 white pine pellets); air flow: 387 L/min (Primary air of 255 L/min and Secondary are: 132 L/min).

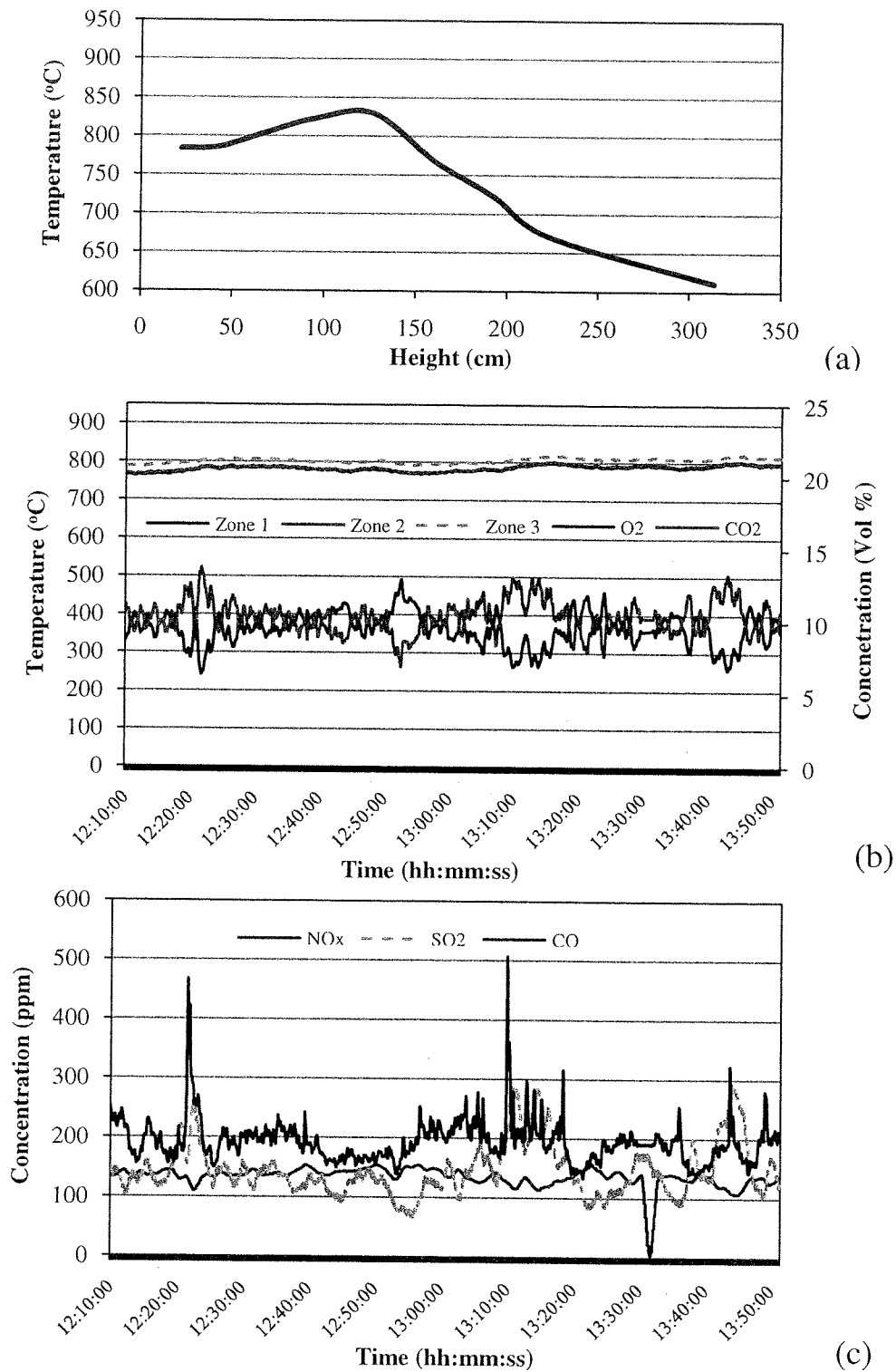


Figure A.13 – Test #12 (as received 20% lignite – 25% peat pellets - 25% white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.41 kg/h (0.58 kg/h crushed lignite & 1.27 kg/h peat pellets & 1.56 white pine pellets); air flow: 372 L/min (Primary air of 255 L/min and Secondary are: 117 L/min).

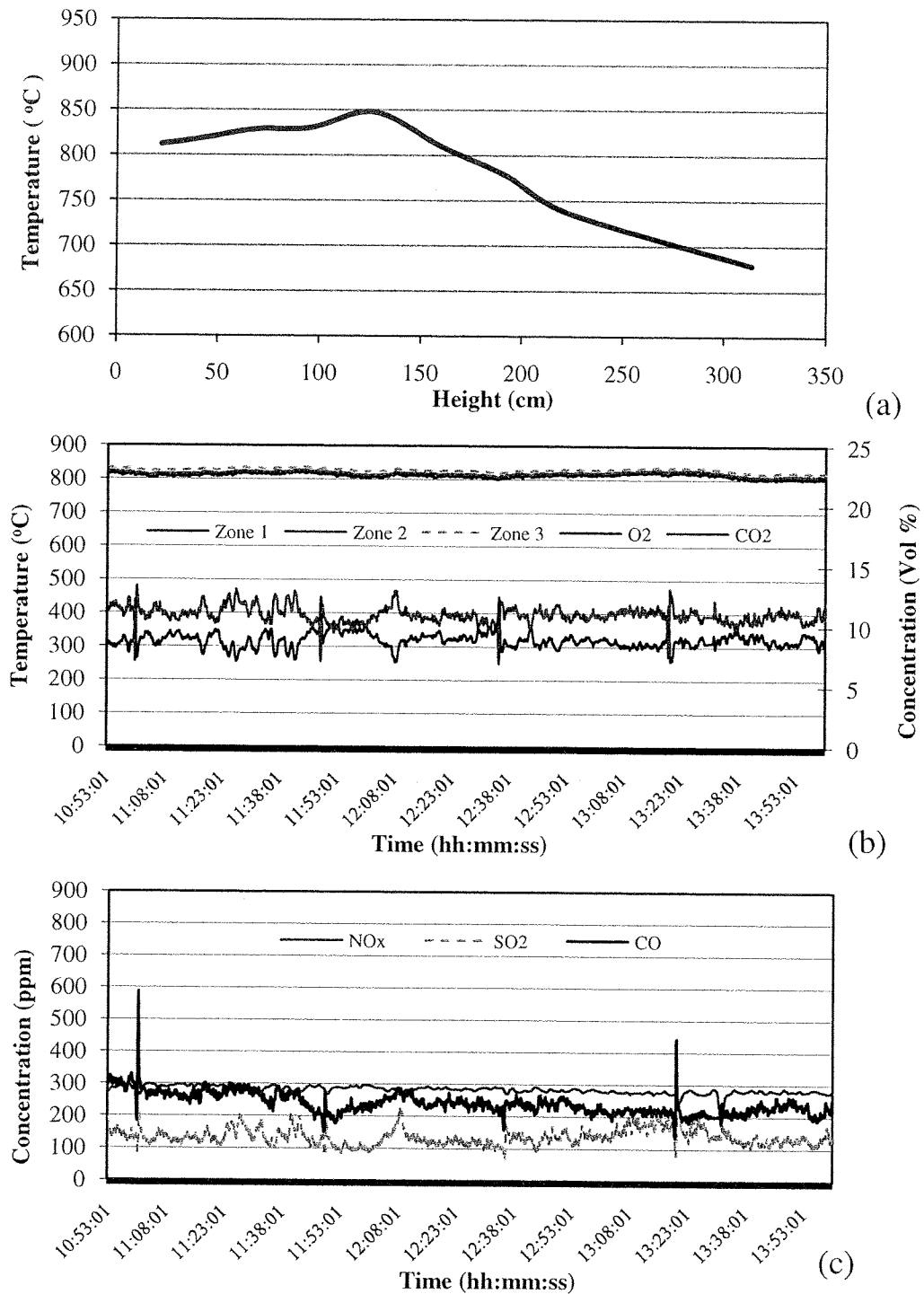


Figure A.14 – Test #14 (as received 100% lignite at 60% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.94 kg/h; air flow: 464 L/min (Primary air of 346 L/min and Secondary are: 118 L/min).

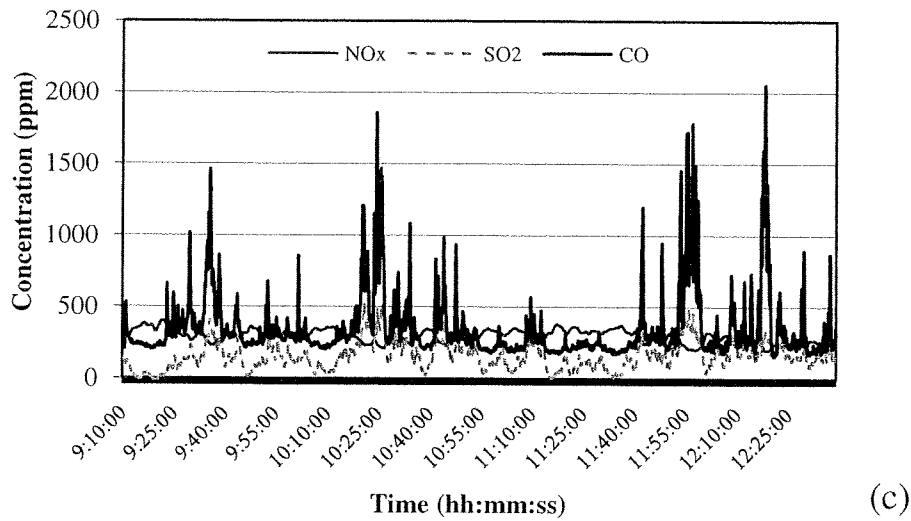
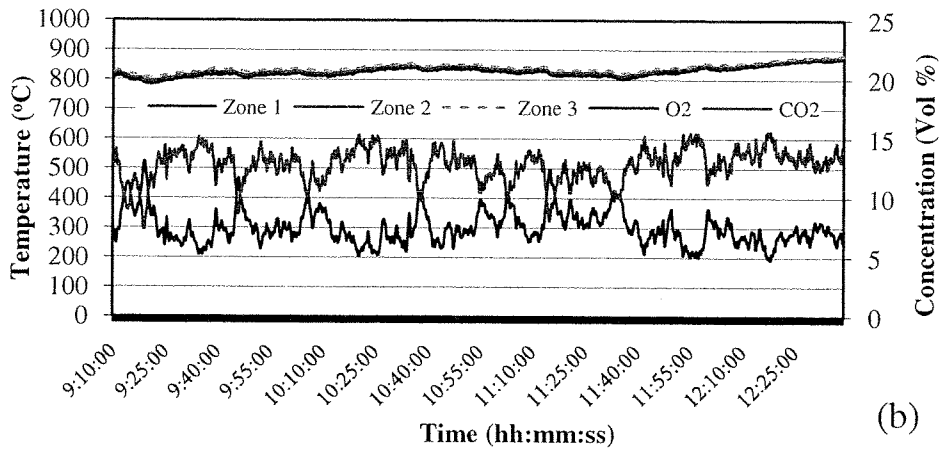
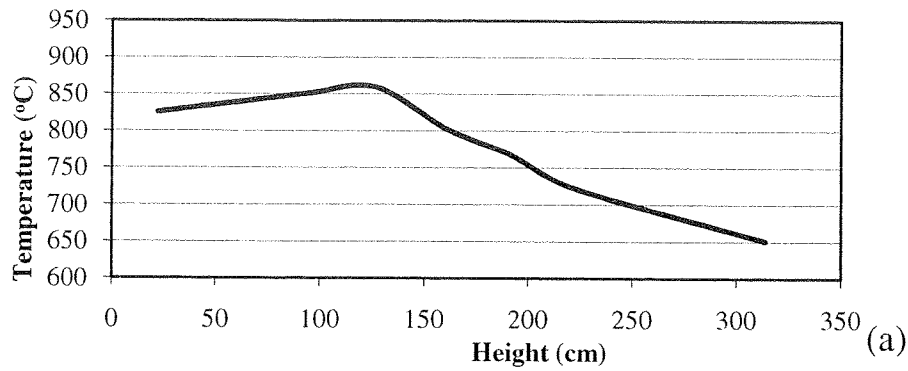


Figure A.15 – Test #15 (as received 100% peat pellets at 60% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.89 kg/h; air flow: 464 L/min (Primary air of 346 L/min and Secondary are: 118 L/min).

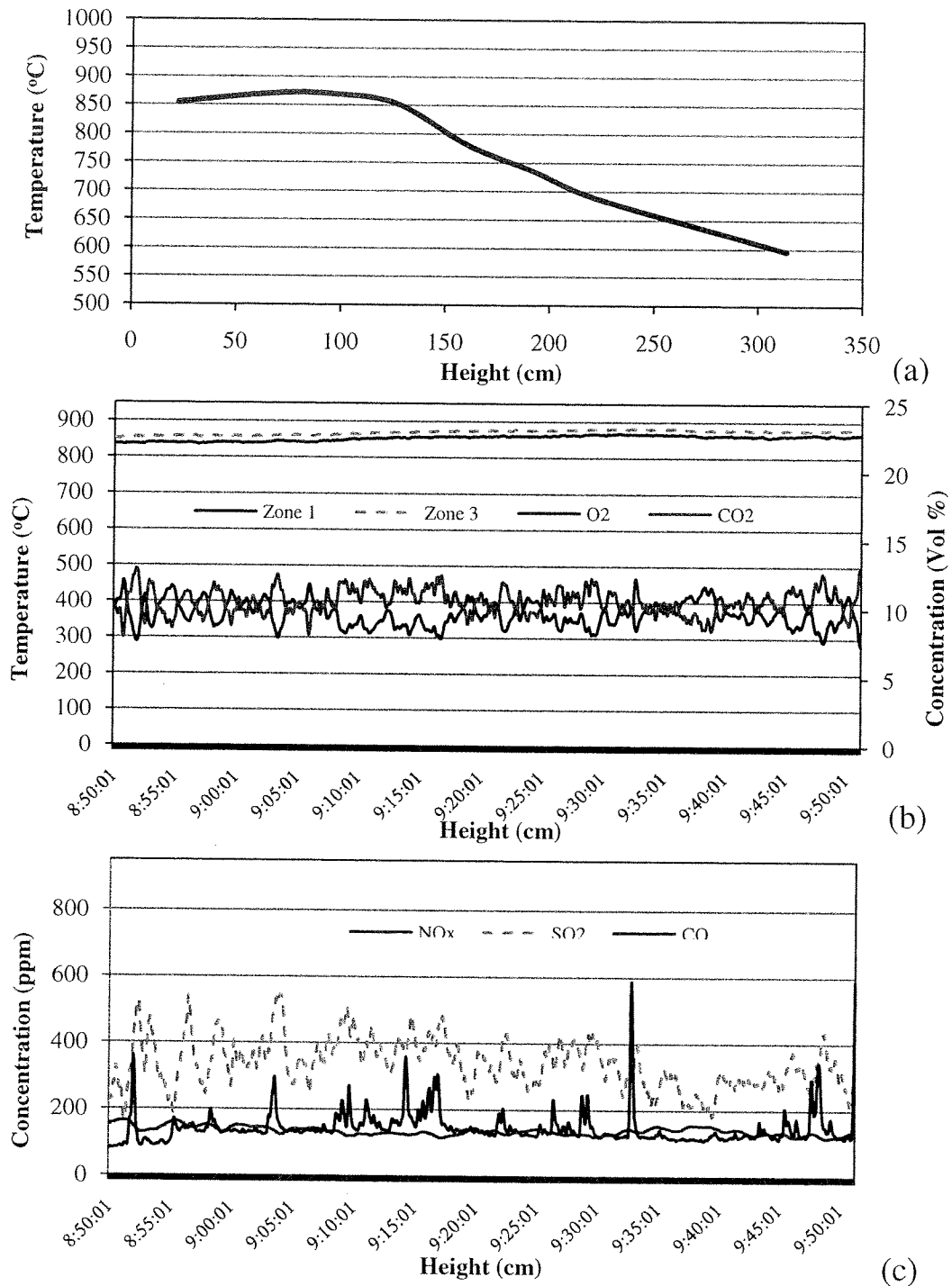


Figure A.16 – Test #16 (as received 100% white pine pellets at 60% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.18 kg/h; air flow: 408 L/min (Primary air of 246 L/min and Secondary are: 163 L/min).

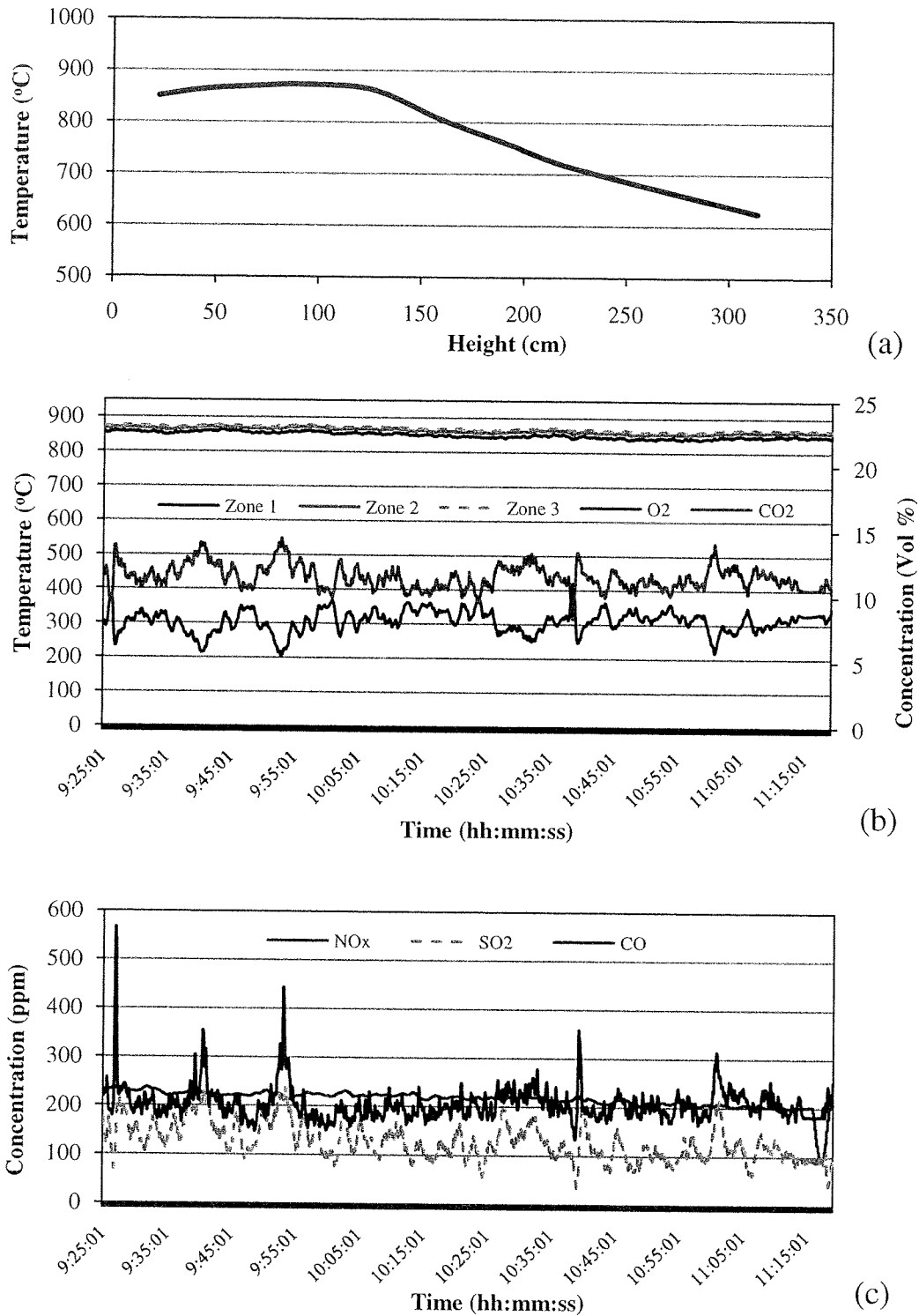


Figure A.17 – Test #17 (as received 50% lignite – 50% peat pellets at 60% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.41 kg/h (1.47 kg/h crushed lignite & 1.94 kg/h peat pellets); air flow: 444 L/min (Primary air of 234 L/min and Secondary are: 210 L/min).

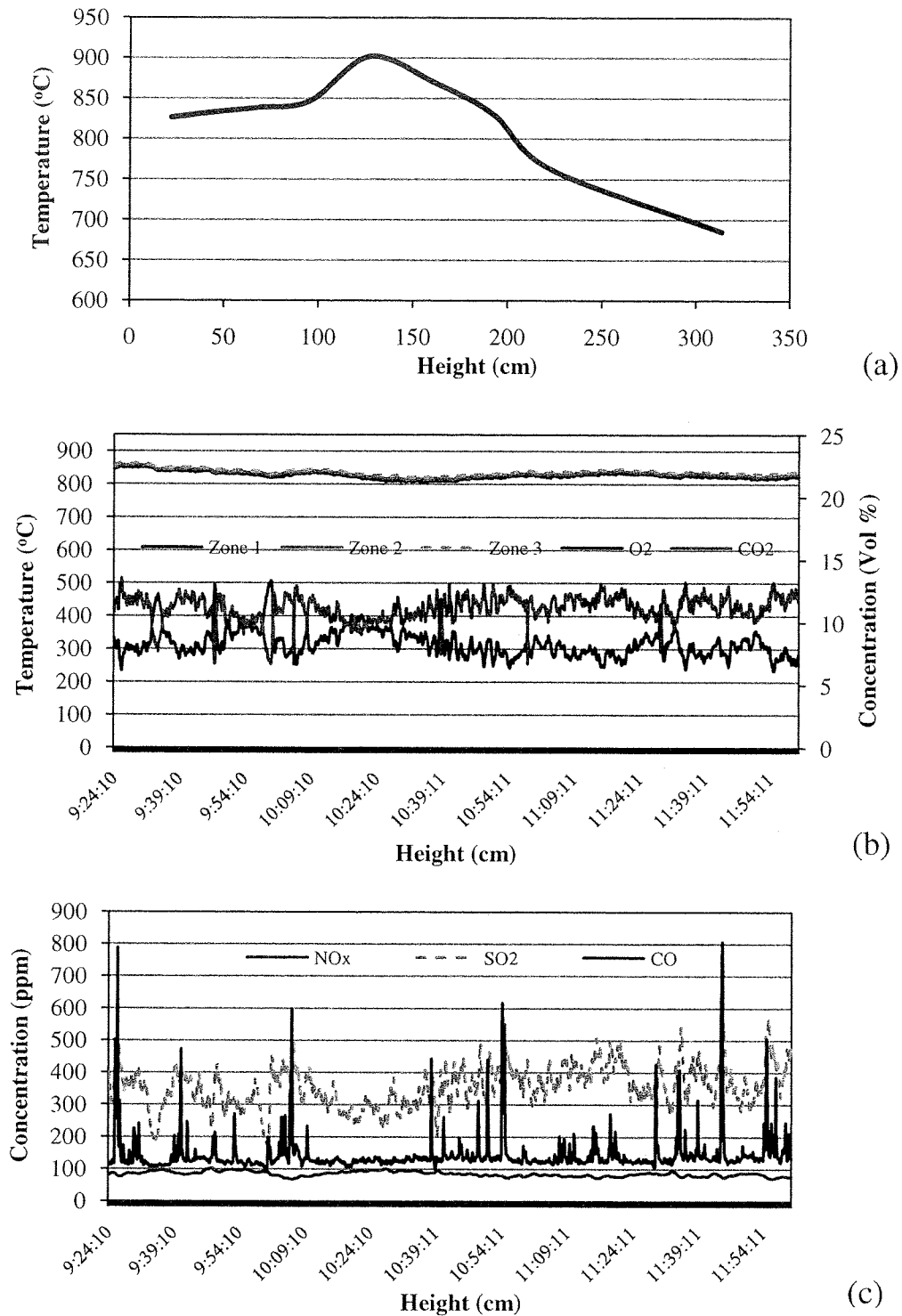


Figure A.18 – Test #18 (as received 50% lignite – 50% white pine pellets at 60% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 3.05 kg/h (1.46 kg/h crushed lignite & 1.59 kg/h white pine pellets); air flow: 437 L/min (Primary air of 275 L/min and Secondary are: 165 L/min).

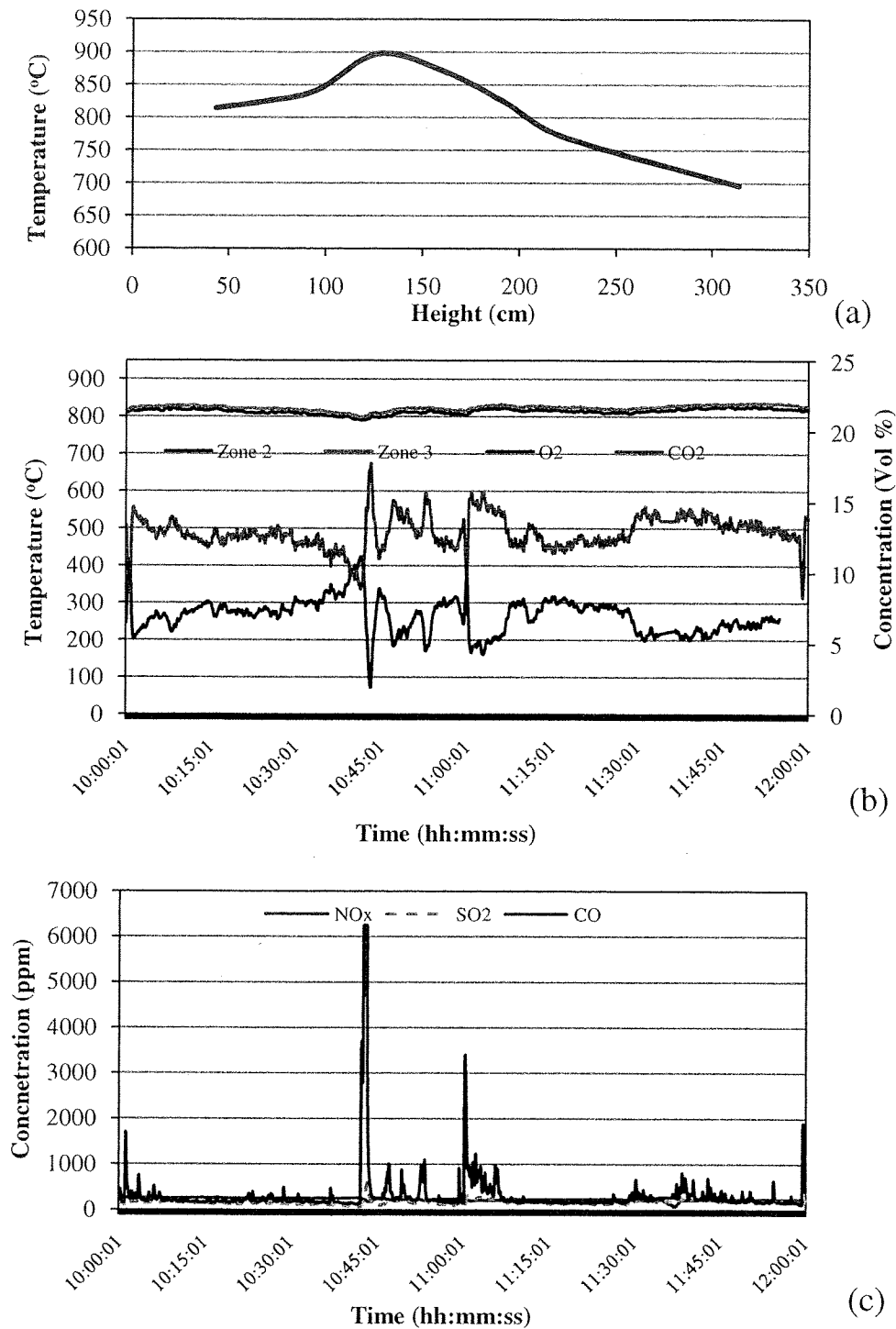


Figure A.19 – Test #19 (oven dry 100% lignite at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.56 kg/h; air flow: 405 L/min (Primary air of 254 L/min and Secondary are: 151 L/min).

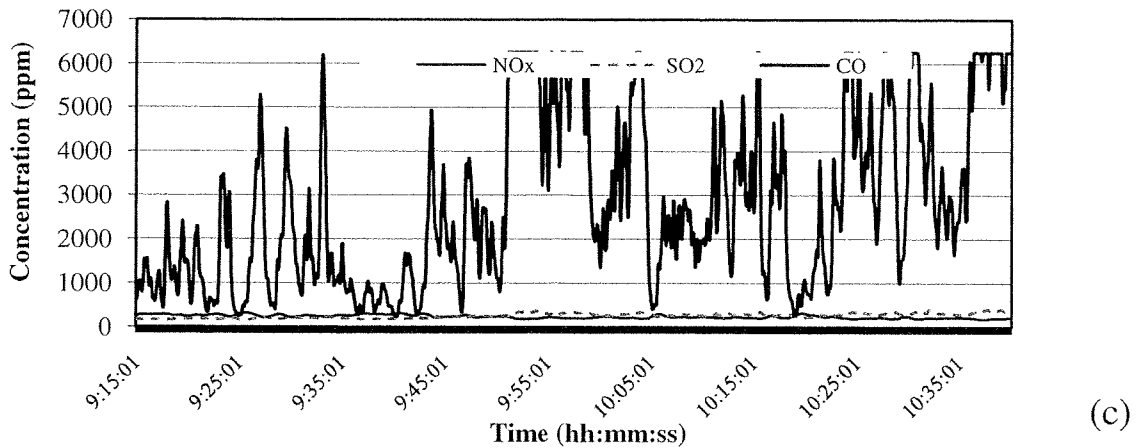
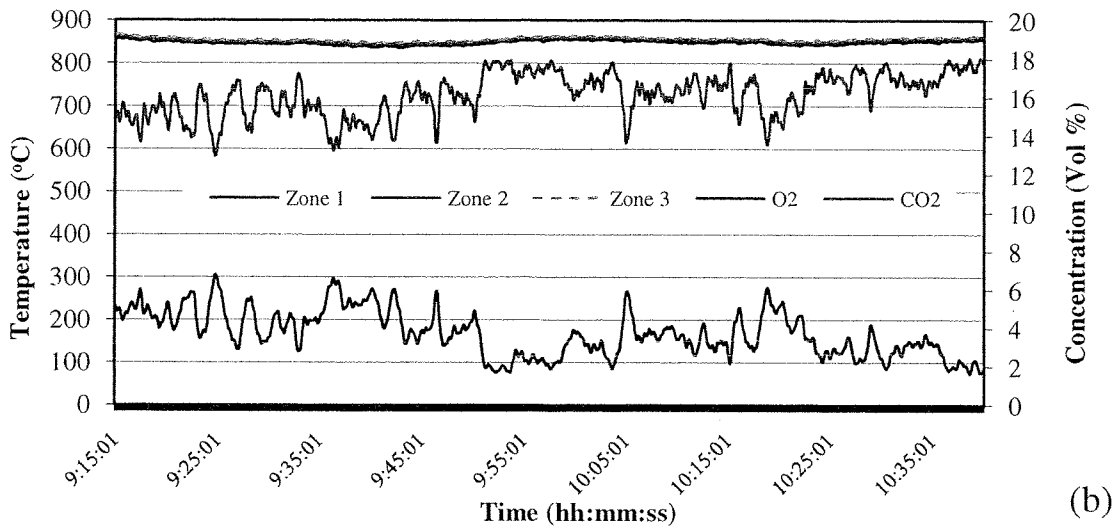
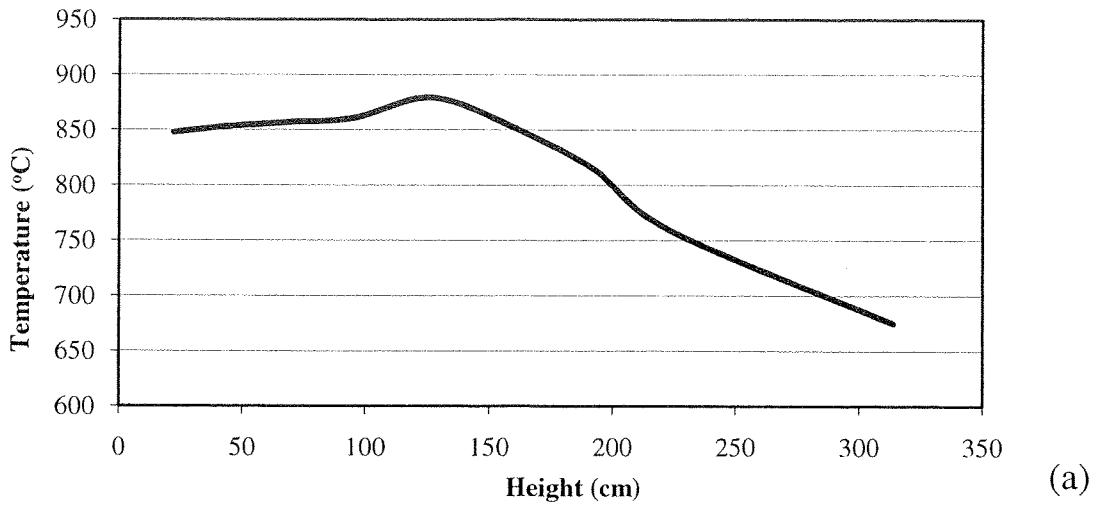


Figure A.20 – Test #20 (oven dry 100% peat at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.84 kg/h; air flow: 379 L/min (Primary air of 255 L/min and Secondary are: 124 L/min).

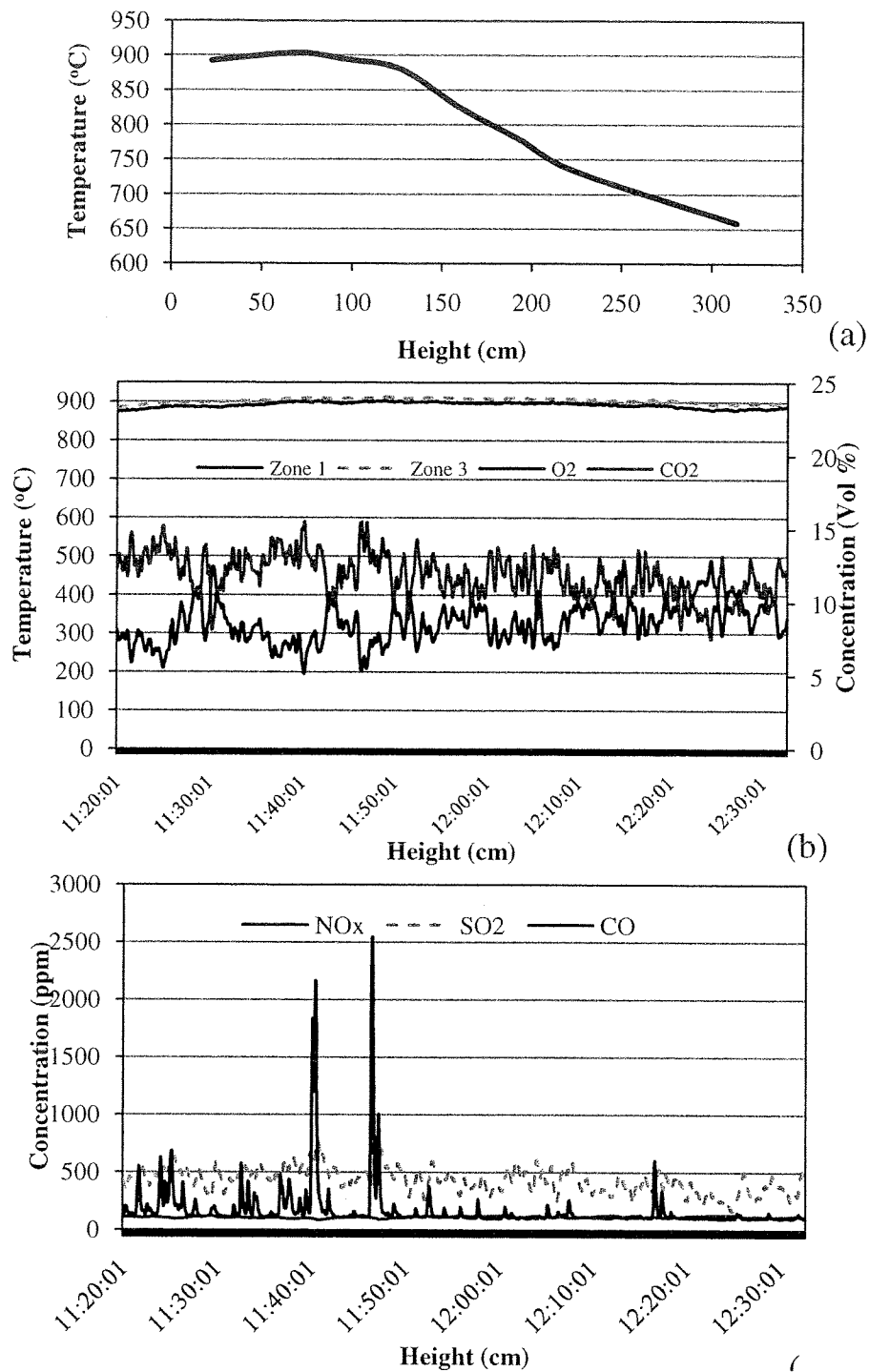


Figure A.21 – Test #21 (oven dry 100% white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.87 kg/h; air flow: 362 L/min (Primary air of 248 L/min and Secondary are: 114 L/min).

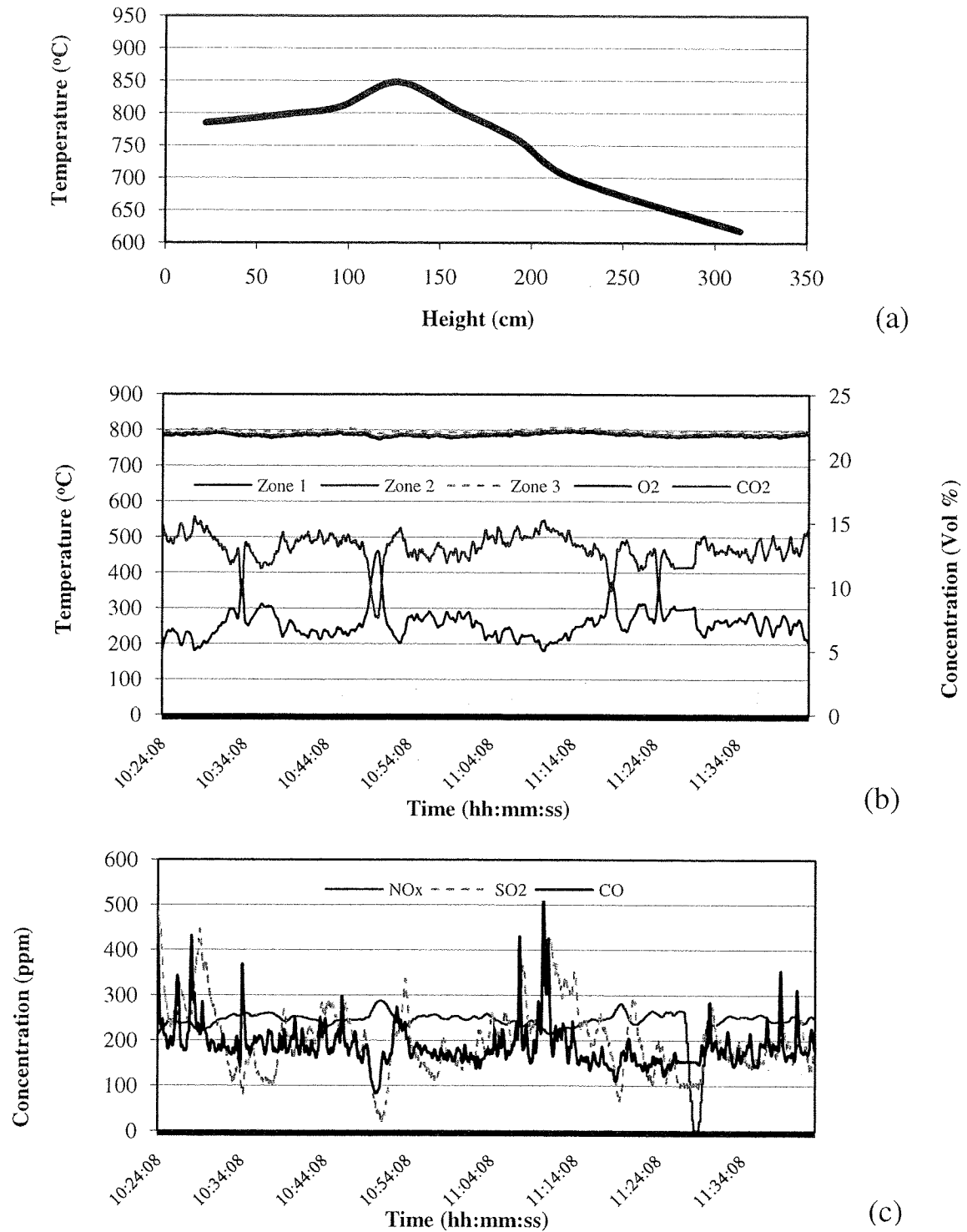


Figure A.22 – Test #22 (oven dry 50% crushed lignite – 50% peat pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.71 kg/h (1.29 kg/h crushed lignite & 1.42 kg/h peat pellets); air flow: 388 L/min (Primary air of 265 L/min and Secondary are: 123 L/min).

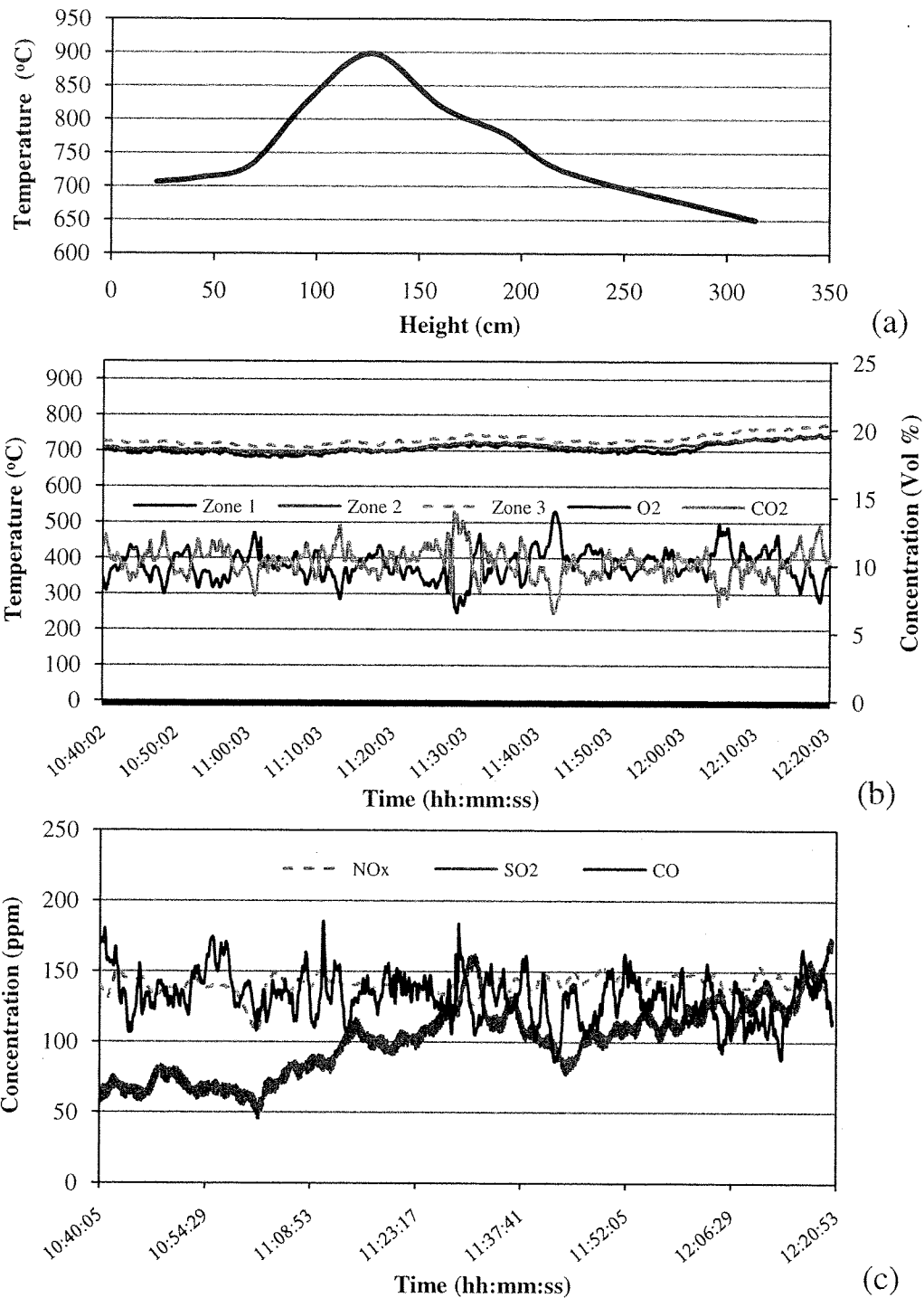


Figure A.23 – Test #23 (oven dry 50% crushed lignite – 50% white pine pellets at 40% excess air). (a) - Temperature distribution along the height of the fluidized bed column; (b) – dense phase temperature (Zones 1 through 3) and concentrations O₂ and CO₂ in flue gas; and (c) – concentrations of CO, NO_x, and SO₂ in flue gas. Other experimental conditions are: fuel feeding rate of 2.73 kg/h (1.29 kg/h crushed lignite & 1.44 kg/h white pine pellets); air flow: 379 L/min (Primary air of 260 L/min and Secondary are: 119 L/min).