

CRANFIELD UNIVERSITY

CHINSUNG MOCK

AN EXPERIMENTAL INVESTIGATION OF SINGLE BIOMASS PARTICLE
COMBUSTION IN A HOT GAS FLOW

SCHOOL OF ENERGY, ENVIRONMENT AND AGRIFOOD
PhD In Energy

PhD
Academic Year: 2016 - 2017

Supervisor: Prof. Vasilije Manović
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This thesis is submitted in partial fulfilment of the requirements for the degree of
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ABSTRACT

Based on direct observation, this thesis describes the combustion behaviour of solid particles. In particular, biomass and co-firing particles reduce carbon dioxide emissions because the biomass is a carbon-neutral resource. Here, the particles are used in pulverised-combustion applications, but their combustion qualities are not identical. Therefore, single particle combustion plays an important role in demonstrating their combustion quality.

Biomass is a renewable energy source and is used in pulverised-combustion applications such as the combustion of low-emission-energy solid fuel. Compared with coal, such solid fuel has a relatively low particle density, more volatiles and less fixed carbon, which results in different combustion characteristics in practical furnaces. The experimental investigation reported herein involves a quantitative analysis of biomass ignition and its volatile flames. The biomass was combusted in a laboratory-scale entrained flow reactor under various oxygen concentrations, with particle size serving as an experimental parameter. The cross-jet configuration, in which the jet injection flow are perpendicular to the main vertical flow on the test rig, leads to the optimal trajectory of entrained single particles and sequential combustion. The combustion process involves heat-up, ignition, devolatilisation and char combustion.

Overall, the experiments investigated (a) general biomass samples, (b) torrefied sludge and (c) single particles of coal and wood mixtures. For small-particle combustion and quantitative analysis, all samples were sieved to obtain particle sizes of a few hundred microns, following which they were separated by using an inclined-slope particle-shape separator to isolate the spherical-like particles. Next, the spherical-like particles from the three particle groups were entrained into a hot gas stream to study their burning characteristics using a high-speed optical camera (7000 frames per second) and optical microscopy with LED backlighting to observe morphological combustion events such as overlapping combustion, volatile ignition and flame modes.

The biomass samples comprised torrefied wood, coffee waste and sewage sludge with sizes ranging from 150–215 to 425–500 μm . In addition, for a comparative study, subbituminous coal was prepared. The experiment reported herein focused on the flame structure of four solid-fuel particles as a function of time and particle displacement; specifically, we look at (a) the effective radii of volatile flame and (b) the volatile-flame intensity. The results illustrate how, in the cross-jet configuration, realistic trajectories of biomass particles lead to burning that depends on particle size. In addition, an optimum range of particle size is suggested for complete burning.

Torrefied sewage sludge particles were prepared under various torrefaction temperatures (473 or 573 K) and residence times (10 or 30 min) and the particles were sieved to obtain particles sizes in the ranges 150–215 and 255–300 μm . To understand the flame structure, the morphology of carbonaceous species in a flame was observed at three points: (a) the centre of pyrolysis, (b) just inside pyrolysis and (c) just outside pyrolysis. Ignition delay and apparent flame are discussed as a function of degree of torrefaction.

The special single particles for co-firing were milled from two types of coal-biomass pellets: (a) 50:50 and (b) 20:80 (coal: biomass by volume). Raw wood and subbituminous coal were also prepared to study their intrinsic characteristics and to make a comparative analysis. Four particles were burned to study their flame characteristics in the range of 10%–40% O_2 , and the impact of fuel mixtures are discussed based on quantitative measurements. Furthermore, the sequential combustion processes under slow heating are compared with those under the current rapid heating rate to compare thermal decomposition.

Keywords:

Single particle, Biomass, Torrefaction, Co-firing, Cross-jet injection, Direct observation

*Dedicated To my beloved wife, Jinyoung
& two daughters, Insuh and Yeonsuh*

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Nomenclature

Alphabet

A_p	Particle surface area	[m ²]
C	Fixed carbon content	[g]
d	Particle diameter	[m]
h	Convective heat transfer coefficient	[W/m ² ·K]
t	Time	[s]
T_f	Flame temperature	[K]
T_g	Surrounding gas temperature	[K]
T_p	Particle temperature	[K]
T_w	Wall temperature	[K]
$m_{b,e}$	Mass of empty bottle	[g]
$m_{b,p}$	Mass of bottle filled with particles	[g]
M	Moisture	[g]
R_f	Flame radius	[m]
R_p	Particle radius	[m]
V	Velocity	[m/s]
V_m	Volatile matter content	[g]
$V_{b,w}$	Volume of bottle	[cm]
$Q_{c,p}$	Conduction	[W/m ²]
$Q_{r,p}$	Radiation	[W/m ²]

Greek letters

ε_p	Particle emissivity	[-]
ρ_p	Particle bulk density	[g/cm ³]
σ	Stefan Boltzmann	[Wm ⁻² K ⁻⁴]

ABBREVIATIONS

CW	Coffee waste
F.C	Fixed carbon
TW	Torrefied wood
SS	Sewage sludge
V.M	Volatile matter

CHAPTER 1

INTRODUCTION: AIM AND OBJECTIVES

1. INTRODUCTION

1.1 Background

Primary energy consumption has been growing ceaselessly, keeping in line with the world's economic development and with population growth. By 2030, rapidly developing countries such as China and India will account for 74 % of the increase in the energy use, as per a report from International Energy Agency (IEA, 2007). As shown in Fig. 1-1 (BP, 2015), the rate of energy consumption has been increasing rapidly in the Asia Pacific region because of the high population and rapid economic growth in this area. Unsurprisingly, energy consumption is nearly concomitant with carbon dioxide emission (see Fig. 1-2) (BP, 2015). As a result, the level of atmospheric CO₂ has reached 404.93 parts per million (ppm) as of October 2016 (NASA). This significant increase in CO₂ emission is largely attributed to the extended use of fossil fuels in power plants to generate electricity and heating (IEA, 2016). Figure 1-3 shows that 40.6% of the world's electricity supply is generated by coal (IEA, 2016), which gives coal the highest share among all energy sources. Currently, coal combustion emits almost twice as much carbon dioxide (228.6 pounds per million British thermal units of energy) as does the combustion of natural gas (117.0) (EIA). The main problem with emitting carbon dioxide is that it contributes to global warming (the Earth's average surface temperature has risen by 0.87 °C between 1906 and 2015, as shown in Fig. 1-4) (NASA). The rate of temperature increase is almost twice as high as in 1950s and will lead to a 2.7 °C increase relative to the pre-industrial temperature by 2100 unless the emission of carbon dioxide is significantly reduced. Such a rise in temperature would result in a dangerous melting of arctic sea ice (13.3% per decade) and land ice (118 gigatonnes per year) and a rapid rise in sea level (3.4 mm per year) (NASA).

In 2015, the Paris agreement, which was negotiated by representatives of 195 countries including the USA, China and India, heralded plans to constrain the increase in the average global temperature to less than 2 °C relative to pre-industrial levels. In contrast to the 1997 Kyoto protocol and the 2009 Copenhagen

summit, the Paris agreement is legally binding. Before the agreement, the European Union had already set a target of 40% reduction in greenhouse-gas emissions and of 27% fuel shares of energy from renewable sources by 2030 (European Commission 2016). The UK has set a 60% reduction target (UK, Climate Change Act 2008) for greenhouse gas emission by 2030, as shown in Fig.1-5. Therefore, the use of biomass and waste material, instead of the use of coal, can play an important role in the reduction of greenhouse gases, especially carbon dioxide. In fact, biomass is a renewable and low-emission energy source that can be substituted for fossil fuels in coal-fired power plants (Van Loo et al., 2010; Vassilev et al., 2013). For a carbon-free environment, the current energy sources should be replaced with renewable energy sources. However, this energy strategy (see Fig.1-6) is only acceptable as a long-term solution if a variety of geometric and technical limitations are overcome. Consequently, combustion and gasification of biomass is currently a feasible solution only for short-term energy production.

Unfortunately, the current power-generation efficiency of biomass-fired power plants is relatively low (16%–25%) compared with that of coal-fired plants (33%–38%) (Robinson et al., 2003), which is attributed to intrinsic differences, as shown in Fig. 1-7. These characteristics cause rapid devolatilisation, short burning time, and low soot flame and flame instability (Baxter et al., 2005). Radiative heat transfer from low soot biomass-flame can be a crucial factor in the low efficiency of a power plant (Snelling et al., 2002; Viskanta et al., 1987; Andersson et al., 2008). Furthermore, in contrast with coal, the type of biomass varies widely in volatile matter and fixed carbon with in different compositions. Therefore, understanding the thermal conversion and combustion of biomass is vital for predicting furnace operation and designing furnaces.

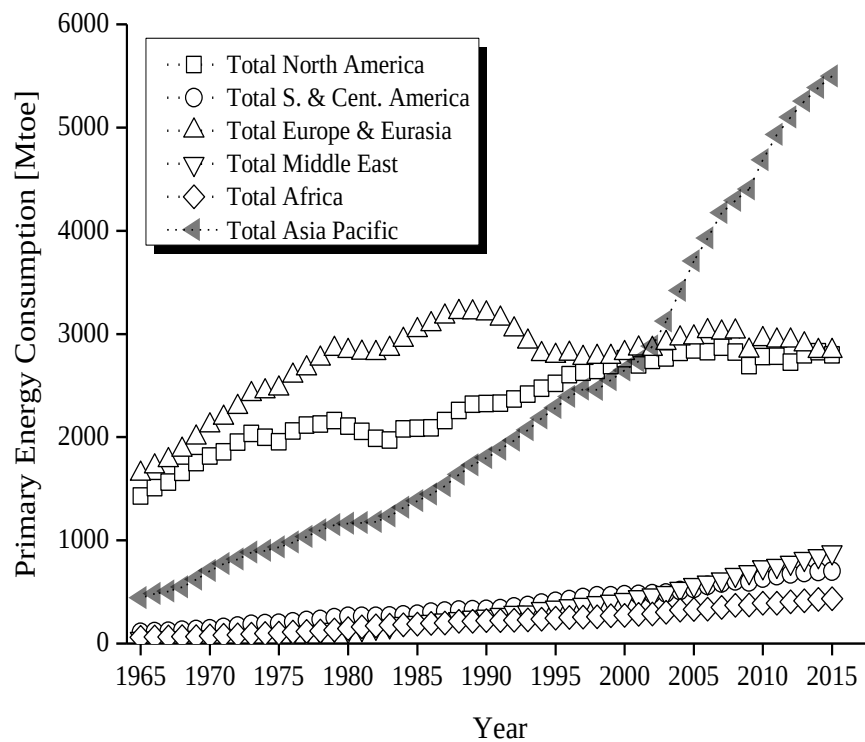


Figure 1-1 Primary worldwide energy consumption from 1965 to 2015 (BP, 2015).

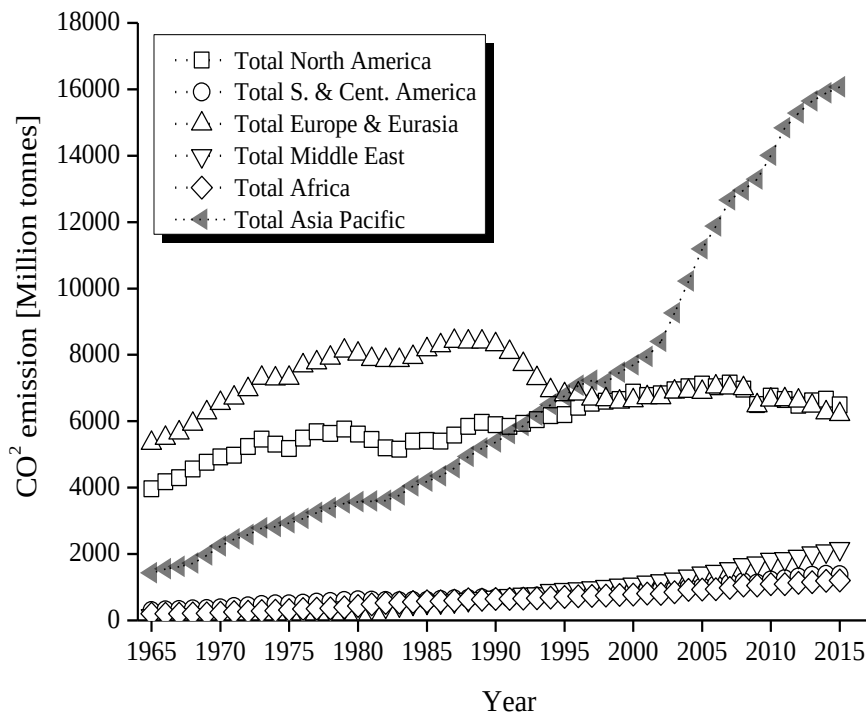


Figure 1-2 Worldwide emission of carbon dioxide from 1965 to 2015 (BP, 2015).

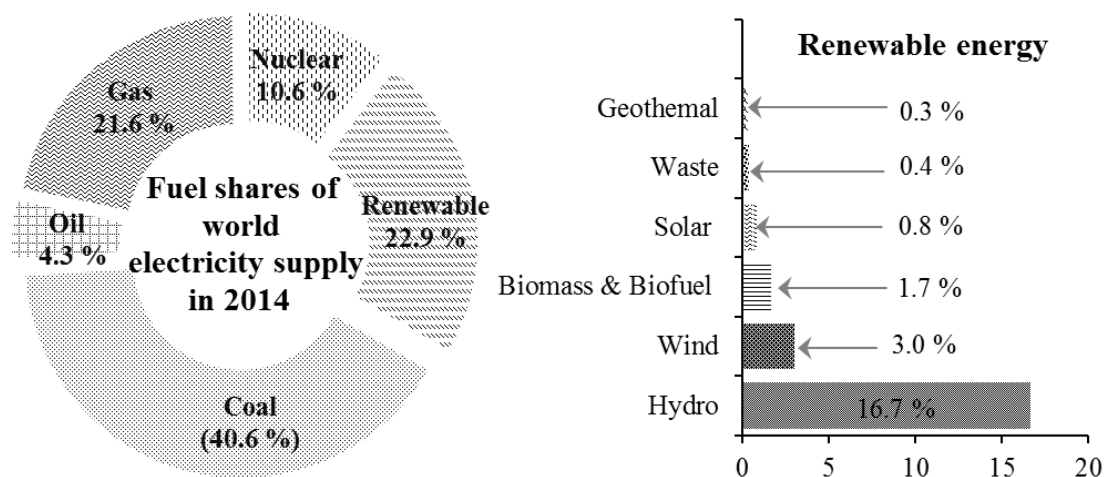


Figure 1-3 Sources of world electricity supply in 2014 (IEA, 2016).

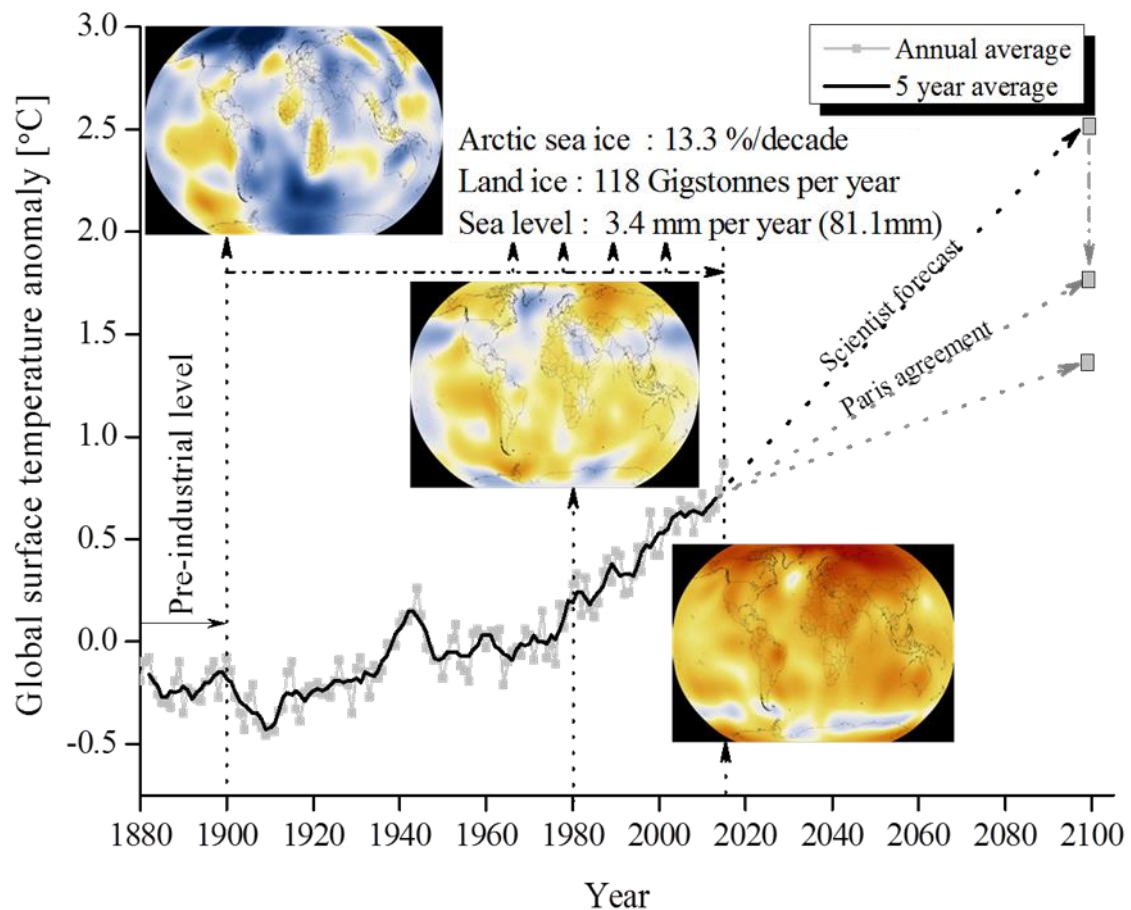


Figure 1-4 Increase of global surface temperature between 1906 and 2015 and scientist forecast to 2100 (NASA).

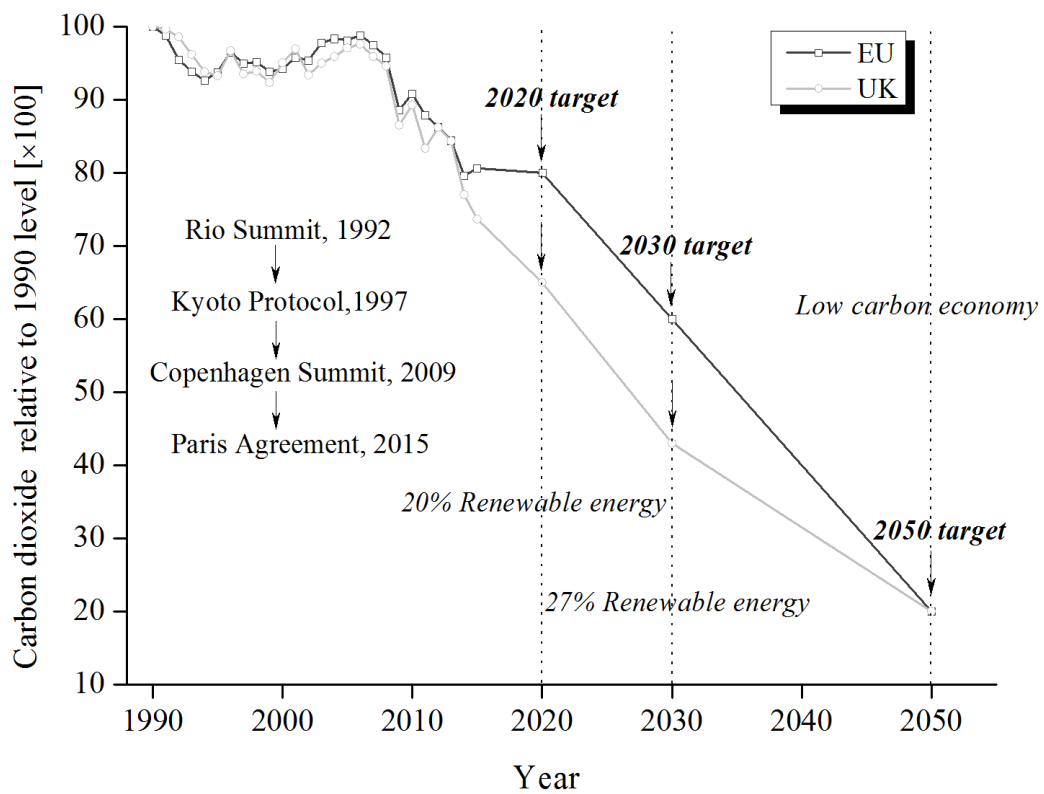


Figure 1-5 Reduction targets of carbon dioxide from 1990 to 2050 based on international environmental agreements (UK, Climate Change Act).

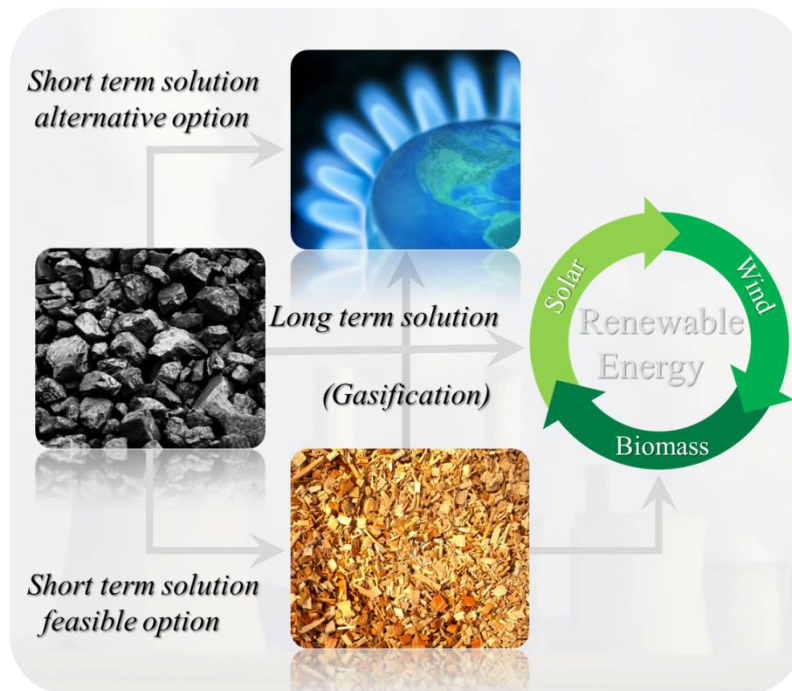


Figure 1-6 Strategy for future energy production.

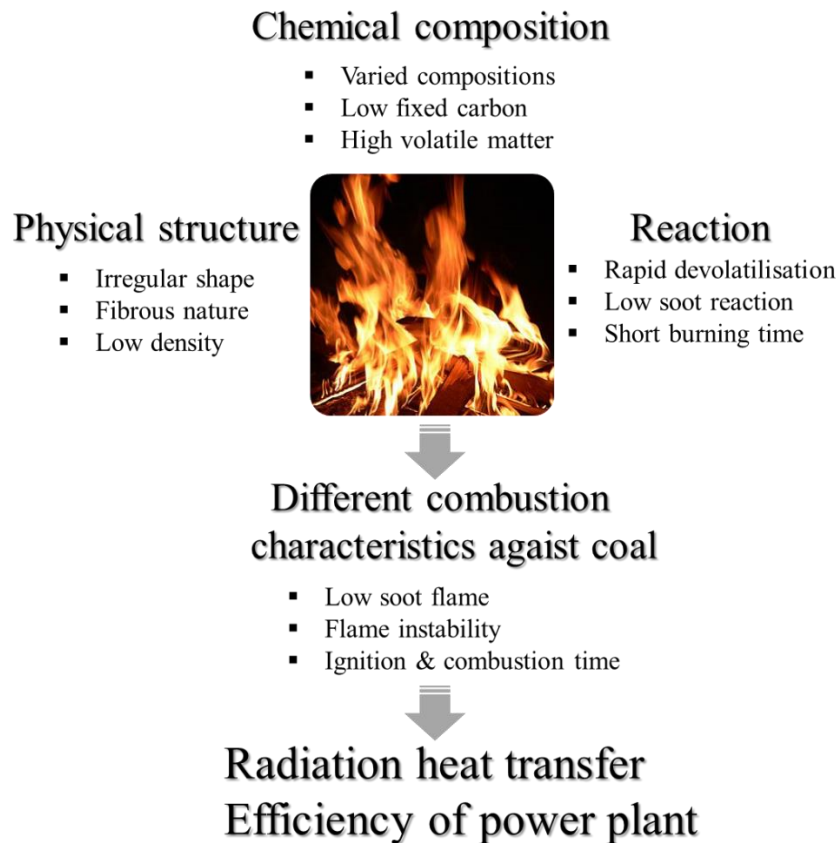


Figure 1-7 Biomass characteristics in terms of chemical composition and physical structure.

1.2 Aim and objectives of study

This study discusses single-biomass-particle combustion based on direct microscopic observation and by considering simple experiments and minimising uncertainties due to particle loading, particle size and environmental conditions in contrast to bulk and group particles combustion (see Fig. 1-8). Characteristic biomass combustion is demonstrated while varying the experimental parameters, such as oxygen concentration, gas temperature and particle type and size. These environmental conditions are similar to those in real furnaces, such as rapid heating rate, hot gas temperature and the non-quiescent condition. This study thus has the following objectives:

1. For single biomass particles a few hundred microns in size, determine the combustion dynamics and particle displacement for heat-up, devolatilisation and char combustion
2. Observe biomass flame structures from burning particles with various experimental parameters such as particle type and size, oxygen concentration and gas temperature, compared with coal particles.
3. Suggest an optimal pulverised biomass particle size that does not drop to the bottom of an entrained flow reactor.
4. Investigate combustion from biomass torrefaction and fuel mixtures with coal for to obtain quality combustion from pulverised solid fuel.
5. Based on the experimental results, describes the modelling of single biomass particle combustion

To complete the objectives of this study, the following tasks must be completed:

1. Construct an experimental facility with environmental conditions similar to those in a real furnace.
2. To observe particle combustion, allow optical access into the furnace with minimal gas-temperature gradient under hot-gas conditions.
3. Introduce cross-jet injection with rapid heating rates for the particle trajectory: solid particles are entrained by a cold carrier gas perpendicularly into an upward-flowing hot-gas stream at 10^5 K/s.
4. Construct a water-cooled injector to implement the initial conditions ($T_p=298$ K and $t_0=0$) for the biomass particles, thereby enabling the monitoring of each combustion process.
5. To quantitative analysis of flame size and intensity, install devices to record the enveloped flame and its char particles simultaneously in clear images.

Burning solid particles observation

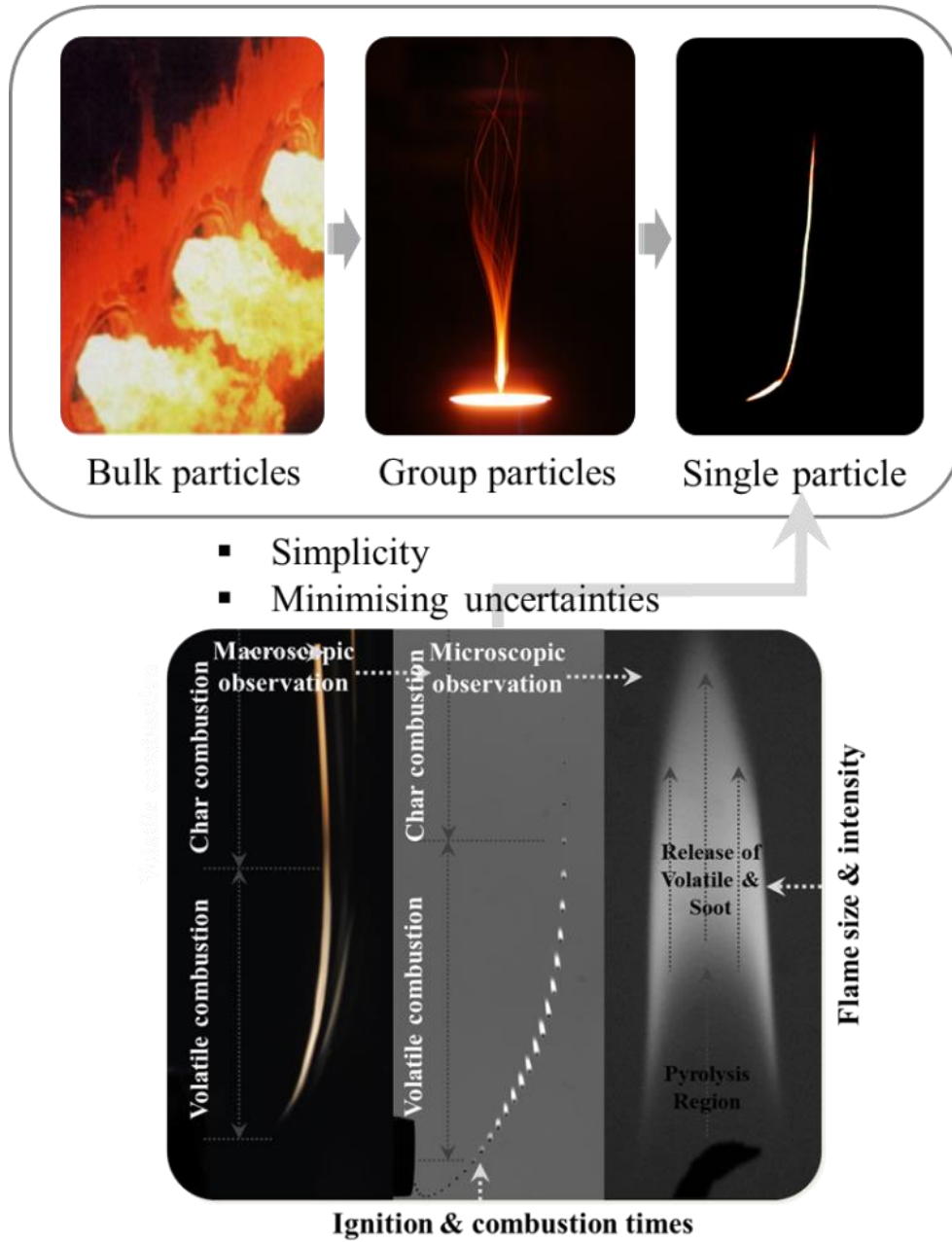


Figure 1-8 Macroscopic and microscopic observation of single burning particle.

1.3 Outline of thesis

This thesis is divided into seven chapters. Chapters 4–6 are based on the paper works listed in Fig. 1-9.

Chapter 1 gives the background of this thesis. The increase in energy consumption and carbon dioxide emission has led to a demand for renewable energy, and biomass combustion is a feasible short-term energy technological solution to replace coal-fired combustion. This chapter discusses the aims and objectives of the experimental investigation into biomass single-particle combustion.

Chapter 2 discusses previous research on single solid-fuel-particle combustion, including direct observation and modelling of single particles. Chapters 4–6 considers experimental research to review biomass combustion characteristics, biomass torrefaction and co-firing combustion for improved fuel-combustion quality.

Chapter 3 explains the experimental approach used herein in detail, including the setup of the laboratory-scale entrained flow reactor, the well-controlled environmental conditions, particle separation and direct observation technique.

Chapter 4 describes the combustion of pulverised biomass particles (torrefied wood, coffee waste and sewage sludge) and compares it with that of coal particles (subbituminous coal). Particles ranging size from 150–215 to 425–500 μm were burned in an entrained flow reactor with cross-jet injection at a rapid heating rate and high temperature. These enabled a description of the combustion process. The development of the flame structure is described as a function time and particle displacement.

Chapter 5 assesses the fuel combustion quality of raw solid fuel and three types of torrefied-sewage-sludge particles created under different pre-thermal temperatures and residence times. The first publication details how raw sewage sludge has poor energy quality and a long ignition delay with a relatively low sooty flame. However, torrefaction can improve flame stability, radiative heat transfer and particle energy density. Particles 150–215 and 255–300 μm in size are

entrained into a hot gas stream. This quantitative analysis is done to demonstrating the effect of torrefaction with valuable desirable flame parameters and ignition.

Chapter 6 studies co-firing of single solid-fuel particles of mixed coal and biomass. This type of combustion is a feasible option in industrial power plants because it provides environmental and economic benefits, such as the reduction of carbon dioxide, sulphur oxide and nitrogen oxide, fuel price stabilisation and fuel flexibility. This chapter focuses on the flame characteristics, such as flame size and intensity, from single particles of coal, 50:50 coal:wood, 20:80 coal:wood and wood. The effect of oxygen concentration and particle size is also discussed to investigate the burning characteristics.

Finally, chapter 7 presents the conclusions and discusses future work.

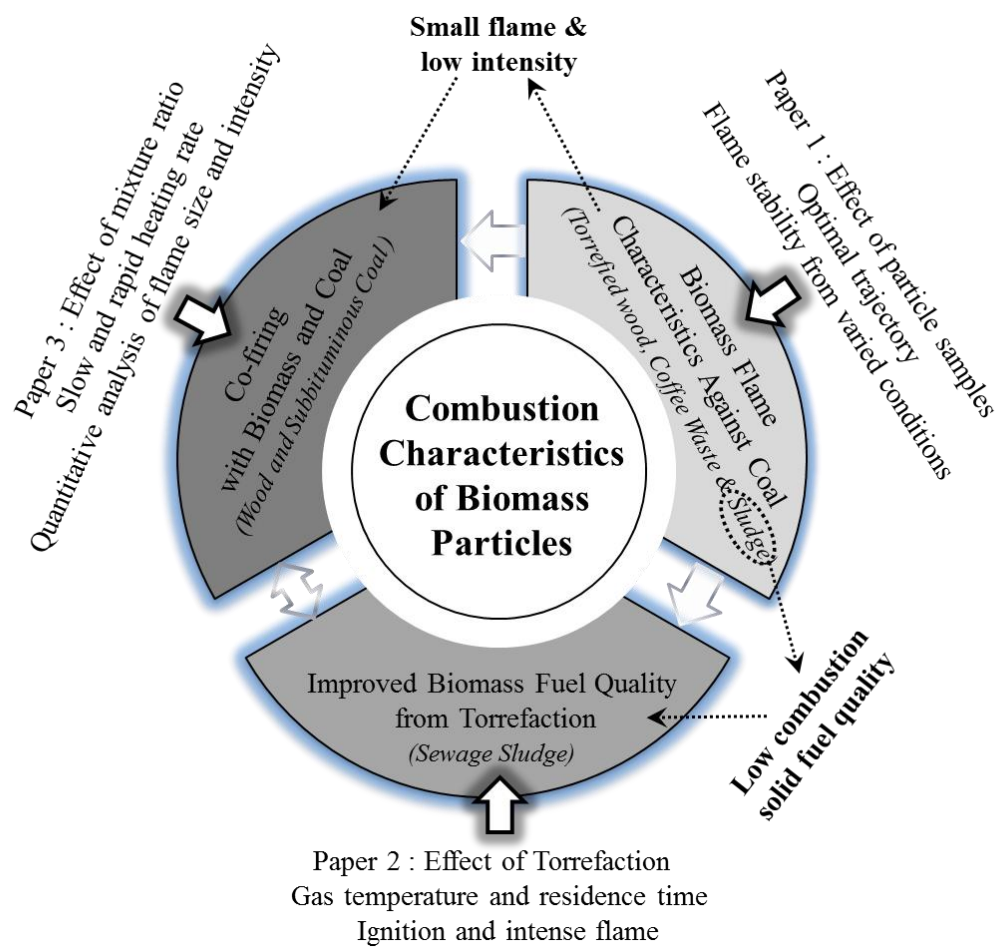


Figure 1-9 Structure of three paper works for biomass particles.

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CHAPTER 2

LITERATURE REVIEW

2. LITERATURE REVIEW

2.1 Combustion of single solid-fuel particle

Experimental investigations of single solid-fuel particles combustion have been conducted along with modelling approaches over the past several decades (Howard et al., 1967; Field et al., 1970; Annamalai et al., 1977; Haynes et al., 1981; Chen et al., 1985; Fletcher et al., 1997, Khatami et al., 2016). In fact, the combustion of a particle involves complicated interactions of physical and chemical events. Therefore, a number of assumptions and simplifications have been made for the single-particle combustion model. This model describes single-particle combustion, including the burning history in which a particle, when exposed to a hot gas stream, ignites rapidly and then starts homogeneous–heterogeneous combustion. This model describes a phenomenon similar to single-liquid-droplet combustion, as the flame-sheet model (Faeth et al., 1977) (see Fig. 2-1), which has been used extensively in research to investigate combustion (Choi., 1985; Timothy et al., 1986; Gururajan et al, 1990). According to the flame-sheet concept, a symmetrical thin flame forms on the particle surface (assuming a stoichiometric ratio).

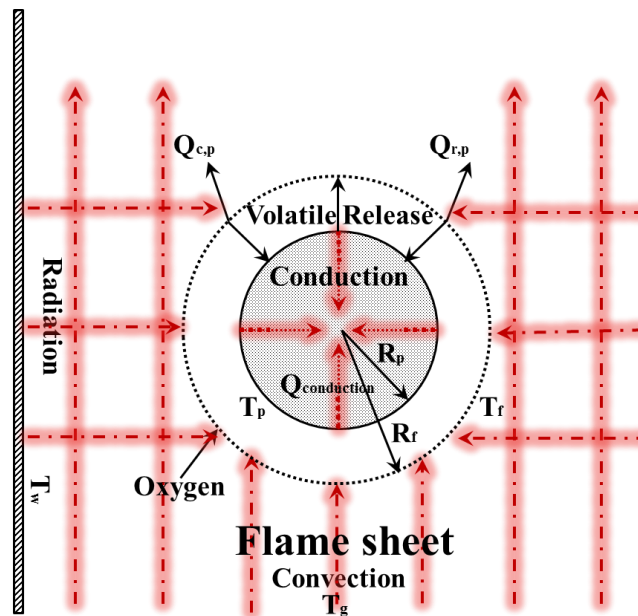


Figure 2-1 Schematic illustration of flame-sheet model in a vertical hot gas stream.

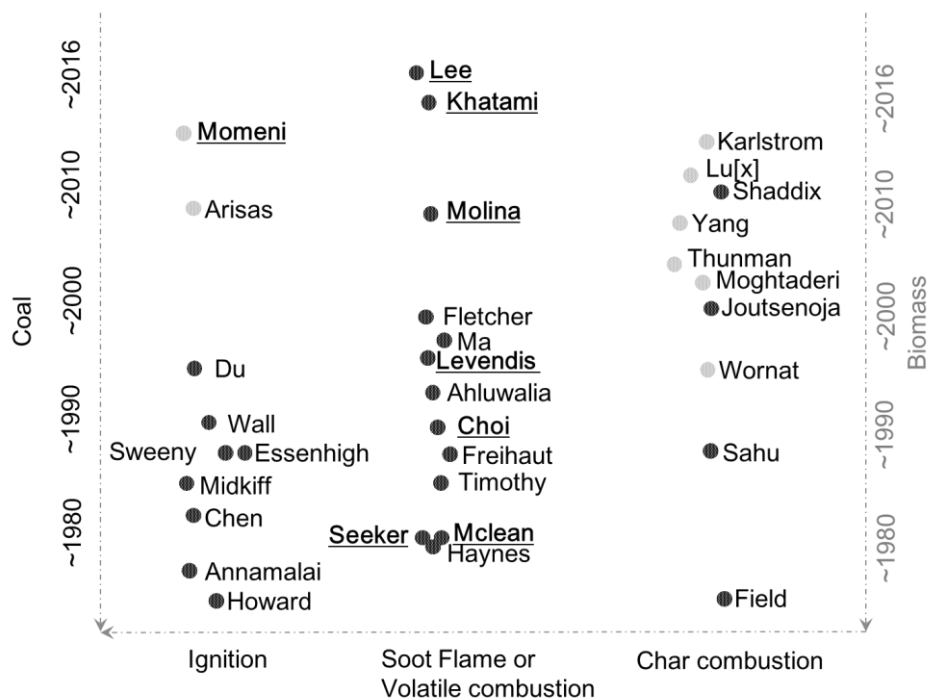


Figure 2-2 Previous literatures from ignition to char combustion.

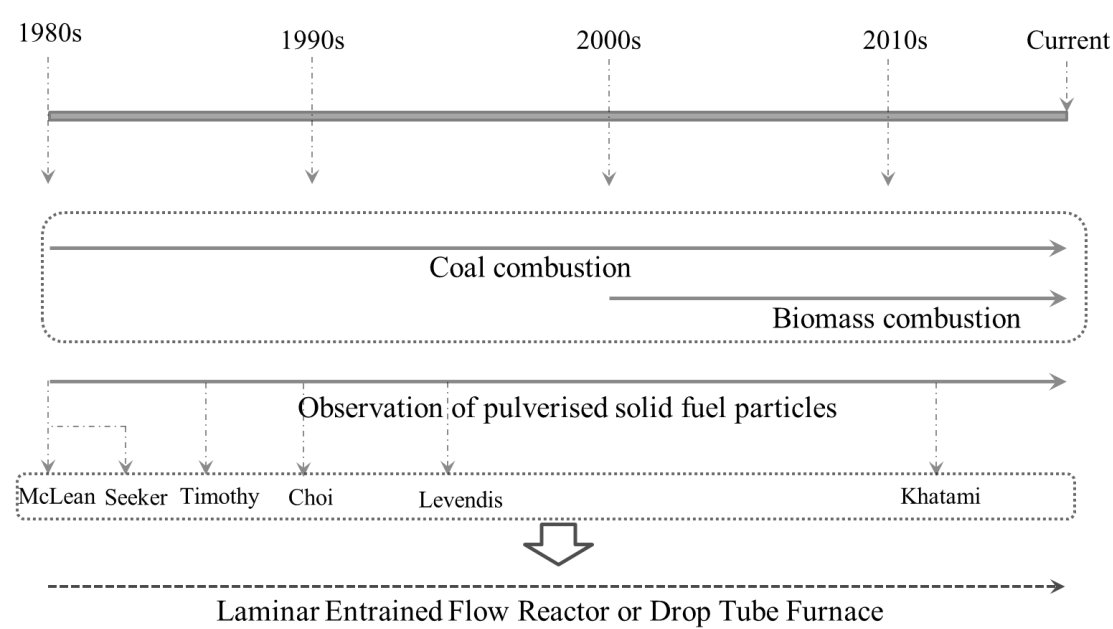


Figure 2-3 Previous literatures of single particle observation.

2.2 Thermal conversion of solid fuel particles

A particle entrained into a hot gas stream is heated up by conduction, $Q_{c,p}$ and radiation, $Q_{r,p}$ from the hot gas flow and from the surrounding wall. Next, volatile and char combustion occurs upon contact with the surrounding oxygen (Choi et al., 1985; Toporov, 2014). These processes are classified as ignition, devolatilisation and char combustion. Figure 2-2 summarises previous researches in terms of combustion events involving coal or biomass particles.

$$Q_{c,p} = h \cdot A_p (T_g - T_p) \quad (2-1)$$

$$Q_{r,p} = \sigma \cdot \varepsilon_p \cdot A_p (T_w^4 - T_p^4) \quad (2-2)$$

where h is the heat transfer coefficient, A_p the particle surface area, T_g is the gas temperature and T_p is the particle temperature. σ is the Stefan-Boltzmann constant, ε_p is the emissivity coefficient and T_w is the wall temperature.

2.2.1 Ignition

Particle ignition has long been of interest (Annamalai et al., 1977; Midkiff et al., 1986; Sweeny et al., 1989; Du et al., 1994). Ignition is affected by fuel properties, particle mass, heating rate and the temperature of the surrounding gas (Essenhig et al., 1989; Wall et al., 1991), which results in a wide range of ignition temperatures (Zhang et al., 1993). In particular, the ignition characteristics of biomass are not identical to those of coal because of widely differing physical and chemical features between the two materials. Grotkjaer et al., (2003) investigated ignition temperature for wheat straw and wood under pulse ignition and thermogravimetric conditions. They reported that for high volatility fuels, ignition temperature decreases with increasing volatile matter, and that this temperature is independent of particle size for low-volatility fuels. Therefore, wood particles have a significantly lower ignition temperature than coal particles. Kuo et al. (2005) investigated the ignition of single wooden spheres heated in a hot gas stream and found different ignition times and modes (smouldering or flaming ignition) in three types of wood spheres. However, all spheres ignited directly with a flame

at high temperature. The researchers attributed the results to the exchange of thermal energy between the volatile matter and the wood.

2.2.2 Devolatilisation

After ignition, volatiles from coal or biomass particles are released with a certain amount of soot particles, thereby forming a volatile flame (Samuelsen et al., 1981; Haynes et al., 1981; Timothy et al., 1988; Fletcher et al., 1997; Demirbas 2004; Rianza et al., 2014). The physical structure of the volatile flame is determined by the fuel type, the surrounding gas temperature and the heating rate (Levendis et al., 2011; Khatami et al., 2016; Mock et al., 2016). In particular, previous research indicates that particle shape and size significantly influences biomass devolatilisation (Liliedahl et al., 1998; Yang et al., 2007; Lu et al., 2010). Lu et al., (2010) investigated the effect of particle size and shape: flake-like, cylindrical-like and spherical-like shapes of wood particles. They reported that the spherical-like particles exhibit less volatile and more tar yields relative to irregular-shaped particle with the same mass. The volatile yields decrease with increasing particle size for all particle shapes. They claim that these discrepancies are due to the particle temperature history and longer average path lengths travelled by tars given the spherical-like shape.

2.2.3 Char combustion

The char combustion of coal has been the subject of numerous fundamental studies (Field, 1970; Sahu et al., 1987; Joutsenoja et al., 1990; Murphy et al., 2010), and the char combustion of biomass has also been scrutinized to improve char conversion and reactivity (Wornat et al., 1996; Thunman et al., 2002; Meesri et al., 2003; Biagini et al., 2009; Li et al., 2015). The char particle of biomass differs significantly from that of coal because of its lower particle density, irregular shape and high porosity.

Wornat et al., (1996) investigated the combustion reactivity of char obtained from pine wood and switchgrass. They reported that both biomass chars are highly reactive—comparable to the reactivity of highly volatile bituminous coals. The

reactivity of the chars decreases somewhat during char combustion because the inorganic constituents experience physical and chemical transformation, and because more reactive carbon is oxidised in the early stage.

To investigate the effect of the surrounding gas temperature, Biagini et al., (2009) studied the char combustion of cacao shells and olive cake in a drop tube reactor. They also observed softening, swelling, melting and bubbles. Li et al., (2015) studied the char reactivity of raw and torrefied biomass produced under real-furnace conditions and found that the torrefied biomass is less reactive than the raw biomass because of pre-thermal conversion of the biomass.

2.3 Direct observation on pulverised single solid fuel particle

Several investigations of combustion events have employed direct observation (McLean et al., 1981; Samuelsen et al., 1981; Timothy et al., 1986; Choi, 1989; Bejarano et al., 2007; Molina et al., 2007; Khatami et al., 2012). Observations of particles were made by optical photography in a laminar entrained flow reactor or in a drop tube furnace. The results provide insights into the morphological characteristics of solid-fuel particles burning in a hot gas flow; be it in ignition modes, flame tails or soot clouds. Such techniques of observation remain an effective tool for tracking volatile flame and obtaining the burning-particle history.

2.3.1 Coal combustion

By direct observation, Mclean et al. (1981) studied the two different-rank coals in the early combustion stage: these particles burned under various combustion conditions. They insisted that ignition is characterised by the initial release of bright volatile matter and that the volatile flame forms a condensed soot-like phase from pyrolytic cracking of hydrocarbons. However, this soot cloud is not observed during devolatilisation of lignite particles. The difference between lignite and bituminous coal was attributed to different chemical compositions, because lignite emits mostly CO, CO₂, H₂O, H₂ and light hydrocarbons whereas bituminous produces both light and heavy hydrocarbons.

By using high-resolution holography, Samuelsen et al. (1981) observed single particles that first form a volatile cloud and then generate soot particles. They claim that this morphological result reflects the flame formation and structure and the soot shape and size. Timothy et al. (1986) studied the combustion of three bituminous coals by using high-speed photography and two-colour optical pyrometer. The photography monitored the flame shape and combustion duration and the soot cloud was observed to form a nearly spherical shell, which explains the flame-sheet model. The shell reportedly increases with decreasing oxygen concentration.

Choi (1989) investigated the early combustion stages of a bituminous coal in an upward-flowing hot gas environment. He also used high-speed photography to make direct *in situ* observations and confirmed that bituminous coal particles generate an intense luminous flame following the heat-up regime. A concentric volatile cloud then appears with a tail-like structure. Choi claims that the volatile flames occur in gaseous, solid or condensable phases and that flames from small particles have a high percent of gaseous phase because of rapid mass ejection from the surface.

Khatami et al., (2012) observed the combustion of different types of single coal with different oxygen concentrations in a bench-scale, transparent drop tube furnace. The experiment was done with both the injector and furnace in quiescent gas conditions. They reported that the combustion is very disparate on the rank of coals. The bituminous particles appeared to undergo physical deformation, such as softening, melting, swelling and the formation of large blowholes and had a very luminous flame with large co-tails. Lignite underwent extensive fragmentation followed by ignition with no apparent volatile combustion. The results also depict the combustion process as having little relative motion because of the quiescent environment, although heat-up, devolatilisation and char combustion time were not clearly reported with the quantitative flame structures.

2.3.2 Biomass combustion

The observation of burning biomass particle is a challenging task as biomass has a low soot flame due to their chemical and physical structure with low particle density. The burning behaviours of the biomass are very depending on their shape and size. There are rare researches for the combustion characteristics of pulverised biomass particles.

Khatami et al., 2014 evaluated the combustion behaviours of sugar cane bagasse, pine sawdust, torrefied pine sawdust and olive residue in a drop tube furnace. The samples of 75-150 μm were burned at 1,400 K and varied oxygen mole fractions (21-50 %) and, the optical pyrometer and high speed camera were implemented to demonstrate the ignition and combustion events. They reported that the biomass has a spherical enveloped flame and the volatile combustion was significantly longer than the char combustion, compared with coal particles. The combustion behaviours are a wide variation in types of biomass.

2.4 Torrefaction of biomass

Torrefaction of biomass is one method to transform biomass particles into coal-like solid-fuel particles. Several studies have established the benefits of torrefaction, such as grindability, shortened ignition time and flame stability (Bridgeman et al., 2008; Van et al., 2011; Chew et al., 2011; Bach et al., 2015; Kihedu, 2015).

Bridgeman et al. (2007) torrefied different biomass types under various torrefaction conditions, and the combustion characteristics of raw and torrefied biomasses were investigated by various thermal analyses. The result was that, compared with raw biomass, torrefied biomass produces greater heat during both volatile and char combustions. The torrefied samples began char combustion quickly because of the reduction of volatile matter, although the char combustion was slower in the torrefied samples.

Kihedu (2015) studied the combustion of torrefied particles by thermogravimetric analysis and found that the physical structures in the torrefied cellulose and

biomass particles changed significantly under torrefaction whereas lignin was not deformed. The combustion of the torrefied particles was slightly slower than that of the raw particles.

2.5 Co-firing of biomass and coal

Several studies of industrial applications of co-firing have been done to determine the environmental and economic benefits (Spliethoff et al., 1998; Tillman et al., 2000; Baxter, 2005; Sahu et al., 2014). Co-firing was found to be a feasible option to reduce the emission of carbon dioxide and to improve fuel stability with price stabilisation. Experimental investigations demonstrated the ignition characteristics and the profiles of chemical reactions by using thermogravimetric analysis (Biagini et al., 2002; Ahn et al., 2014). Unfortunately, no direct observation has been reported the combustion of mixed single particles of pulverised size.

Lu et al. (2008) used vision-based measurement techniques to study the flame from coal-biomass in an industrial-scale combustion test facility. They measured the ignition points, brightness and flame temperature to gain insight into the impact of co-firing coal and biomass. These combustion parameters provided valuable information on the performance of this combustion and on flame characteristics. They reported that the ignition point is determined by the biomass fuels because of their combustion characteristics and that the flame stability depends only weakly on the biomass mixture ratio. However, experimental uncertainties remain, such as particle loading, particle size and environmental conditions.

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CHAPTER 3

EXPERIMENTAL METHOD

3. EXPERIMENTAL METHOD

This chapter discusses particle-sample preparation, laboratory-scale entrained flow reactors and the environmental conditions of combustion. In fact, observing burning pulverised biomass particles is difficult because of their extremely irregular shape and the resulting low flame intensity and fast devolatilisation. A well-controlled reactor, sample preparation and separation and direct observation make such an investigation of biomass combustion possible and provides valuable experimental data to compare with models that describe these biomass particles. The preparation of torrefied particles and co-firing particles created under special treatments is also discussed for single-particle combustion.

3.1 Samples

3.1.1 Biomass particles

For the work discussed in Chapter 4, three types of single biomass particles were prepared to compare their combustion with that of subbituminous coal particles. The first type of single biomass particle consisted thermally treated torrefied wood, which formed a pellet at 573 K. The second type consisted of coffee waste, which is the residue of extracted coffee waste. Finally, the third type consisted of sewage particles, which are made of waste materials and closely resemble a stiff clay soil with a less porous surface. To prepare samples for this experiment, pellets of torrefied wood, coffee waste, and sewage sludge particles were milled and then sieved to obtain particles ranging in size from 150–215 to 425–500 μm , as shown in Fig. 3-1. For sieving, seven sieves of differing pore diameters were prepared: 150, 215, 250, 300, 355, 425 and 500 μm . However, the particle shapes after sieving remained extremely irregular. In the experiment, only spherical particles were used to minimise physical uncertainties and regulate particle trajectories. Irregularly shaped particles, including extremely flat and cylindrical particles, are not suitable for the cross-flow configuration. Such particles can lead to a non-quantitative analysis of burning particles due to undefined drag coefficients and random, non-uniform particle trajectories.

3.1.2 Torrefied sewage sludge particles

For the work discussed in Chapter 5, torrefied sewage sludge particles were prepared under different thermal temperatures and residence times. The reason that sewage sludge was selected for this investigation of torrefaction combustion is that this raw particle undergoes poor-quality combustion (based on the results discussed in Chapter 4). Three types of torrefied particles appear under different thermal conditions: 473 K for 30 min, 573 K for 10 min and 573 K for 30 min. The particles were also sieved to obtain particle sizes ranging from 150–215 to 255–300 μm . The torrefaction method of sewage sludge particles is also discussed in the 3.2.2.

3.1.3 Co-firing particles with biomass and coal

Single wood particles with various amounts of coal were prepared to investigate co-firing, the results of which are discussed in Chapter 6. For this study, the biomass consists of pine wood logged in South Korea and subbituminous coal mined in Indonesia by Adaro Energy. Two wood:coal mixture ratios were studied: 80:20 and 50:50. The particles were first separated into three size groups (215–250, 250–300 and 300–355 μm) by using seven sieves with differing pore diameters: 215, 250, 300 and 355 μm . The next section explains how single particles for co-firing were made with various fuel-blending ratios.

3.1.4 Sample properties

All particles were subjected to a proximate and ultimate analysis on an as-received basis, as shown in Table 3-1. This data were acquired by using a thermogravimetric analyser (TGA-701) and an AC600 calorimeter at the Energy and Environment Research Centre of the Korea Advanced Institute of Science and Technology. All biomass contained more volatile matter and less fixed carbon content than the subbituminous coal from Indonesia, and the ratio of volatile matter to fixed carbon of these biomass particles was higher than that of the coal particles. In addition, the chemical composition of these biomass particles varies, which results in significantly differing combustion. For co-firing particles, the

volatile matter and fixed carbon mass fraction of the 50:50 (coal:biomass) blended particles exceeded that of coal particles by approximately +15% and -16.6%, respectively. For the 20:80 blended particles, these figures are +26.7% and -27.7%, respectively. The bulk density of the particles was measured by using a simplified bulk density technique that involves filling a bottle with pulverised particles. The bulk density P_p is given by

$$P_p = (m_{b,p} - m_{b,e}) / V_{b,w}, \quad (3-1)$$

where P_p is the particle bulk density, $m_{b,p}$ is the mass of the bottle filled with particles, $m_{b,e}$ is the mass of the empty bottle and $V_{b,w}$ is the volume of the bottle. Of the solid fuel particles prepared, the subbituminous coal is the densest (0.77 g/cm³) and the raw pine wood is 0.34 g/cm³). The approximate energy density is calculated from the lower heating value and the bulk particle density, which indicates that the coal has almost twice the energy density of the biomass particles.



Figure 3-1 Preparation of pulverised biomass particles by milling and sieving.

Table 3-1 Properties of biomass.

Sample	Proximate analysis (wt. % ar) ¹				Ultimate analysis (wt. % daf) ²					LHV ^{3&1} (MJ/kg)	Particle bulk density (g/cm ³)	Approx. energy density (MJ/m ³)
	V.M	F.C	Ash	M	C	H	O	N	S			
Torrefied wood	69.9	22.5	0.95	6.65	51.5	5.1	37.2	0.2	0	20.50	0.58	11,890
Coffee waste	72.9	11.1	5.8	10.2	49.4	5.7	35.3	2.6	0.4	20.82	0.66	13,741
Sewage sludge	61.2	7.89	25.0	5.91	38.6	5.9	20.6	0.9	0.1	17.14	0.59	10,112
Subbituminous coal (Adaro)	42.0	46.1	1.5	10.4	64.4	4.7	18.1	0.9	0.1	25.43	0.77	19,581
Pint wood	81.5	9.7	0.1	8.5	48.5	6.5	43.2	0.15	0.13	18.23	0.34	6,215
Wood-coal (80:20)	68.7	18.4	1.25	11.7						19.83	0.43	8,527
Wood-coal (50:50)	57.0	29.5	0.56	13.0						21.91	0.57	12,489

¹as received ²dry, ash free ³lower heating value

3.2 Preparation of pulverised biomass samples

3.2.1 Separation of spherical-like particles

The key issue of single biomass particle combustion is how to obtain particles with a spherical-like shape. To separate by shape, we propose to use a novel method involving two inclined planes, as shown in Fig. 3-2, which discriminates between particles based on their translational and rotational motion. We used fibreboard covered with uncoated paper (glossy paper provides insufficient friction for rolling). The angle of the plane with respect to the horizontal was determined from a number of trials, leading to a first plane at 45° and second at 60°, which proved effective for discriminating between particles with differing shapes. Flat-like particles are held at the upper zone of the first inclined plane and cylindrical-like particles are collected at the lower zone of this same plane. For the second plane, spherical-like particles are collected at the lower zone. This method allows groups of flat-like, cylindrical-like and spherical-like particles to be separated effectively. If this shape separation at a pilot scale can be adapted using this method before injection, then ignition, combustion time and flame stability will be improved.

3.2.2 Torrefaction of particles

Torrefied particles were thermally treated at temperature in the range 472–573 K under atmospheric pressure (Van der Stelt et al., (2011) & Ciolkosz et al.,(2011)) and residence time. Hence, raw sludge particles were burned at 473 K and 573 K to study the effect of torrefaction. These parameters are deterministic in the subsequent single particle combustion. During torrefaction, the mass fraction of volatile matter decreases with increasing mass fraction of fixed carbon. Figure 3-3 describes the preparation of three types of torrefied sewage sludge particles, which are used in the work described in Chapter 5. This preparation was done cautiously in several steps. Step 1 consists of a thermal treatment, whereby raw pulverised particles are placed on a ceramic plate in an electric furnace and heated to 473 or 573 K. The particles are held at the given temperature for 10 or 30 min to prepare one of the three types of torrefied particles. In step 2, the

particles are placed on a cold plate to cool them, thereby extinguishing the volatile flame and quenching the devolatilisation. However, during this process, the particles may become wet because of the temperature difference between the ceramic plate and the cold plate. To remove this moisture (step 3), the cooled particles are dried by placing them on a hot plate at 373 K for 5 min. Three types of torrefied sewage sludge particles were prepared via this process: 473 K for 30 min, 573 K for 10 min and 573 K for 30 min.

3.2.3 Co-firing particles

For the work discussed in Chapter 6, we prepared single particles a few microns in size with a coal:wood fuel ratio of 50:50 or 20:80. Figure 3-4 describes the process to create these pulverised single particles, which do not occur naturally. Step 1 consists of milling by species, following which the output is sieved to obtain particle sizes under 100 μm . Step 2 consists of mixing 500 ml of pulverised coal and either 200 or 800 ml of wood particles in a container. In step 3, the particles are first mixed to bond particles. In this process, water are added to 2000 g per m^2 of uniformly distributed particles. Tsuchiya et al.,(2017) reported that moisture adjustment plays a significant role in the pelletization of a group-pulverised biomass with coal because coal does not cohesively lump without additional water. They also noted that the pellet, which comprised 50% brown coal 50% rice bran, added 32.5% water content, which is similar to our experimental conditions. The particles are then pelletized to make pellets. The co-firing particles are obtained by milling and sieving these pellets and separating them by shape as explained above and in Figs. 3-1 and 3-2.

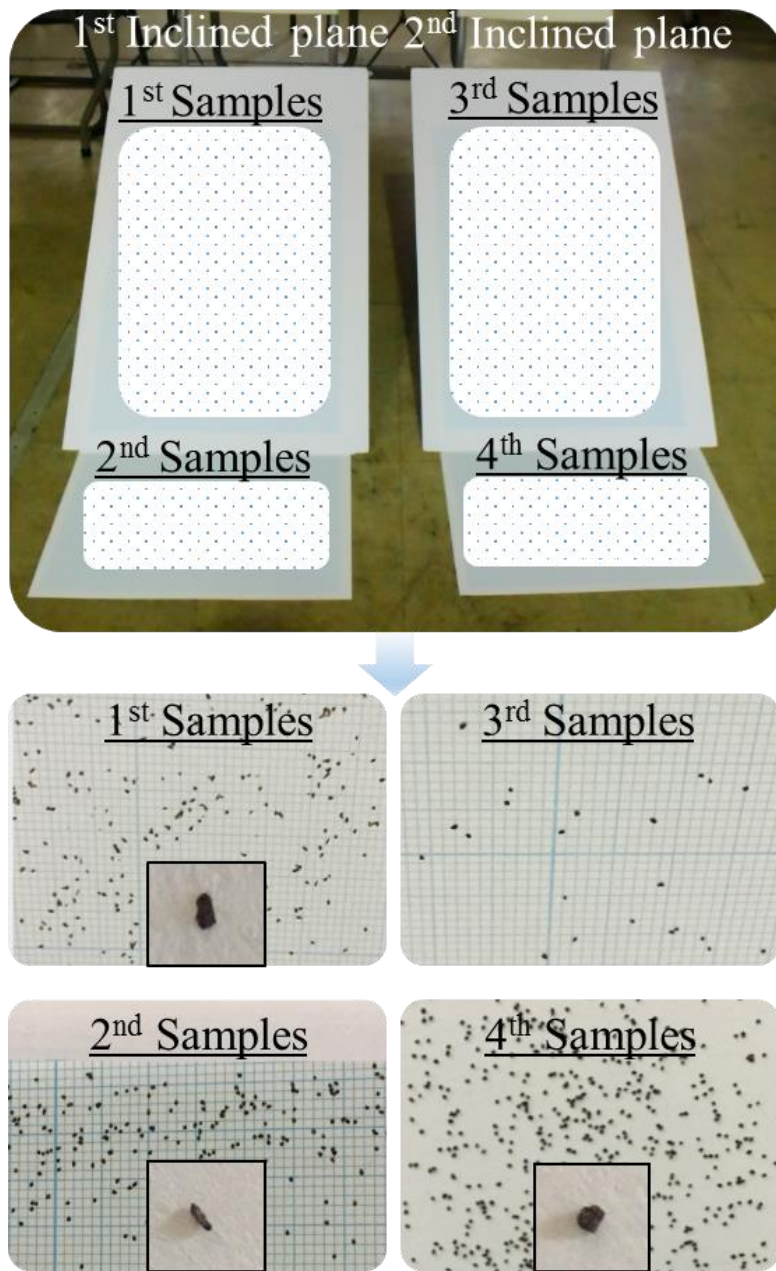


Figure 3-2 Using an inclined slope to separate particles by shape. First (second) plane is inclined with respect to the horizontal at 45° (60°).

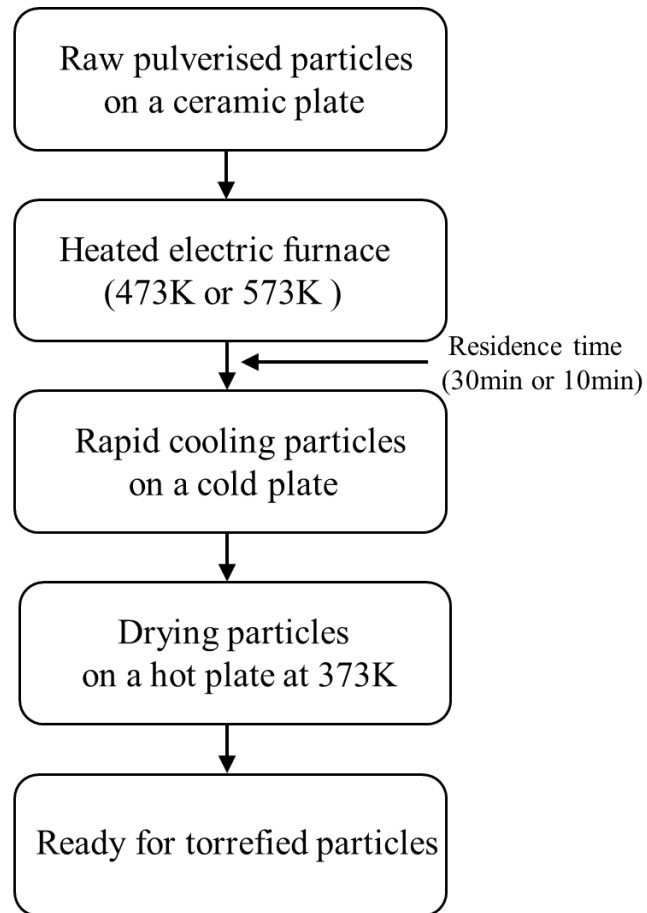
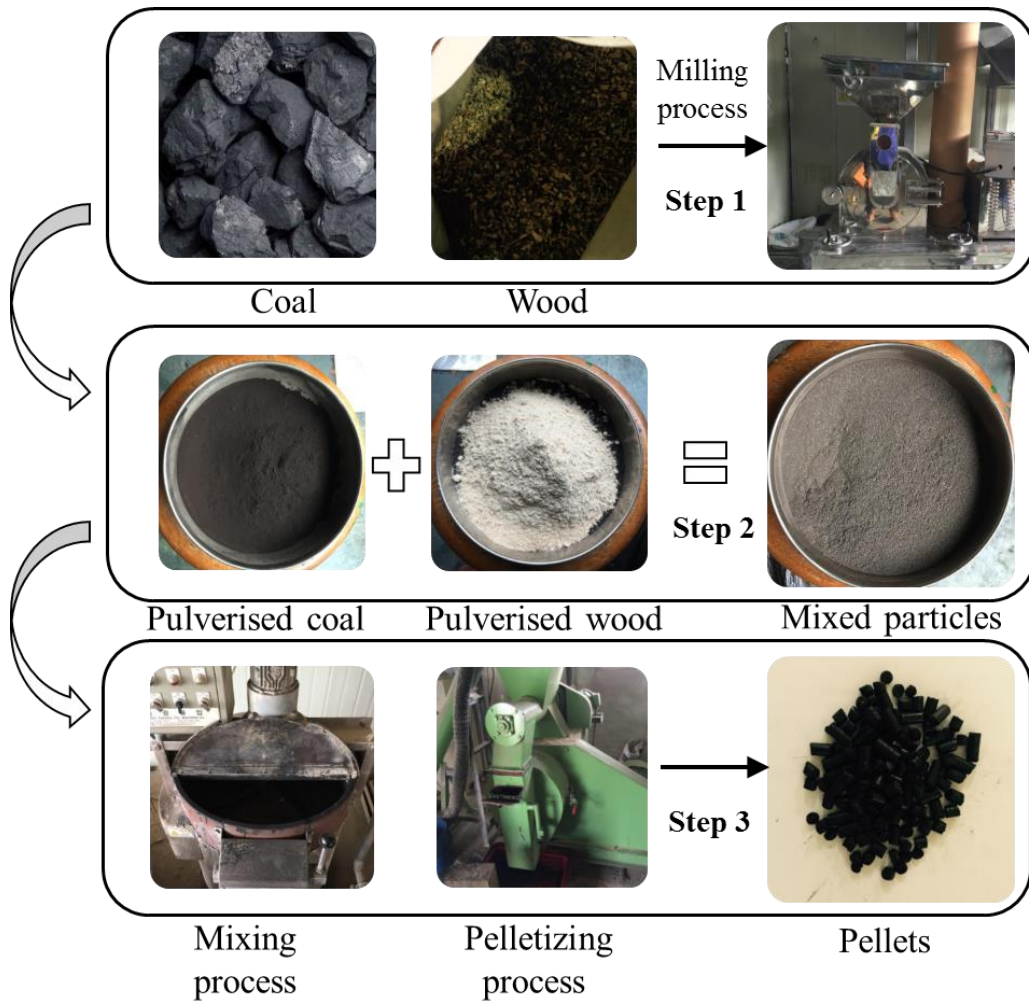


Figure 3-3 Torrefaction process by means of electric furnace. Three types of torrefied sewage sludge particles were prepared via this process: 473 K for 30 min, 573 K for 10 min and 573 K for 30 min.



Step 1: Milling process of coal & wood

Step 2: Mixing process of pulverised coal & wood

Step 3: Pelletizing process of mixed particles

Figure 3-4 Preparation of pulverised particle with coal/wood mixture for co-firing.

3.3 Experimental setup

3.3.1 Laboratory-scale entrained flow reactor

The experiment was done in a laboratory-scale entrained flow reactor, which consists of a rectangular quartz tube, a honeycomb burner, a guard heater, a water-cooled injector and a particle-feeding system, as shown in Fig. 3-5. For optical access to the burning particles, this reactor is equipped with a test section above a ceramic straightener to allow particles to be monitored via a high-speed camera. The injector is arranged in a cross-jet configuration, which is a major difference with respect to a drop tube furnace. The effect of the cross-jet configuration is explained in the 3.3.2. The rectangular quartz is 45 mm × 45 mm × 500 mm to minimise the effect of the refractive index, and the honeycomb burner is positioned at the bottom of the quartz tube. The post-combustion gas flows upward at ~1 m/s in a hot gas stream. The electrical guard heater shields the quartz to minimise the temperature difference except at the test section through which the particles are observed. Inside the reactor, particles are entrained into the hot gas stream by a cold carrier gas and then ignite immediately near the tip of the injector. Figure 3-5 shows the temperature gradient in the test section as determined by a simulation done with Fluent 13.0.

The experimental procedure is described by the flowchart in Fig. 3-6. Prior to particle injection, environmental conditions such as the hot gas stream and oxygen concentration are prepared. The next step is to open an air cylinder before opening a propane gas cylinder to ensure safety; then, ignition starts on the honeycomb just after opening the valves of the oxygen and propane gas cylinders. To maintain a uniform hot gas temperature and flow velocity, the guard heater is heated to 1073 K. An air jet flow is then entrained into the hot gas flow prior to particle injection. These steps play a crucial role in the reproducibility and quantitative analysis of burning particles.

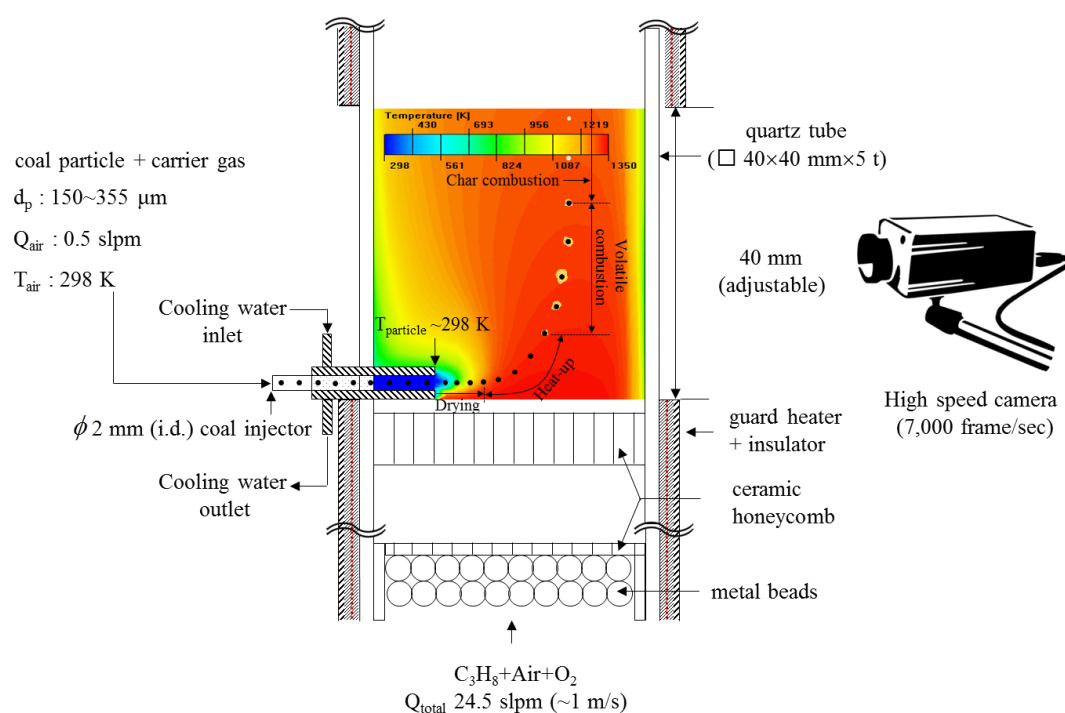


Figure 3-5 Schematic of laboratory-scale entrained flow reactor.

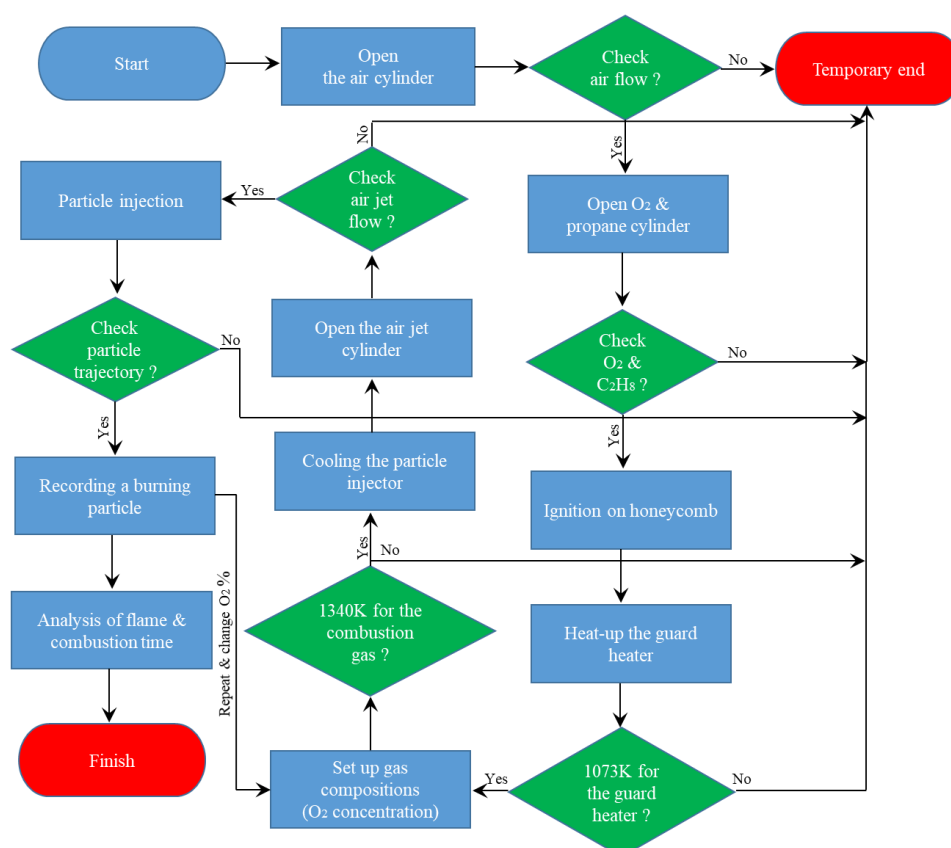


Figure 3-6 Flowchart describing the experimental procedure.

3.3.2 Cross-jet flow configuration

Turbulent mixing in the flow of a cross-jet configuration is a common feature of practical burners for fuel injection (Ryu et al., 1997) and, this aerodynamic effect between vertical and horizontal flows plays important role in flame stability, low-emission combustor design and combustion characteristics (Andrews et al., 1992; Elfeky et al., 2014). Current industrial pulverised coal-biomass furnaces use this type of burn design, so the cross-jet injection in the experimental setup is a feasible and realistic feature for investigating particle-burning characteristics. This jet flow in the laboratory-scale entrained flow reactor creates a complicated flow field, which is due to a non-quiescent condition (in contrast to a drop tube furnace, in which the quiescent condition holds with free jet flow; see Fig. 3-7). Most experimental studies to date (Khatami et al., 2012, Riaza et al., 2014) used the quiescent condition. The results are therefore limited to discussions of the quantitative trajectory of burning particles and physical flame structures as a function of time and particle displacement. Conversely, with the entrained flow reactor, the upward-flowing hot gas stream and the leftward-flowing cold carrier gas compensate for the limitations of the flow configuration in the previous studies. The sequential combustion regimes such as heat-up, ignition, and devolatilisation and char combustion can be described based on the trajectory of a burning particle with an apparent volatile flame and a burning char surface (see Fig. 3-8). The interaction of mixing flows enhances particle motion and allows particle mass reduction to be predicted once the combustion characteristics of pulverised particles are determined. The present study does not treat these phenomena but leaves them for future studies.

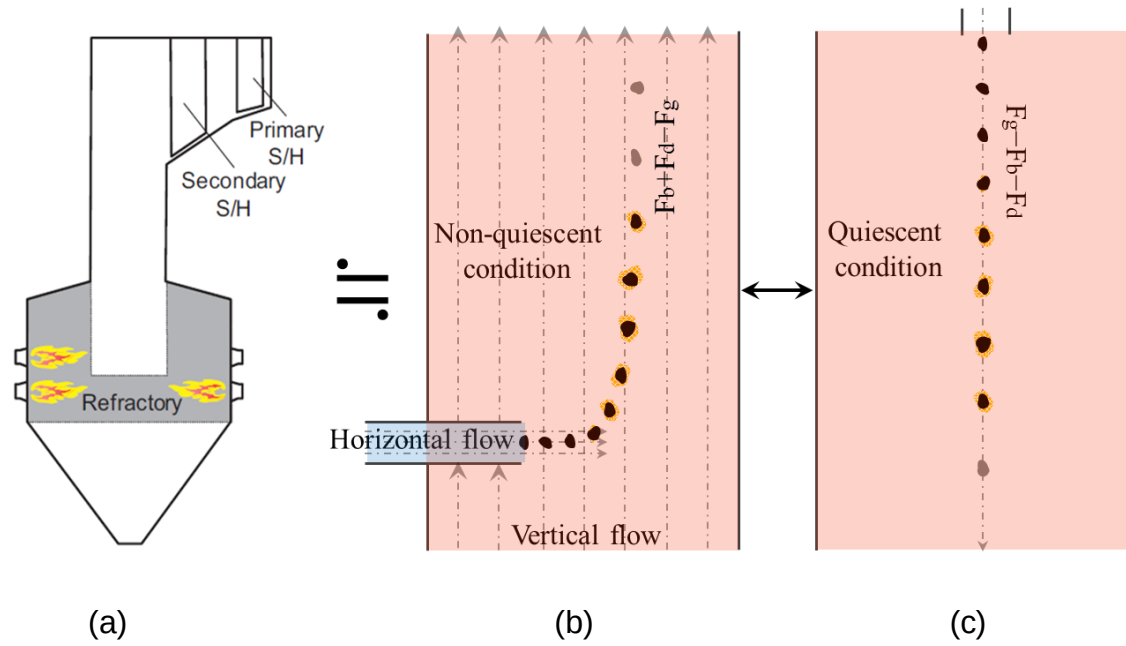


Figure 3-7 Comparison of flow field conditions between current reactor and drop tube furnace: (a) Industrial furnace, (b) Cross-jet configuration, (c) Free jet configuration. The non-quiescent conditions were similar to those of the industrial furnace, as shown in Fig. 3-7(a). Here, the schematic of the industrial furnace was a 100-Me retrofit boiler under oxy-fuel combustion (Park et al.,2013).

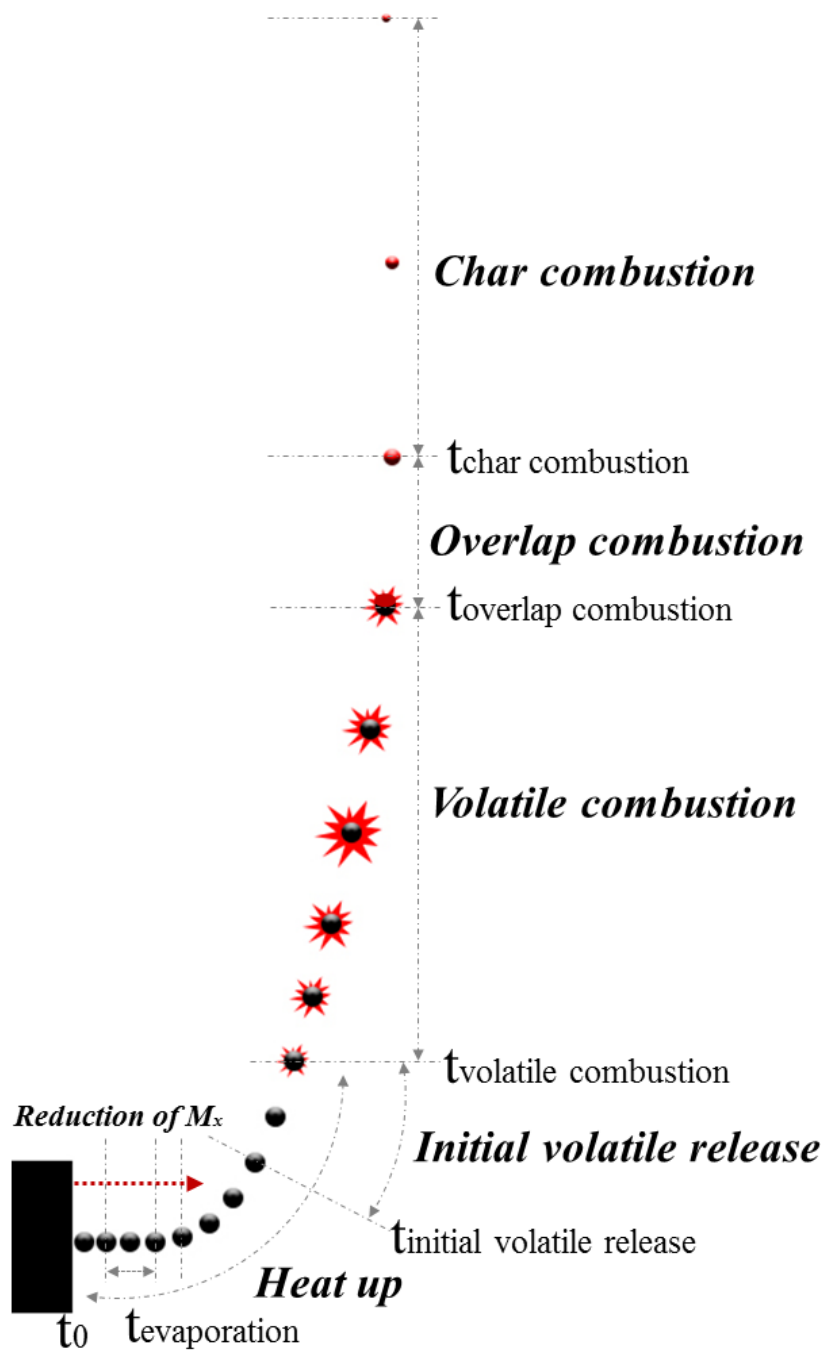
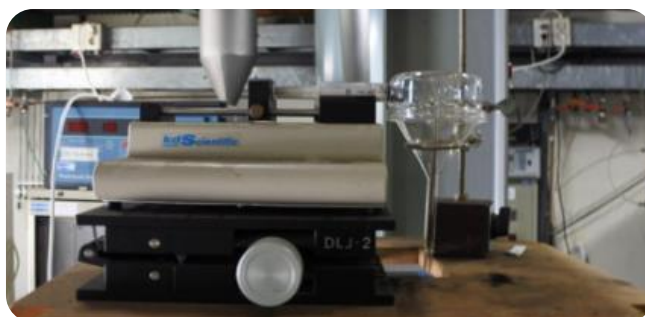


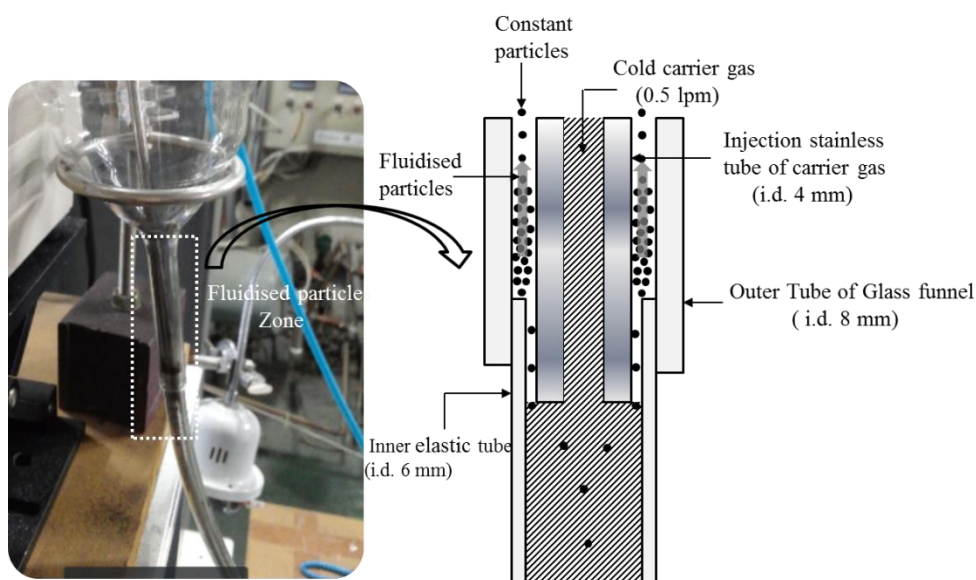
Figure 3-8 Sequential combustion processes in cross-jet injection.

3.3.3 Particle feeding system

The single particle feeder exploits a fluidised bed of solid particles that drop from a scientific syringe injector. The feeder consists of the scientific syringe injector and a glass funnel, as shown in Fig. 3-9. The injector injects a group of particles into the glass funnel at a uniform rate. Backpressure occurs because of a small air gap between an inner elastic tube and the cumulative particles in an outer tube. Finally, the particles in the fluidised bed drop into the particle injector at 20~30 particles/min. The flow rate of the carrier gas is 0.5 L/min for particles in the size range of 150–500 μm .



(a) Scientific syringe injector



(b) Particle-feeding mechanism using fluidised bed

Figure 3-9 Apparatus for particle-feeding system.

3.3.4 Water cooled injector

Figure 3-10 shows the water-cooled injector designed to inject single biomass particles. The main purpose of this injector is to execute the initial volatile release of biomass particles at relatively low temperatures compared with coal particles. If an injector without this type of cooling jacket were placed at the same position in the reactor, the ignition of biomass particles could start upstream of the tip of the injector because of the high temperature inside the injector. Such an event would prevent the clear combustion process as a function of time, especially in the heat-up regime. Thus, the injector consists of three stainless-steel double-walled pipes: an outer pipe with 10 mm outer diameter and 8 mm inner diameter, a cooling-water connection pipe with 6.35 (1/8 inch) mm outer diameter and 4.35 mm inner diameter and an inner pipe with 4.8 mm outer diameter and 2 mm inner diameter. Tap water was supplied continually, which kept the inner pipe under 298 K despite the external wall of the injector being exposed to the hot gas stream.

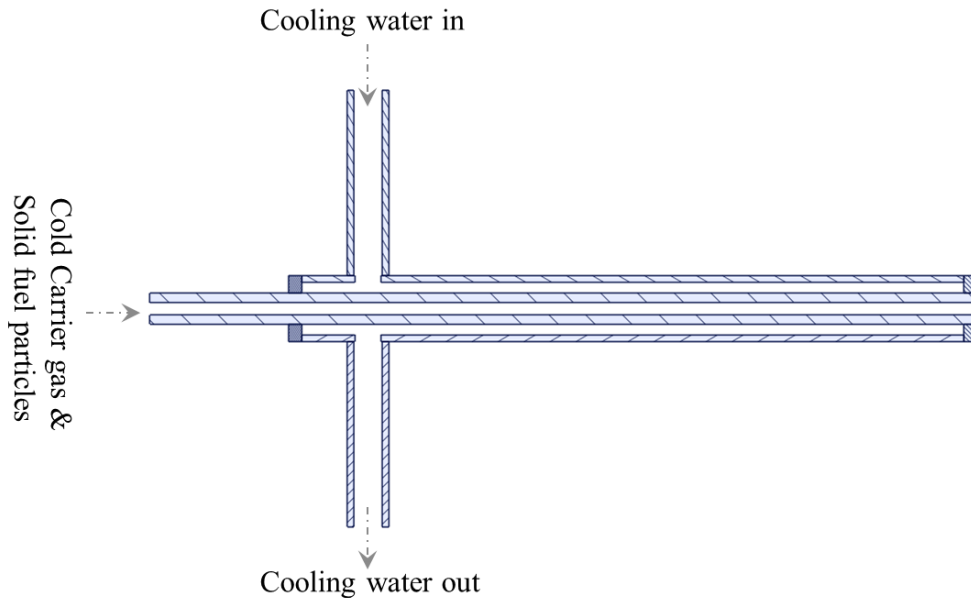


Figure 3-10 Schematic diagram of cooled injector.

3.3.5 Particle observation system

A high-speed camera (Phantom V710, Vision Research, USA) was used to directly observe the burning particles at 7000 frames per second. To enlarge the

particles with combustion events, a micro-lens (Micro-NIKKOR 105 mm, f/2.8, Nikon, Japan) was fitted to the camera. A LED backlight at 5600 K (colour temperature) was installed at the rear of the quartz cell, as shown in Fig. 3-11. Without the backlight, char particles cannot be observed because of the high brightness of the volatile flame. This backlight has controllable brightness and uniform luminescence to provide simultaneously clear images of both volatile flame and char particle. The flame intensity depends on the type of solid-fuel particle and on the environmental conditions. Therefore, the backlight intensity plays an important role in comparing the flame structures. The camera is equipped a 25.6 mm × 16.0 mm CMOS sensor, which provides a resolution of 1280 × 800 pixels. Based on calibration with quantified observation errors, the pixel size was determined to be 58 μm and the exposure time for this pixel size was 1/30 second for all solid particles.

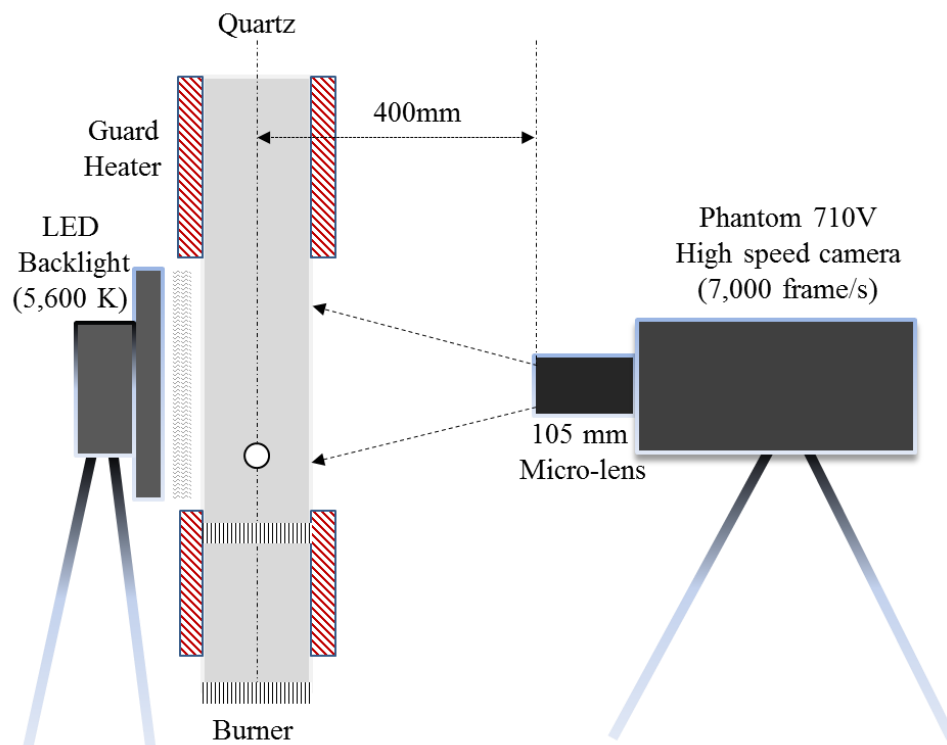


Figure 3-11 Schematic of particle observation system with high-speed camera and LED backlight.

3.4 Environmental conditions

3.4.1 Post combustion environment

C_3H_8 , oxygen and air were supplied to the honeycomb to supply the post-combustion gas stream. The oxygen concentration could be tuned from 10% to 40% in the fixed total flow rate (24.5 slpm) to study the flame characteristics as a function enriched oxygen. The flue gases were N_2 (43.27%–73.27%), O_2 (10%–40%), H_2O (9.56%) and CO_2 (7.17%), as shown in Table 3-2.

Table 3-2 Burner inlet flow rates and equilibrium composition of combustion gases.

Burner gas input [L/min]					
[%]	Equivalence ratio	C ₃ H ₈	Air	Air (Carrier gas)	O ₂
10	0.54	0.6	23.28	0.5	0.62
21	0.36		19.79		4.11
30	0.28		16.93		6.97
40	0.23		13.75		10.15
Equilibrium composition [volume fraction, %]					
[%]	X _{N₂}	X _{O₂}	X _{H₂O}	X _{CO₂}	
10	73.27	10	9.56	7.17	
21	62.27	21			
30	53.27	30			
40	43.27	40%			

3.4.2 Gas temperature and velocity

For optical access to the burning particles, a strong temperature gradient in the quartz is inevitable between the inner wall and centre line of the hot gas stream, so the particle injector was positioned 10 mm from the wall to avoid coming into thermal contact with the relatively low gas temperature. The environmental hot gas temperature was measured using an R-type thermocouple. Figure 3-12 shows the profile of this temperature gradient, and the particle temperature before injection is 298 K because of the cold carrier gas and the water-cooled injector. The mixing zone of the leftward-flowing cold carrier gas and the upward-flowing hot main gas stream appear clearly. The zone of highly interacting flow at 0 mm along the y axis also suffices to affect particle motion and combustion.

Figure 3-13 shows the numerically calculated horizontal velocity profile of the flow velocity. The particles gain momentum in this direction, but their velocity in the horizontal direction decreases rapidly as the particles rise. During the release of volatile matter, the particle velocities vary according to these physical quantities. All experiments were done under identical vertical and horizontal velocities: ~1 m/s for the post-combustion gas and ~2.5 m/s for the cold carrier gas.

Lee et al., 2016 discuss the velocities of post-combustion gas and cold carrier gas in a cross-jet apparatus. During the release of volatile matter, the particle velocities vary according to these physical quantities, so all experiments were done with identical vertical and horizontal velocities.

The CFD simulation was performed in steady state using the pressure-based implicit solver as shown in Table 3-3. The RNG k-epsilon model was used to solve the flow in the reactor in which the flow is compressible. The effect of gravity and the P1 model were then applied for flow direction and temperature gradient. A simple algorithm was used to achieve pressure–velocity coupling with relaxation factors of 0.8 pressure, 0.2 momentum and 1.0 temperature and viscosity. The boundary types and conditions used are presented in Table 3-4. The temperature of the reactor wall and, therefore, the temperature of the injector surface was assumed to be 1173 K, i.e. an adiabatic wall. The actual flow and

temperature of the burner and injector were determined via our experimental results. The mesh was generated from the unstructured grids shown in Fig. 3-14, and there were approximately 850,000 cells to eliminate any errors that may arise. The convergence was achieved by applying residuals of the order of 10^{-7} for energy and 10^{-4} for flow and turbulent kinetic energy.

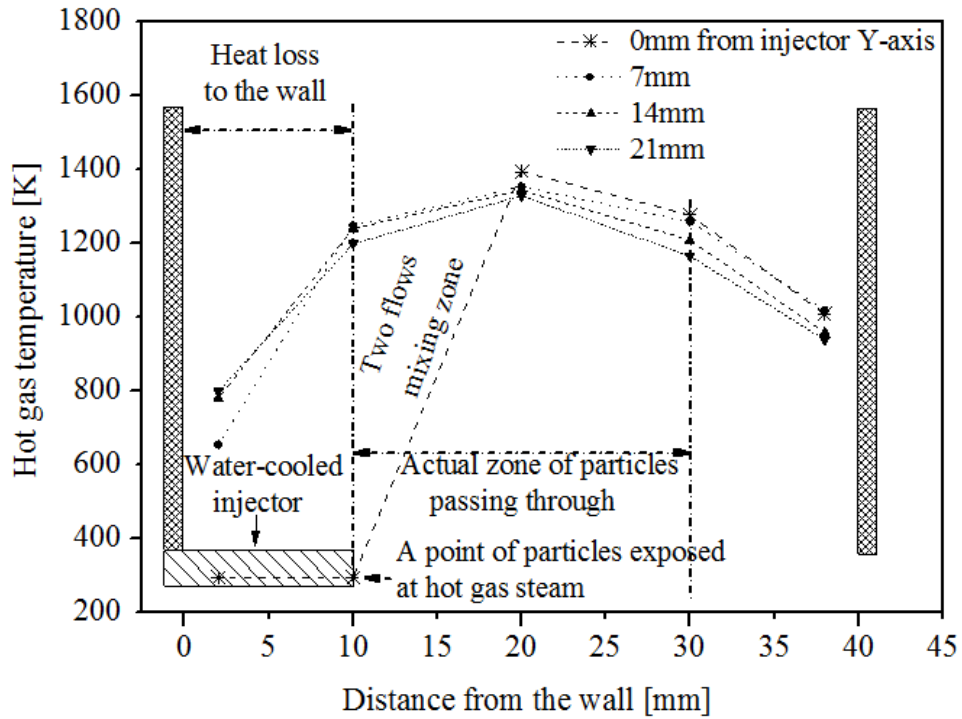
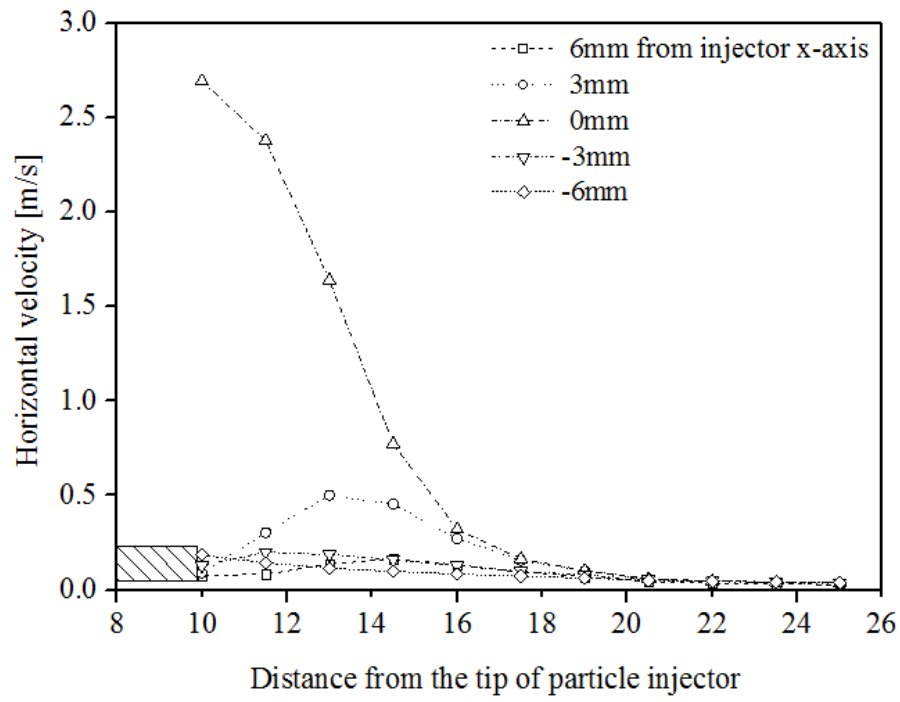
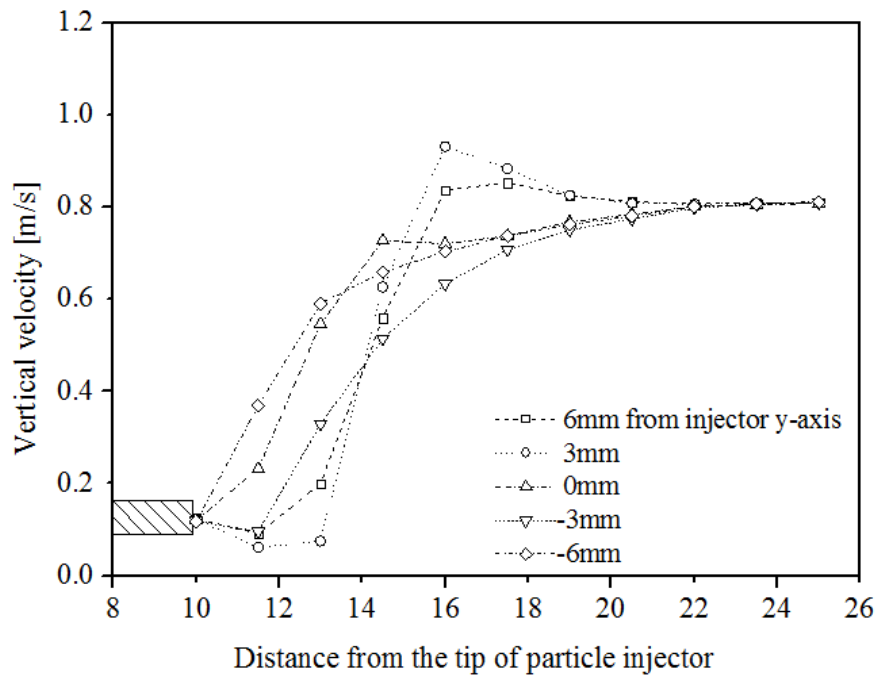


Figure 3-12 Temperature of surrounding gas in optical-access section of laboratory entrained flow reactor.



(a)



(b)

Figure 3-13 Velocity in optical-access section of laboratory-scale entrained flow reactor: (a) horizontal velocity (b) vertical velocity.

Table 3-3 Numerical scheme (Model parameter settings)

Item	Models
Solver	Pressure-based, implicit, steady
	The effect of gravity
Viscous model	RNG k-epsilon
Radiation heat transfer	P1 model
Energy equation	Enable
Under-relaxation factor	Pressure:0.8 Momentum :0.2 Temperature, viscosity: 1.0

Table 3-4 Boundary types and conditions

	Boundary types	Boundary condition settings
Reactor wall	Wall	Temp: 1173K
Injector wall	Wall	Adiabatic, heat flux:0W/m ²
Burner inlet	Velocity inlet	Temp: 1340K, Velocity: 1m/s
Injector inlet	Velocity inlet	Temp: 283K, Velocity: 2.5m/s

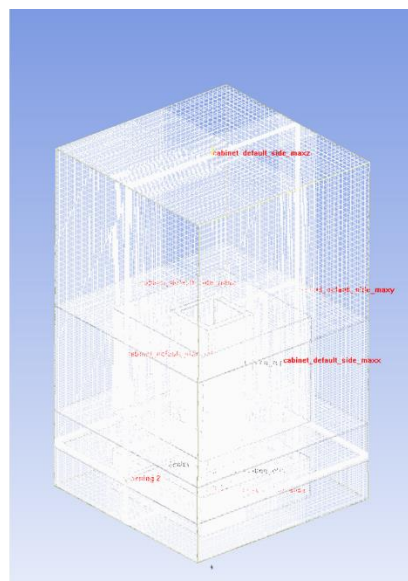
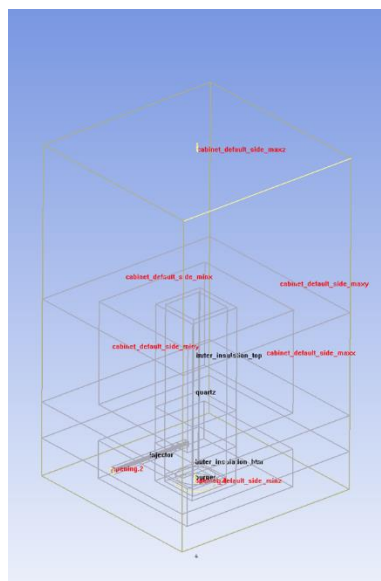


Figure 3-14 Geometry of the reactor and generated mesh for our CFD simulation

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CHAPTER 4

Combustion behaviour of relatively large pulverised biomass particles at rapid heating rates

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4. COMBUSTION BEHAVIOUR OF RELATIVELY LARGE PULVERISED BIOMASS PARTICLES AT RAPID HEATING RATES

4.1 Abstract

A pulverised solid fuel particle in a hot gas stream appears to have different characteristic behaviours at several stages, including heat-up, release of volatile matter, gas phase and solid combustion. The characteristics of these stages may vary distinctly depending on devolatilisation rate, the particle temperature history and its chemical and physical properties. Biomass particles manifest different combustion behaviour from that of burning coal particles under the same combustion conditions because they contain more volatiles (less fixed carbon), and they have a relatively lower particle density due to their fibrous structure. This paper presents an experimental study of burning behaviour of different types of biomass particles (torrefied wood, coffee waste and sewage sludge). The main experimental parameters—gas temperatures of 1,090 K and 1,340 K, and O₂ concentrations ranging from 10% to 40%—were employed to investigate the burning of biomass through a direct-observation approach using a high-speed photography technique at 7,000 frames/s. In the case of firing/co-firing, biomass particles must be larger than the coal particles in order to achieve an equivalent thermal balance due to the higher energy density of coal. Therefore, the selected biomass samples were in the size range from 150–215 µm to 425–500 µm. The experimental setup has a cross-flow configuration for particle injection in order to enhance interaction between the particle and the two different streams—a cold carrier gas at 298 K, and upward-flowing post-combustion gases. It is believed that the employed experimental conditions are similar to those in a realistic furnace with a rapid heating rate of 10⁵ K/s. The experiment significant results, including the effective radii of the volatile flames, degrees of their flame intensity and the maximum size of a particle are important for validation of models of single biomass particle combustion.

4.2 Introduction

Single solid fuel particles have been researched for several decades in an attempt to gain a fundamental understanding of their combustion behaviour. When a particle is exposed to a hot gas stream and a rapid heating rate, it immediately undergoes a rapid temperature increase prior to the release of volatile matter with its initial ignition [1–4]. These thermal decomposition and combustion stages are determined by environmental conditions and the physical structure of the solid particle in relation to its chemical composition [5–7]. In particular, pulverised particles are expected to burn rapidly in industrial furnaces [8, 9] however, particles of this size tend to have inconsistent flame structures and at low heating rates. Observation of these burning particles under rapid heating to high temperature, along with their flame structures and time durations of devolatilisation and combustion, would not be a simple task. Biomass has a great potential as a CO₂-neutral, low-emission energy source of heat and electricity through various applications such as combustion and gasification [10, 11]. However, biomass particles have high compositional variability, a fibrous nature and an irregular shape. They also contain highly volatile matter and are of low particle density. These physical and chemical differences from coal result in dissimilar thermal conversion and characteristic combustion behaviour during the early stages; compared with coal, biomass combustion can offer a faster reaction rate, non-uniform gas-evolution profile and longer volatile-combustion duration [12–14]. However, these kinetic behaviours with flame structures may be inconsistent for different types of biomass and solid waste fuel due to large variation in their physical structures and chemical compositions. The different volatile flames of each biomass type influence on the operating efficiency of their applications because of diverse quantity of radiant energy, which are dominated by flame size and luminosity.

The size of biomass particle in pulverised combustion is expected to be larger than that of the coal particle because of low particle density and faster devolatilisation rate and, the biomass particle are not be pulverised to the same sizes as coal particle due to different milling behaviours and non-economic pre-

processing [11, 15]. The increase of particle size is likely to enhance the ignition delay and quantity of partly unburned residue compared with a small volume of coal [16, 17] in an identical environment. Combustion behaviour is attributed to particle-size distribution and enhanced oxygen concentration as well as combustion temperature. In practical applications, solid particles are generally entrained perpendicularly into a hot gas stream along with a carrier gas at a rapid heating rate of 10^4 – 10^5 K/s [18]. This experiment examines biomass particles under analogous operating conditions, so as to explicitly identify the temporal variations in the burning behaviour of each particle. This is capable of describing faithful combustion processes with gaining a fundamental understanding of each burning biomass particles.

A number of previous experimental observations of particle combustion have been performed using different approaches to investigate ignition delay, kinetics and burnout time [19–22]. McLean et al. [19] introduced direct observation of an early stage of combustion, capturing the burning particle at high gas temperature. This result gave basic evidence of the physical phenomena associated with pulverised coal combustion, such as the development of a radiative volatile flame. Khatami et al. [20] observed combustion behaviour in a quiescent environment and found that biomass has a spherical flame envelope with low luminosity and that the durations of volatile and char combustion decreased with increase in oxygen concentration due to the higher temperatures of the burning particles. Yin et al. [21] also captured informative images of spherical and cylindrical biomass particles to investigate their characteristic behaviour. Although these experimental observations have provided an acceptable fundamental understanding of fuel particles, the combustion of a single biomass particle has yet to be observed, which would provide an outline of the processes of volatile combustion and burnout as well as overlapping combustion. Thus, there is a lack of insight into the combustion behaviour of biomass in pulverised combustion due to the unclear physical structures of the volatile flame. In addition, previous research has rarely focused on the sequential combustion stages of pulverised biomass with quantitative analysis. In the present study, the determination of the optimal burning conditions of pulverised biomass particles is first attempted at a

rapid heating rate under a cross-flow configuration. This layout enables a distinct description of the burning particle that is displaced along with the development of its volatile flame structure as a function of time. In addition, the maximum size of a particle that can be burned completely without dropping to the bottom of the reactor is determined from the interaction between the particle and the two perpendicular streams. Consequently, an explanation of burning particles at these environmental conditions with measured values could be supported for the mathematical model of a single biomass particle.

4.3 Experimental setup

4.3.1 Particle samples and separation

The biomass samples prepared for the experimental work include torrefied wood, coffee waste and sewage sludge, as shown in Fig. 4-1. Torrefied wood was thermal treated by environmental gas temperatures of 573 K. The thermal treatment converts oxygen to CO and CO₂ along with the increase of energy density and hydrophobicity. This torrefied particle contains less volatile matter and relatively more fixed carbon than the raw particle. Coffee waste is the residue of an extracted coffee bean, which is also thermal treated originally, whereas sewage sludge is one of the most widely used waste materials and has the highest ratio of volatile matter to fixed carbon. However, the sludge also has the highest ash content among these particles, which is largely the cause of its low energy density and burnout time. The material analysis of these particles is shown in Table 4-1 and, the proximate and ultimate analysis are based on as received and dry, as free basis, respectively. These analysis data of four solid fuel particles was obtained from TGA-701 thermogravimeter, TruSpec elemental analyser and AC600 calorimeter at Energy & Environment Research Centre, KAIST. From the particle bulk density, the approx. energy density of subbituminous coal particles (19,581 MJ/m³) is almost double times than that of three biomass particles. Torrefied wood, coffee waste and sewage sludge particles have 11,890, 13,741 and 10,112 MJ/m³ of the energy density.



Figure 4-1 Pellets and single particles of the three biomass materials.

Table 4-1 Chemical compositions of biomass

Sample	Proximate analysis (wt. % ar) ¹				Ultimate analysis (wt. % da) ²					LHV ^{3&1} (MJ/kg)	Particle bulk density (g/cm ³)	Approx. energy density (MJ/m ³)
	VM	F.C	Ash	M	C	H	O	N	S			
Torrefied wood	69.9	22.5	0.95	6.65	51.5	5.1	37.2	0.2	0	20.50	0.58	11,890
Coffee waste	72.9	11.1	5.8	10.2	49.4	5.7	35.3	2.6	0.4	20.82	0.66	13,741
Sewage sludge	61.2	7.89	25.0	5.91	38.6	5.9	20.6	0.9	0.1	17.14	0.59	10,112
Subbituminous coal (Adaro)	42.0	46.1	1.5	10.4	64.4	4.7	18.1	0.9	0.1	25.43	0.77	19,581

¹as received ²dry, ash free ³lower heating value

Separation of biomass particles is approached cautiously because of their fibrous and tenacious nature, using several methods, including the pulverisation (Step 1) and sieving (Step 2) processes shown in Fig. 4-2. The step 1 is a preliminary process to pulverise pellets to make small particles. The step 2 separates the sample particles by the different 7 sieve sizes of testing sieves; 150, 215, 250, 300, 355, 425 and 500 μm . To reduce this limitation, the shape separation (Step 3) is used by an inclined plane. It is used to separate different shapes of particles based on their translational and rotational motions. A1 uncoated paper on a fibreboard with high-density were used for the shape separation process because matte and gloss coating papers were too low frictional resistance to apply the

inclined planes. The sand paper may be one of option but, almost dropped particles are remained in a top or middle of the inclined plane when the paper is used. The angle of inclined plane and horizontal dropping of particles were also the significant parameters in the step. The optimum angles were determined by a number of trials; a first plane has 45° and second one, 60° . Finally, high humidity and uncleaned surface must be avoided during the process.

In this experiment, irregular shapes, such as those which are extremely flat and cylindrical with high aspect ratios, are not suitable for the cross-flow configuration. The undefined drag coefficients obtained from these irregular shapes can lead to random trajectories with non-uniform particle motion, resulting in non-quantitative analysis of burning particles. To reduce this limitation, an inclined plane is used to separate particles based on their translational and rotational motions, so as to collect particles of moderate shape, as shown in Fig. 4-2. Particles with flat shapes stop at the upper zone of the first slope as they have the highest friction rate, and cylindrical and spherical particles collect at the lower zone. The slope is then adjusted to have different angles and the separation is run again on only the particles at the bottom, until only spherical particles remain due to their lower inertial force. Using this approach, the groups of spherical, cylindrical and flat shapes are prepared properly.

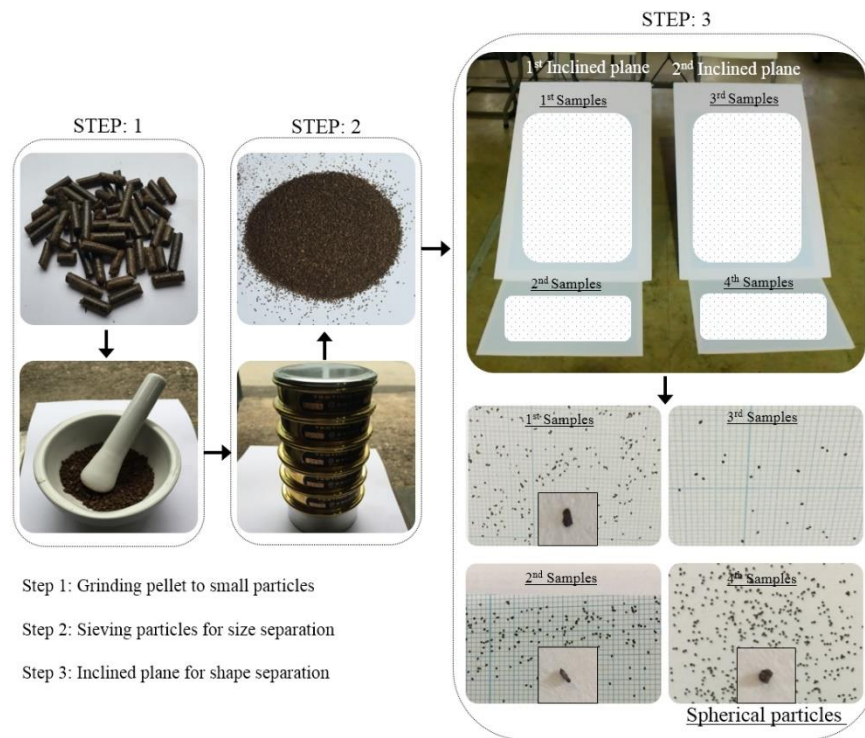


Figure 4-2 Pre-process for particle separation by means of sieving and inclined plane methods.

4.3.2 Single particle reactor coupled with cross-jet injection

The laboratory-scale entrained single particle reactor shown in Fig. 4-3 has its gas temperature, flow velocity and oxygen concentration controlled by the post-combustion gas, guard heater and water-cooled injector. In this environment, a particle is expected to be exposed to a uniform flow at high temperature to reduce experimental uncertainty from the flow straightener. The reactor is made of a rectangular quartz cell of 45 mm × 45 mm × 500 mm to minimise the refractive index for observation of the combusting particle. The water-cooled injector is installed to maintain the initial particle temperature of 298 K and the guard heater forms the external wall of the cell to prevent large losses through heat transfer. The single particle feeder is based on fluidised bed of solid particles that are dropped from a scientific syringe injector. Back pressure occurs in the double tubes, and the particles in fluidised bed are dropped into the particle injector. We measured how many particles were inserted to a hot gas steam in a minute and, the injection rate was 20-30 particles/min. The flow rate of the carrier gas in the

particle injector is determined to be 0.5 L/min to lift particles over 150 μm . The upward and vertical flow velocities are constant for all particles to investigate comparable combustion time and particle displacement.

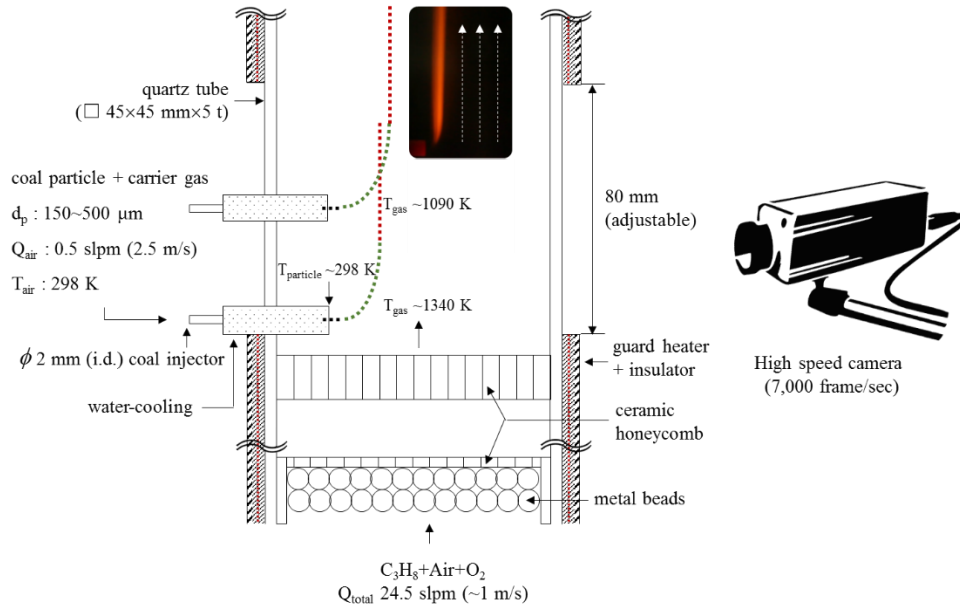


Figure 4-3 Schematic diagram of the experimental setup at 1,090 K and 1,340 K of gas temperatures.

4.3.3 Operation conditions and particle size

The post-combustion gas produces a high temperature in the upward stream from the honeycomb. In the quartz cell, substantial heat loss is inevitable between the wall and a hot gas stream, in which a high temperature gradient appears and particles pass through. The environment gas temperature is calculated on the basis of the radiation loss of the probe of an R-type thermocouple [23]. The temperature profile is shown in Fig. 4-4. The high-mixing zone between the leftward-flowing cold carrier gas and the upward-flowing hot gas stream is clearly shown to affect transient combustion behaviour. Particle temperature before injection remains at 298 K and reaches a certain high temperature as a particle passes through the hot gas stream. To avoid large heat loss, the position of the injector is located 10 mm from the wall.

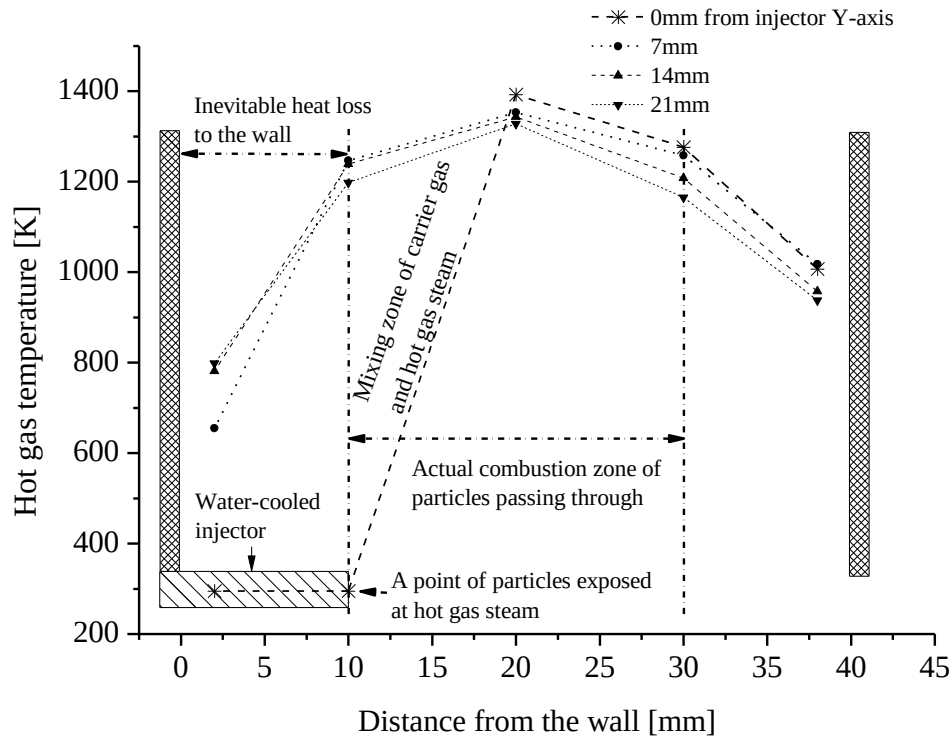


Figure 4-4 Temperature profiles measured from the experiment.

The amount of oxygen is supplemented from 10.4 % to 40.1 % of the total product gases. After the combustion of C_3H_8 , flue gases such as N_2 (38.2–67.9 %), O_2 (10.4–40.1 %), H_2O (12.4 %) and CO_2 (9.3 %) are yielded. The group sizes of the solid particles are prepared in nominal size ranges of 150–215, 255–300, 355–400 and 400–500 μm to determine the largest size at which the particles are burned completely.

4.3.4 Observation of the biomass particles

A high-speed camera (Phantom V710) is used to observe burning particles at 5,000–7,000 frames per second with a micro-lens and back lighting. It is equipped with a complementary metal oxide semiconductor (CMOS) image sensor of size 25.6 mm $\times$ 16.0 mm with a resolution of 1,280 $\times$ 800 pixels, and is capable of recording the motions of particles. This camera enables analysis of the combustion of a single particle in great detail. The observation zone is extended by adjusting the micro-lens, as the prepared biomass particles are larger than

those in previous experiments [24, 25], and the calibration is carried out with a circle-scale reticle. The size of a pixel is measured to be 58 μm and, a light-emitting diode (LED) backlight at 5,600 K (colour temperature) is installed at the rear of the quartz cell. This enables direct observation of a burning particle's ignition, flame structure and char combustion.

4.4 Mechanism of biomass pyrolysis and sequential

Biomass contains a variety of proportions of cellulose, hemicellulose and lignin, which results in variations in the gas-eruption profile and mass reduction that depend on the type of biomass [26]. It is widely accepted that hemicellulose is decomposed at a temperature range of 493–588 K, cellulose at 588–673 K and lignin over a wide range of 433–1,173 K [27]. The typical gases produced by biomass combustion include H_2 , CO, CO_2 , H_2O and CH_4 as light hydrocarbons, as well as tar and char in primary pyrolysis. It is generally assumed that char combustion starts successively after volatile flame is dissipated as volatile evolution is fast enough to move the pyrolysis zone away from the particle surface [28, 29]. This is called sequential combustion processes and, typical sequential process of a particle in the experiment is shown in Fig.4-5. Char combustion may occur in early gas-phase combustion stage, if oxygen reaches the particle surface. This burning behaviour is called simultaneous combustion processes [30, 31]. In the simultaneous combustion, volatile flame does not lift on the surface along with a thin flame structure. Overlapping combustion is attributed to low gas temperature, small particles and type of particle [32]. In addition, the irregular shapes of the biomass particle and the volatility of the flame may be related to the overlapping combustion. Consequently, the physical characteristics of the volatile flame on biomass particles in the early combustion stage are significant role in determining two combustion processes.

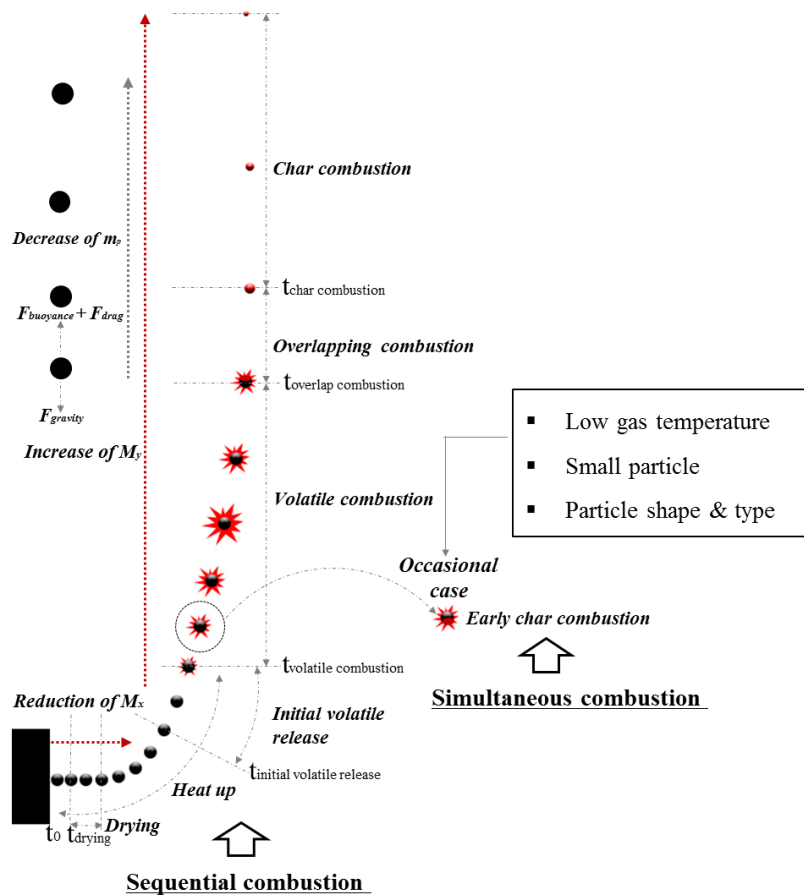


Figure 4-5 Sequential regimes of a solid fuel particle during combustion.

4.5 Results and discussion

4.5.1 SEM images observed from biomass particles

The scanning electron microscopy (SEM) images of the three raw biomass types during the combustion process as shown in Fig.4-6. These particles were collected from the electric furnace where a hot gas temperature is identical to the entrained flow reactor. The burning particle after volatile ignition with the maximum size of flame was ejected from the furnace and then quenched the flame quickly on the cold plate. For the particle image of char combustion, the particle was prepared after extinction of its flame. The NOVA 230 SEM was carried out in KAIST and, the backscattered 9 images were captured in these parameters; Acc.V: 10.0 kV, Spot: 3.0 and Magn: 650-800 x. The external physical structures, with their small pores and irregular shapes, are remarkably

similar between raw torrefied wood and coffee waste. However, torrefied wood contains a high proportion of fibrous cellulose in its transformed structures due to thermal pre-treatment. Raw coffee waste is a physically mixed formation with a number of small cumulative particles along with porosity. Raw sewage sludge closely resembles a stiff clay soil with less porous surfaces. During combustion processes, these raw biomass particles experience an increase in porous surface with a certain swelling due to the melting and softening of the particles. Torrefied wood shows a significant physical transformation at high environmental temperature during the combustion process. Compared with coffee waste and torrefied wood, sewage sludge has numerous cracks on its surface. The particles of all chars are apparently deformed from the shapes of the raw particles due to release of volatile matter and subsequent physical deformation, and the particle volume starts to decrease due to surface oxidation.

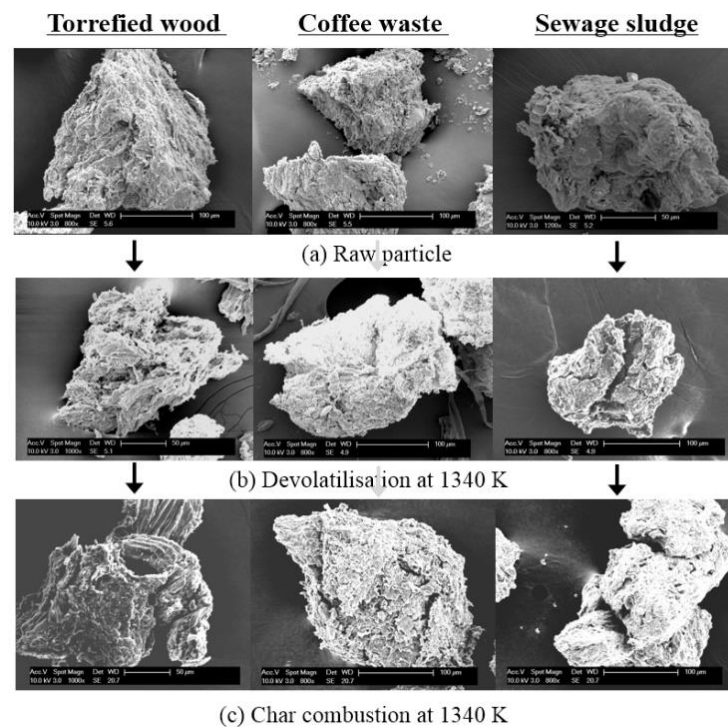


Figure 4-6 SEM images of three different biomass types. In the upper row, raw particles of torrefied wood, coffee waste and sewage sludge are shown and the time series of the physical deformation of these three particles during combustion are presented along each column.

4.5.2 Observation of the sequential combustion process and its characteristic flame structure

For an explicit description of sequential combustion processes, a particle injected from the tip of the water-cooled injector is maintained at 298 K and the combustion is assumed to begin ($t = 0$) when it is exposed to a hot gas stream. The particle is first heated up with initial drying process and then starts to release volatile matter, upon which it is immediately ignited after gas erupts from the solid particle. After these stages, a flame is observed away from the surface of the particle, forming a luminous boundary at which oxidation of the product gas takes place through a secondary particle reaction. The degree of luminosity is dominantly attributed to soot density in the flame and can be increased by using a hotter gas stream or particle temperature. The entire development of a volatile flame from the ignition of the gas phase to its extinction is observed to take place for particle size of 150–215 μm at all oxygen concentrations. Complete observation of the period for particle size 425–500 μm is limited due to limitation of the visualisation field. Photographic images of three particles are superimposed over a time interval of 2 ms in Fig. 4-7. This enables a distinct description of a burning particle as it is displaced along with the development of its volatile flame structure. These results help to predict the mass reduction of particles because of the cross-flow configuration. In this layout, a particle starts drying very quickly in the mixing zone of the horizontal and vertical streams, and then moves in the horizontal direction at high momentum due to the cold carrier gas. After passing through the transient point, rotating particles go upward because of the buoyancy and drag force acting on the particle overcoming gravity.

For sequential combustions at 21 % O_2 and 150–215 μm particle size, different combustion behaviour in terms of residence time and displacement is seen for the four particle types. A coal particle undergoes a sequential combustion process; this particle has a flame with high soot content and experiences a shorter period of volatile combustion than do the three biomass particles because of the presence of less volatile matter. The charred coal immediately experiences oxidation after extinction of the homogenous combustion. On the other hand, torrefied wood and coffee waste have volatile flames with different physical

structures from that of the coal particle. The relatively sooty flame for torrefied wood lasts 30 ms, whereas coffee waste has a very thin flame with duration of volatile combustion of approximately 14 ms. The different durations can be attributed to interactions between volatile matter content and soot formation. An increase in particle temperature leads to a change in its structure because of a high mass-reduction rate. During the combustion process, temperatures of the particle and the flame are much different. Timothy et al. [33] reported that the surface temperature while the flame envelope exists is even lower than the temperature of the flame. Finally, sewage sludge initially has an unclear volatile flame, which then forms a thin, nearly transparent volatile flame at an early stage due to its low carbon content.

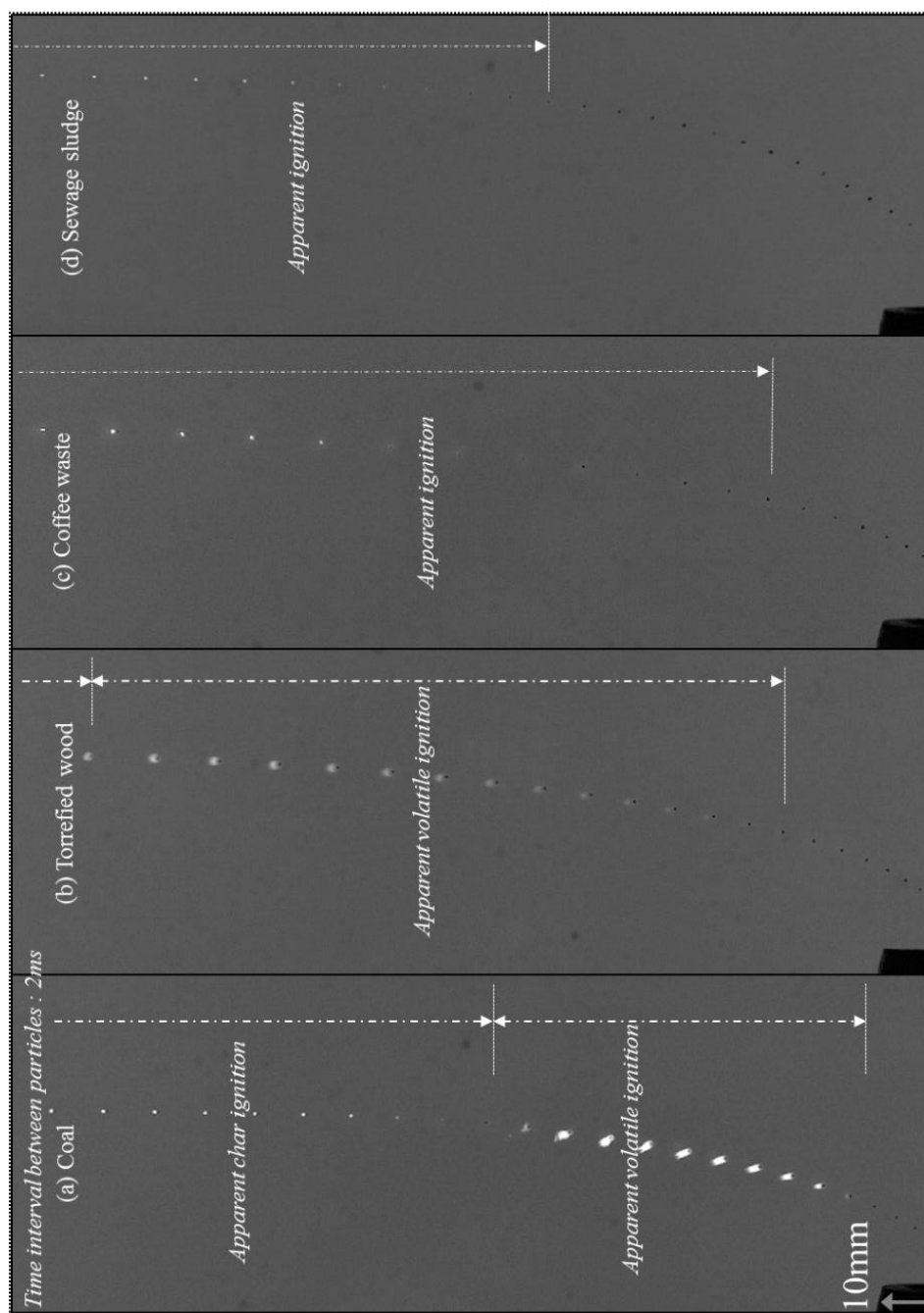


Figure 4-7 Sequential combustion process including overlapping and char combustion for 155–215 μm particles of four different samples at 21 % oxygen concentration and 1340 K: (a) sub-bituminous coal, (b) torrefied wood, (c) coffee waste, and (d) sewage sludge

To provide a comparative analysis of sooty flames for particles with different physical structures, the superimposed images of four solid particles at 300–355 μm and 10 % O_2 are captured at identical conditions shown in Fig. 4-8. In general, biomass has an early initial release of volatile matter compared with coal at a low heating rate, such as in a thermogravimetric analyser. Sub-bituminous coal ignites a bit earlier compared with the three biomass particles in the same particle size group. Different onset times of ignition between biomass particles are also observed and can be attributed to their compositions and physical structures.

The flames of burning biomass particles are relatively smaller and less sooty than those of coal due to the relative soot formations from reactions with tar at high temperature. It is accepted that this physical configuration is dominantly determined by complicated interactions between volatile matter, carbon content, particle density and different rates of devolatilisation. The three biomass particles have less bulk density, compared to coal particle density (0.77g/cm^3); the density of torrefied wood, coffee waste and sewage sludge are 0.72, 0.86 and 0.76 times than that of coal. This low density of biomass particles may result in the shorter gas-phase combustion. However, these biomass particles have higher mass volume fraction of volatile matter to coal, and thus, the duration of gas-phase combustion for biomass is still longer than that of the coal. The longer volatile combustion time are affected by the high mass of volatile matters; from bulk density measurement, torrefied wood, coffee waste and sewage sludge have 1.9, 2.3 and 1.7 g in the equal volume. Coal still has the lowest mass of volatile content at 1.6 g although it has a higher bulk density. The calculation was measured total mass of torrefied wood (2.71 g), coffee waste (3.20 g) and sewage sludge (2.84 g) in 4.82 cm^3 as the mass fractions of volatile matters of each particle were given in Table 1. In addition, the mass of fixed carbon of torrefied wood, coffee waste and sewage sludge are 0.6, 0.4 and 0.2 g while coal has 1.7 g that enhances different char combustion behaviours between biomass and coal particles. That is, volatile matter content is a major factor in determining combustion time. Under direct observation, an elongated flame is detected on all particles at 10 % oxygen concentration. The shape of the flame structures is due to the low diffusion rate of oxygen with the effect of buoyancy and it is apparent that coal has the flame

with the highest aspect ratio. At this particle size group, biomass particles have even higher elongated flames than that at 150–215 μm because a larger volume particle contains more volatile matter and carbon content.

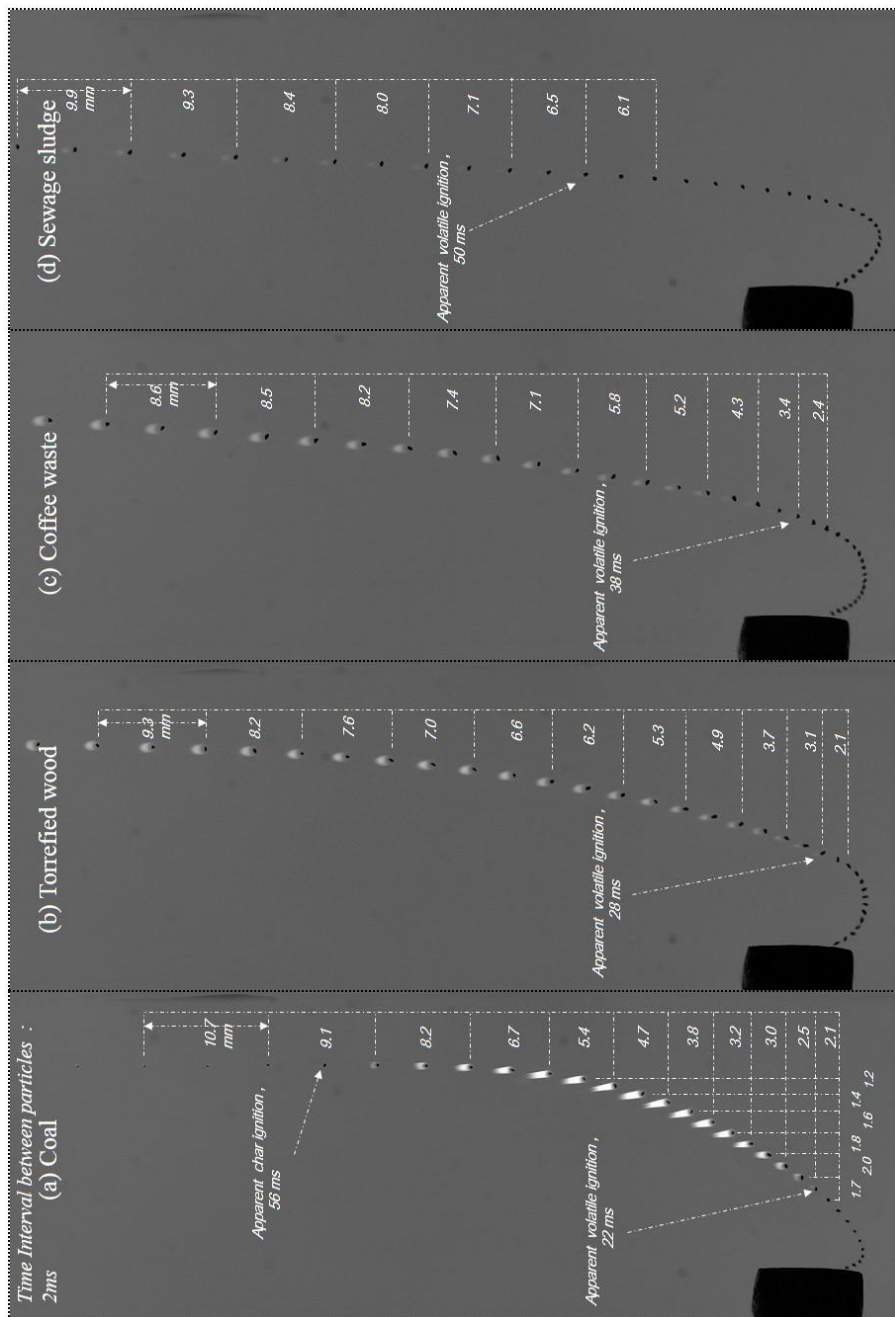


Figure 4-8 Flame structures and luminosities of the superimposed coal and biomass particles entrained into hot gas streams of 1,340 K (300–355 μm , 10 % oxygen concentration). The particle displacement after the injection is marked in the time interval of 2 ms and apparent volatile ignition occurs within a few milliseconds depending on the type of solid particle.

The intensity of volatile flames for the four particles is converted into a greyscale image by means of a numerical data matrix shown in Fig. 4-9. Identical backlighting is used in all images to minimise the error in the numerical solution. In the imaging process, each pixel of the image presents light intensity on a greyscale from 0 to 255, and the numerical backlighting data are extracted from the images. The intensity of the flame is then divided by the maximum value of grayscale (255) for comparative analysis of each image. Coal has max. 43.2 % of the highest intensity between 0.78 and 1 in the luminous flame whereas torrefied wood, coffee waste and sewage sludge account for 13.4, 10.4 and 4.1 %, respectively.

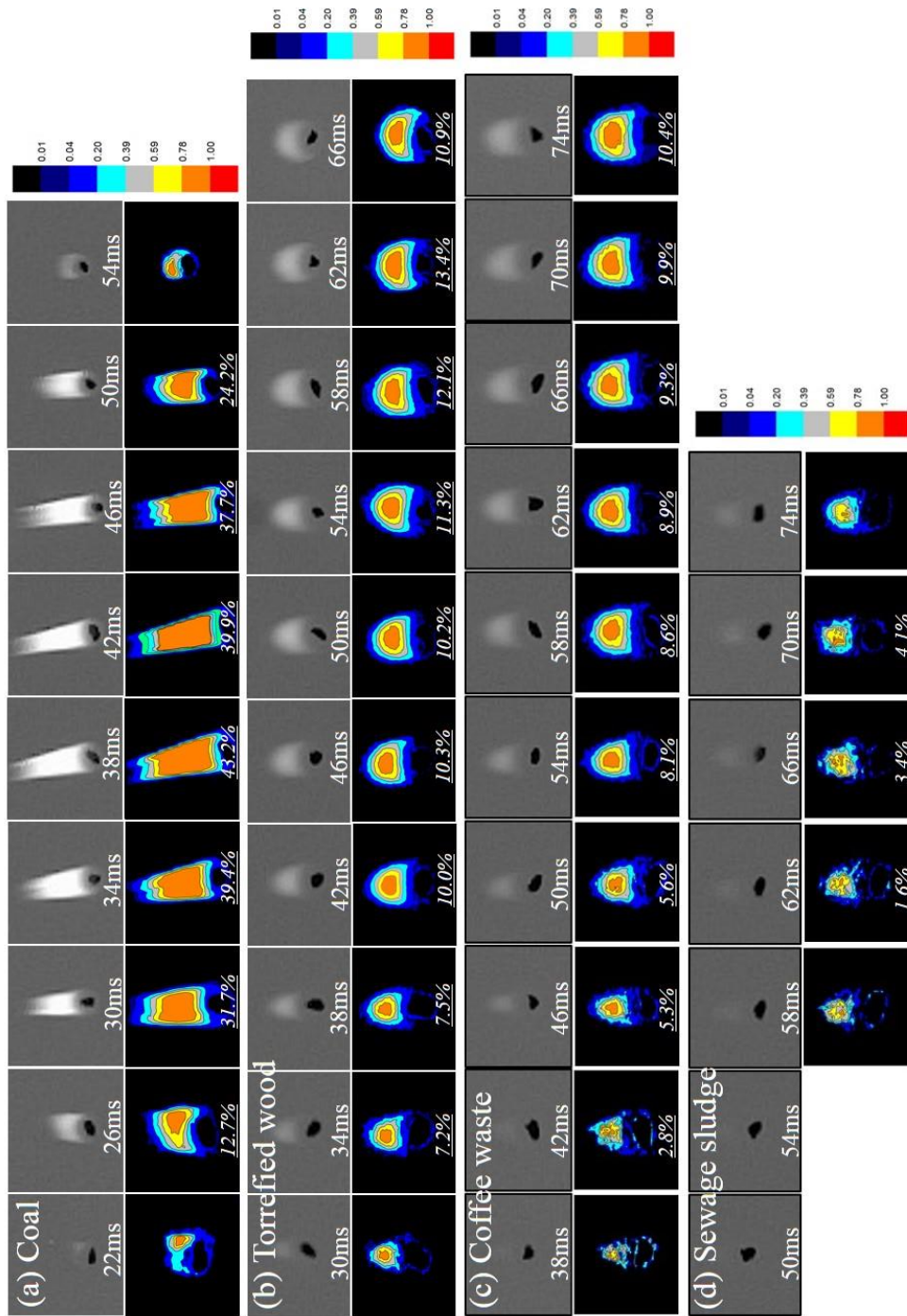


Figure 4-9 Captured images from burning particles of 300–355 μm and the normalised intensity of their flames represented by the imaging process.

4.5.3 Effects of biomass and enhanced O₂ concentration

The comparative combustion behaviour for different biomass types and different O₂ concentrations are presented in a series of images shown in Fig. 5-10. Increase in the oxygen concentration for each particle is revealed to result in different physical structures of the volatile flames with different onset times of ignition. The earlier apparent ignition of coal occurs at all oxygen concentrations, and the biomass flame size is smaller than that of coal for all size groups examined. However, the three biomass types had different flame intensities with different ignition delays and overlapping combustion at the early stage. Torrefied wood, coffee waste and sewage sludge manifest different changes with oxygen concentration. Kuo et al. [34] pointed out that ignition behaviour such as the structures of the volatile flame, ignition time and early ignition are mainly determined by the properties of the biomass. Normalised intensities of actual flames for different particles are shown in Fig. 5-11, but a whole period is not detected until the extinction of volatile flame because of the limitation of the visualisation section. The size of volatile flame on a particle exhibits a nearly symmetrical profile as from the experimental results. Therefore, the unmeasured data due to the limited visualisation field were predicted in Fig. 5-11 and 12. Fig. 5-11 presents the profiles with predicted values. Based on a previous study [35], these differences between particles are partly attributed to different ratios of hydrogen to carbon, which affect the soot volume fraction. The particle is heated by radiation from soot flame from feedback mechanism [29] along with the combustion wall and also by convection from a hot gas steam in a reactor. For that reason, the particle temperature is affected by a degree of soot flame. Accordingly, low soot and invisible flames influence on an ignition delay, flame instability and low radiation in visible and near-infrared spectral ranges. The radiation from emission of soot particle in a flame is important role in burning rates and their spread rates [36–39].

The size of volatile flame on a particle exhibits a nearly symmetrical profile as from the experimental results. Therefore, the unmeasured dates due to the limited visualisation field were predicted in Fig. 5-11 and 12

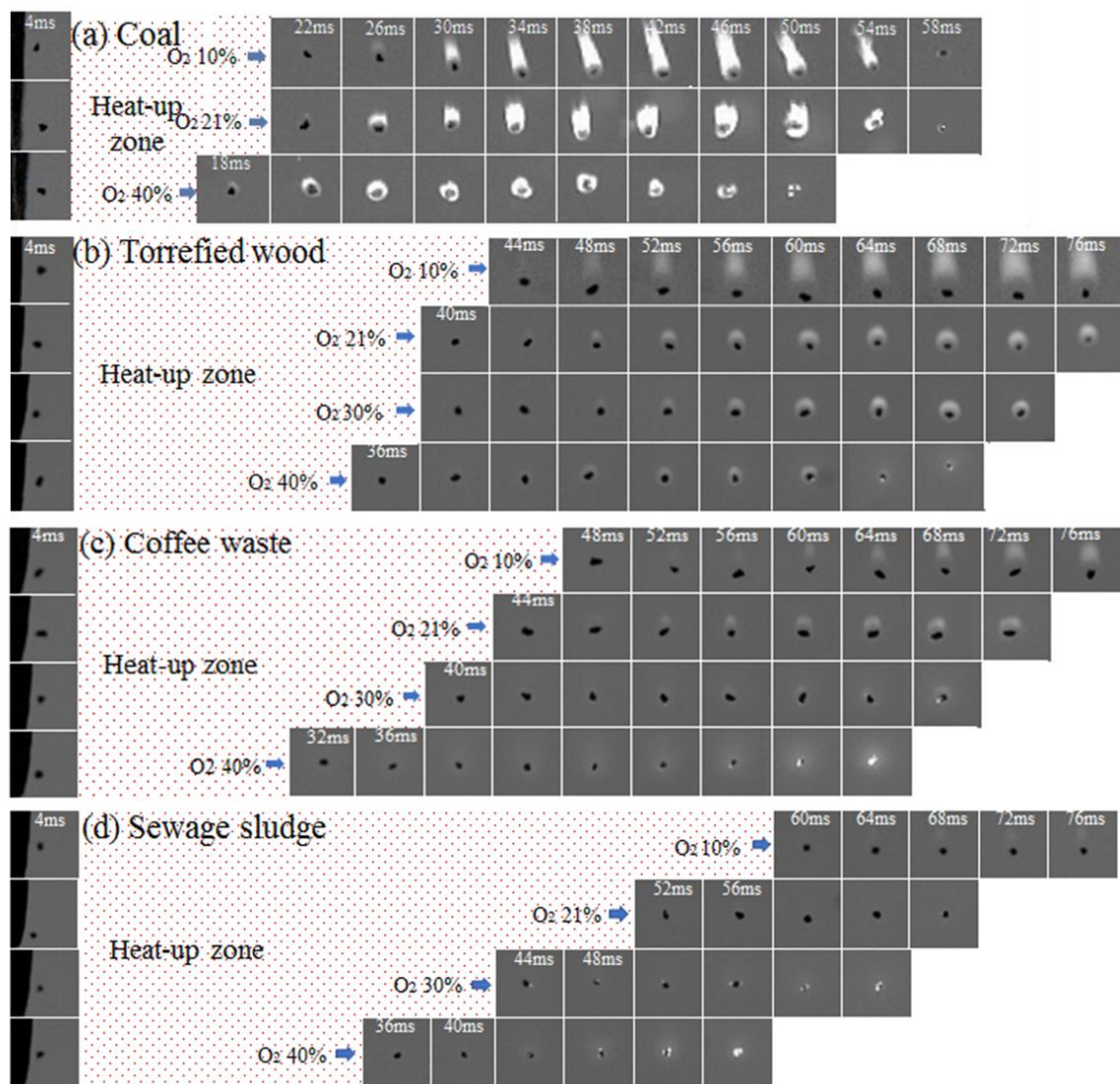


Figure 4-10 Comparative combustion behaviour over time intervals of 4 ms, obtained from the set of burning particles of size 255–300 μm at 1340 K as the oxygen concentration is increased.

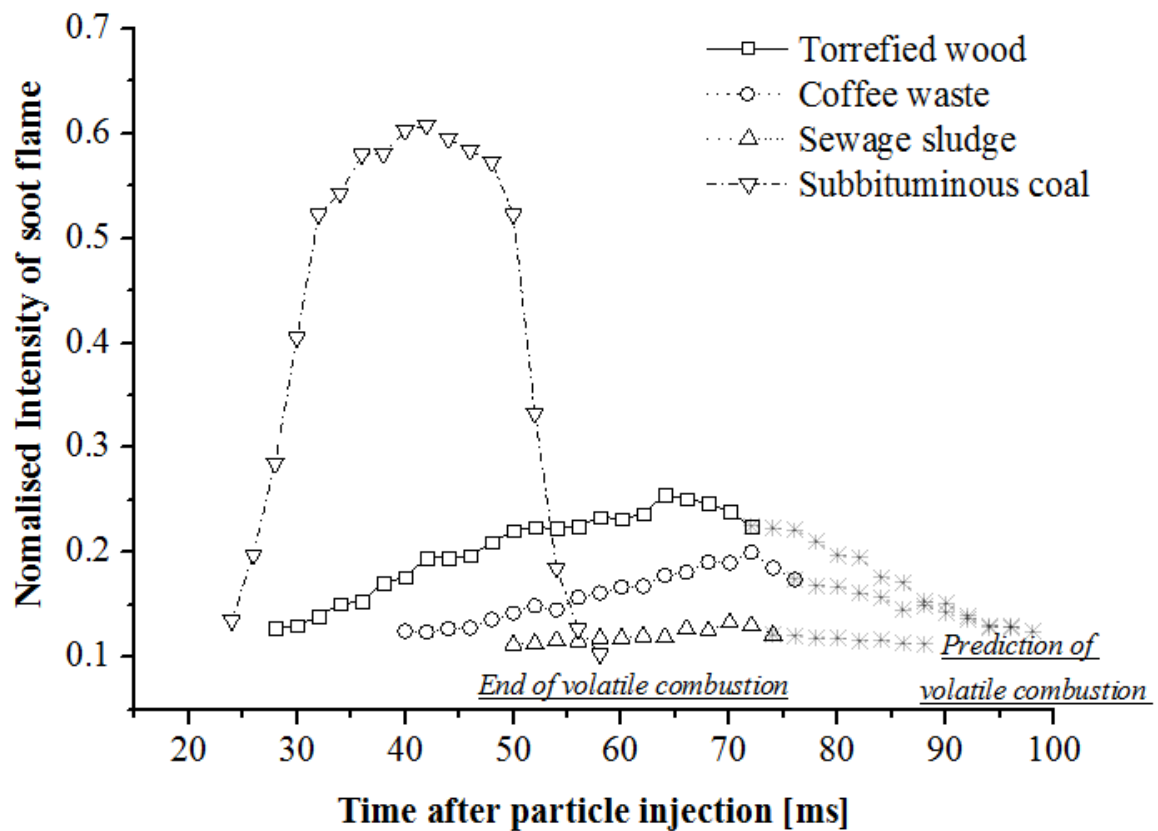


Figure 4-11 Effect of different fuel particles measured from grayscale images of 300–355 μm particles exposed at 1,340 K. Biomass particles are still burning during the volatile combustion stages and the predicted lines of the volatile flame are extended due to the symmetrical tendency of the pattern.

The ratio of the radii of effective flame to particle size is plotted for the biomass particles as a function of the oxygen concentration, as shown in Fig. 5-12. The profile which has unmeasured flame is also extended to predict the whole flame history. The effective maximum ratio between torrefied wood, coffee waste and sewage sludge with 255–300 μm particles varies by 5.2, 3.5 and 3.4, respectively, at 10% oxygen concentration. The size of the volatile cloud decreases with a shorter duration of devolatilisation as the oxygen concentration increases. Previous work [24, 40] reported that a fast mass reduction during devolatilisation is due to higher oxidation of the gas phase. The decreases in the radius and shorter duration are only clearly observed in torrefied wood and coffee waste over all enhanced oxygen concentrations. The radius for sewage sludge is not detected when the oxygen concentration is over 21 % as the particle has too little soot and an invisibly thin flame. Interestingly, the reduction in volatile radius is remarkable in torrefied wood as oxygen concentration varies between 10 % and 20 %. It is believed that sewage sludge particles below 255–300 μm have significant low radiant energy due to thin and invisible flames, which may affect the power generation in pulverised biomass plant. These flame structures, which contain soot particles and gas phase in a flame, are important role in radiant energy. The energy are attributed to the flame size and its high intensity and, the measured parametric values can be discussed by the time averaged radiation [41], $Q_r = \sigma \epsilon_T T_f^4 A_f$ where σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-11} \text{ kW/m}^2 \text{K}^4$), ϵ_T is the flame emissivity, T_f^4 is the average flame radiation temperature and A_f is the flame surface area.

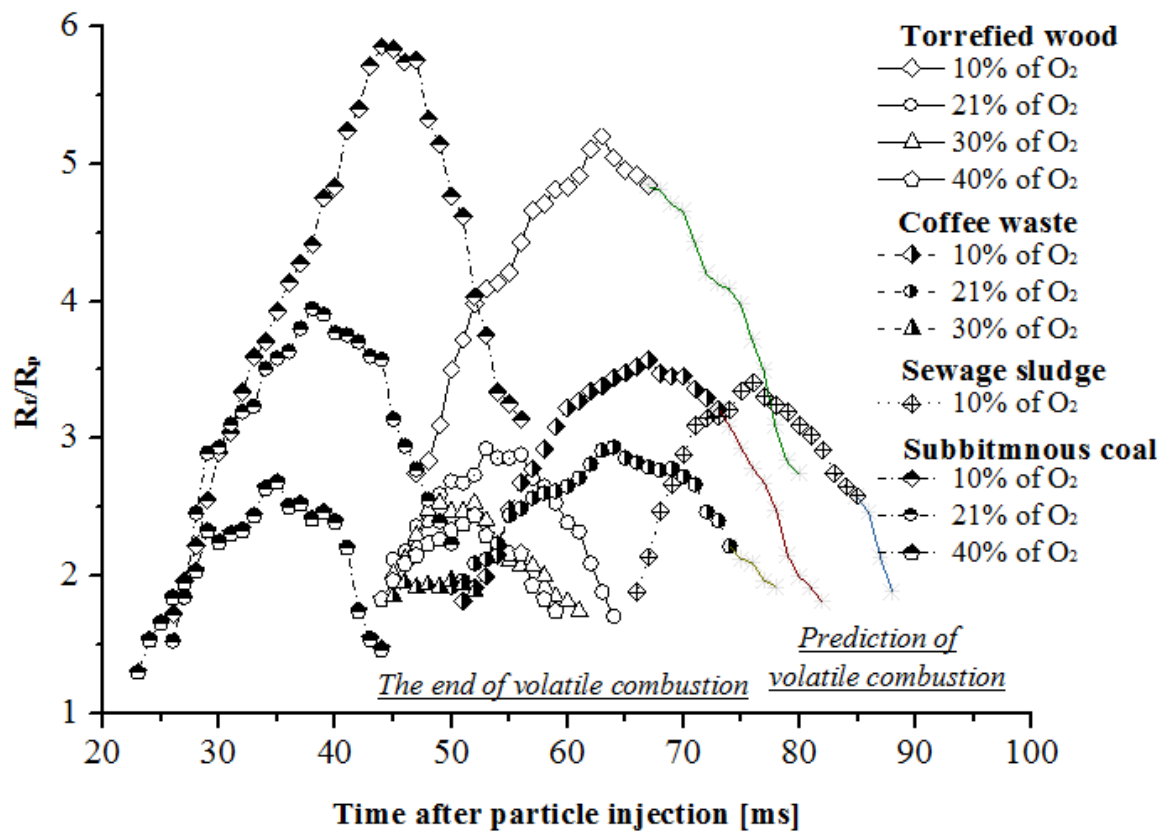


Figure 4-12 Effect of oxygen concentration on torrefied wood, coffee waste and sewage sludge with 255–300 μm particles at 1,340 K. Volatile flames of sewage sludge are not detected for oxygen concentrations over 21 % due to low soot and very thin volatile cloud formation.

Average ignition delay against time is analysed for the three biomass particle types of 155–215 μm and all oxygen concentrations, as shown in Fig. 5-13. It is apparent that the heating time and durations of homogenous and heterogeneous combustion decrease as oxygen diffusivity increases. From the figure, longer volatile combustion and shorter overlapping combustion are observed in torrefied wood (which has experienced thermal pre-treatment), whereas coffee waste and sewage sludge have relatively shorter durations of volatile combustion. In the case of 155–215 μm particles, early onset of char ignition appears only for coffee waste and sewage sludge, which may be related to the rapid increase in particle temperature, enabling a shorter duration of devolatilisation.

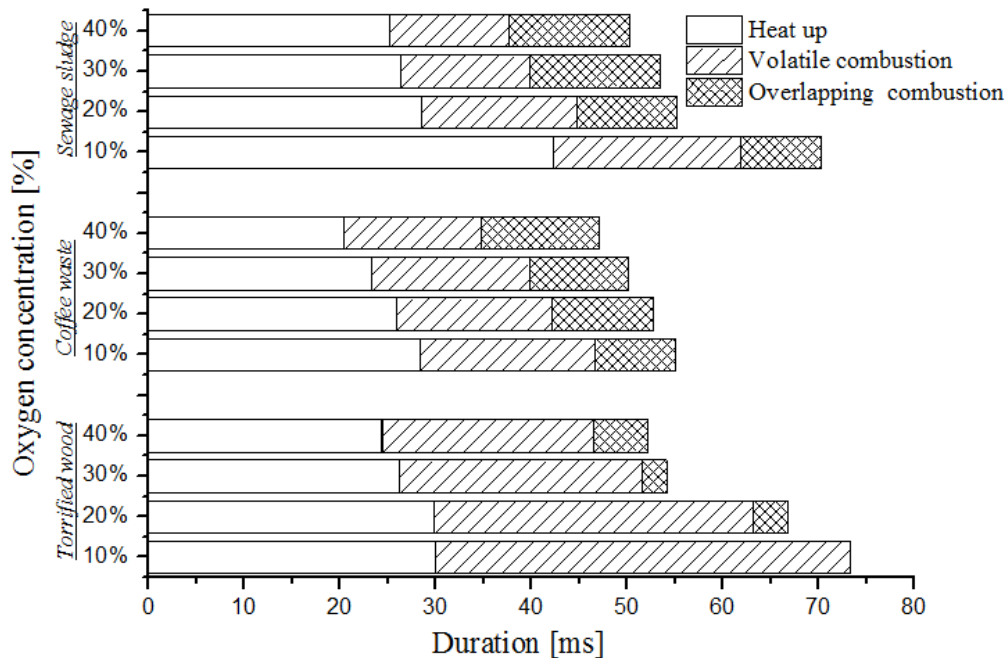


Figure 4-13 Average duration of heat up and the end of volatile combustion for three biomass particles (155–215 μm) particles at 1340 K and quantitative measurements of burning time vs. oxygen concentrations.

4.5.4 Effect of environmental gas temperature on combustion behaviour

The burning of particles enables discussion of the effect of temperature conditions on combustion behaviour. At 1,090 K and 1,340 K, the trajectories of coal and torrefied wood are compared in Fig. 5-14 to characterise the volatile

flames. Both particles at 1,090 K form volatile flames of smaller sizes with lower intensity, and the flame of torrefied biomass even becomes transparent with longer ignition delay. This suggests that significant soot formation does not occur at low temperature, along with low volatile release rate, as compared with a higher gas temperature of 1,340 K. Fig. 5-15 shows that the average duration of heat-up at 1,090 K is longer than that at 1,340 K. The apparent change in the heat-up duration at low temperature as a function of oxygen concentration is more prominent than that at 1,340 K. This is consistent with the result from a previous study [6], which showed that the effect of oxygen concentration on ignition delay and burnout time is expected to be slightly more pronounced at lower temperature.

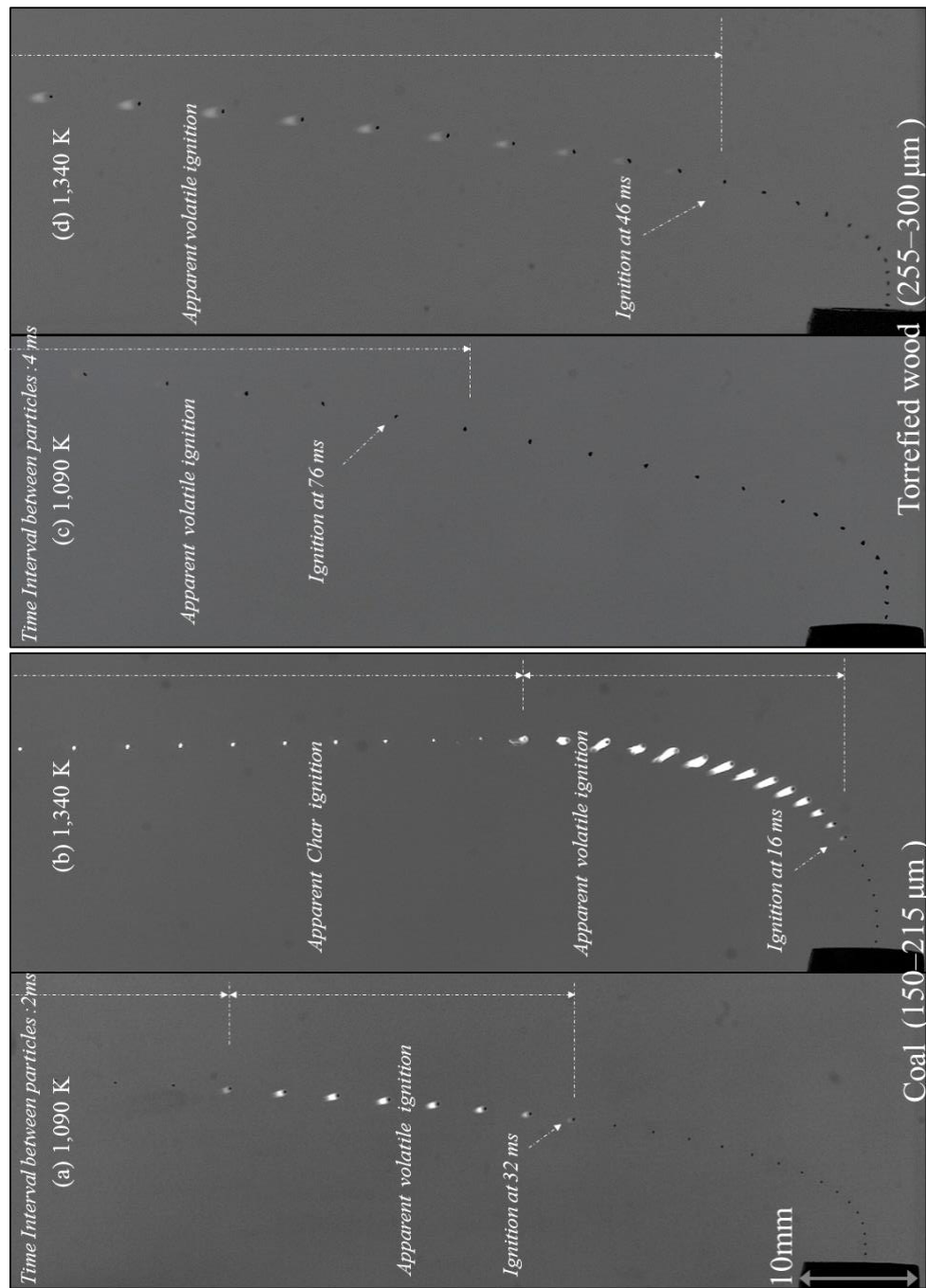


Figure 4-14 Comparative volatile flames and ignition behaviour of coal and torrefied wood between 1,090 K and 1,340 K at 10% of O₂: coal, 150–215 μm and torrefied wood, 255–300 μm.

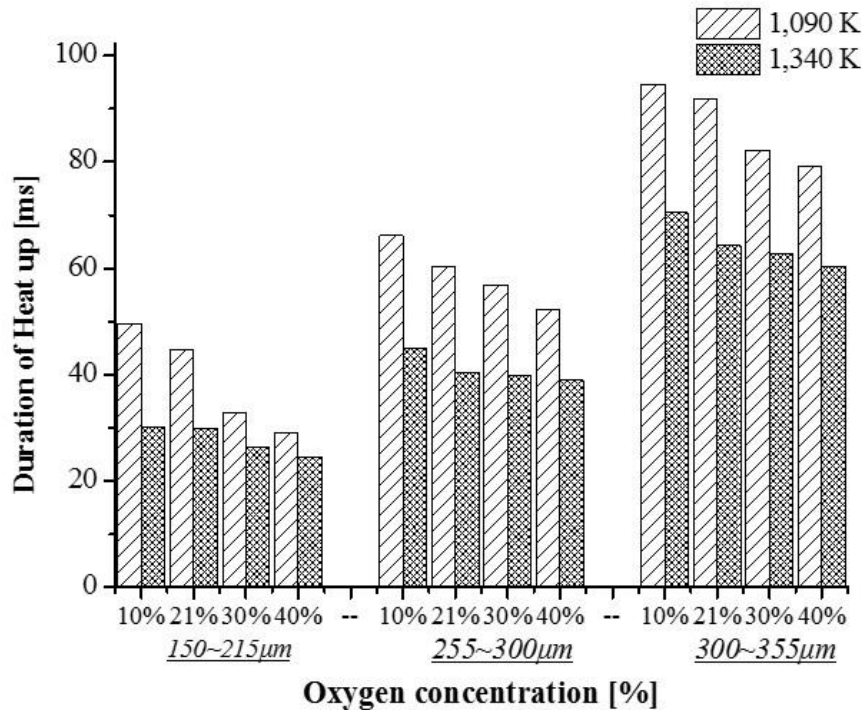


Figure 4-15 Average duration of heat up for torrefied wood particles of 150–355 μm under different gas temperature and oxygen concentration conditions.

4.5.5 Effect of particle size on combustion behaviour

Several researchers [42, 43] have studied intra-particle effects during combustion. In general, the temperature of a large-sized particle is controlled by the surrounding temperature and this particle has an intra-particle temperature gradient. However, a pulverised particle under 200 μm has a small temperature gradient which does not affect the rate of devolatilisation [15, 44]. Fig. 5-16 illustrates the average duration of heat-up for particles of each of the three biomass types with particle size in the range from 150–215 μm to 355x425 μm, each taken over 20 particle samples. The transience point of ignition delay for torrefied wood occurs at the size group of 255–300 μm and coffee waste at 215–255 μm, where average time of heat-up increases more sharply, probably due to an intra-particle effect.

Fig. 5-17 illustrates the maximum effective radius of volatile flame for particles in the ranges from 155–215 μm to 355–425 μm under oxygen concentrations of 10 and 21 %. First, a higher effective radius is quantitatively measured at low oxygen concentration for all particles. Second, R_f/R_p in torrefied wood undergoes only a marginal change with a relatively sooty flame from 155–215 μm to 355–425 μm at 10 % oxygen concentration. However, this radius (R_f/R_p) decreases with particle size increase at 21 % oxygen concentration. The radius of torrefied wood and coffee waste with 255–300 μm particles is almost equal to that at 21% oxygen concentration, but coffee waste has a very thin, low soot flame when its particle size is 155–215 μm . Consequently, coffee waste is required to be at least 255–300 μm in size to achieve an equivalent flame structure to torrefied wood. Finally, an invisible or very thin flame is detected for sewage sludge when it is burned at 21 % oxygen concentration. The raw sewage sludge in these experimental conditions is low combustion quality of biomass. An increase in sludge particle size might enhance the flame stability, but a large particle would drop to the bottom of the reactor without combustion. To avoid this, a higher gas temperature or thermal pre-treatment of sewage sludge might be required.

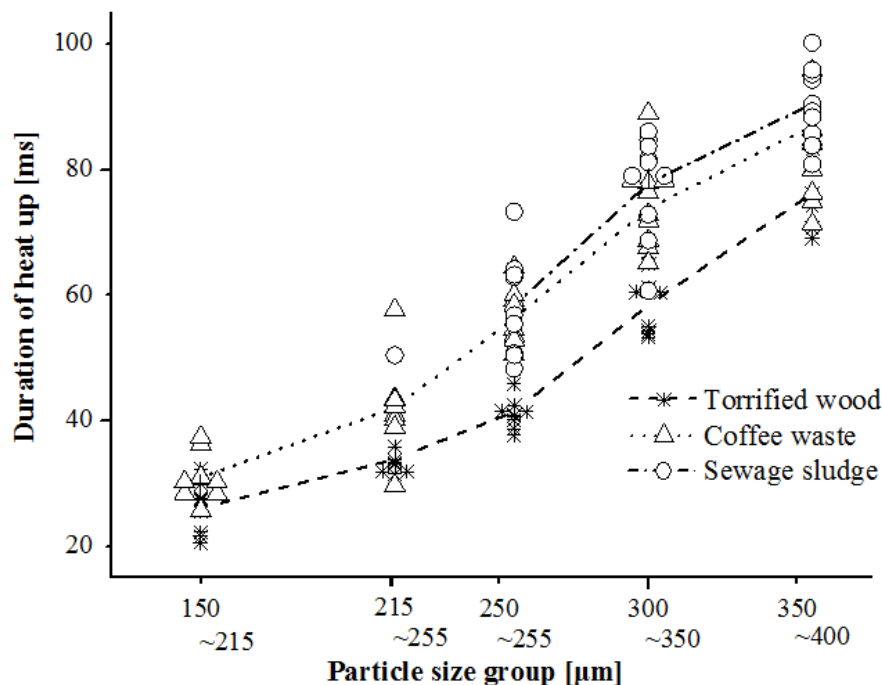


Figure 4-16 Experimental data on ignition delay for biomass particles in the range 150–400 μm at 1340 K and 21 % of oxygen concentration.

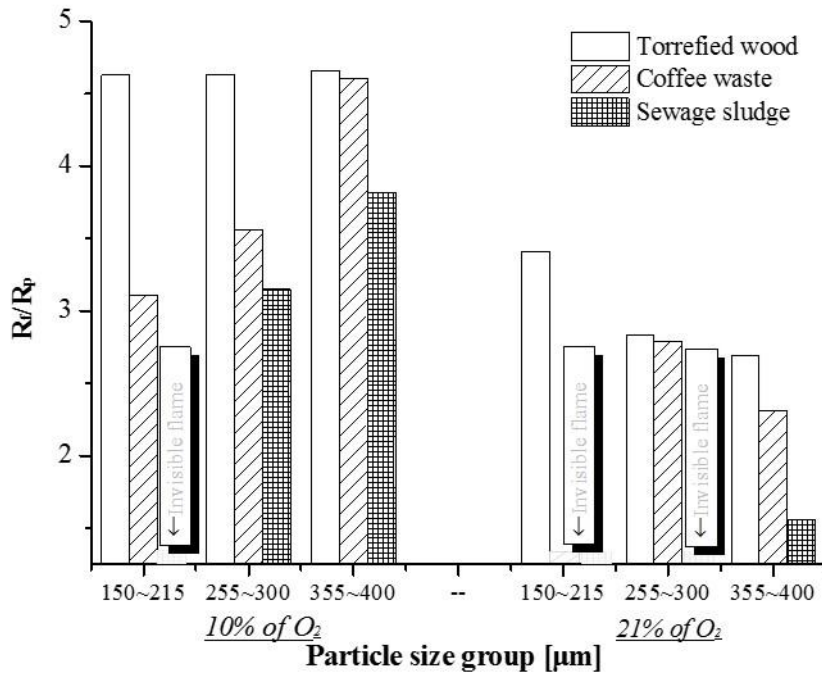


Figure 4-17 Average effective flame radii of three biomass particle types in the range 150–400 μm between 10 % and 20 % oxygen concentration.

4.6 Discussion for special cases

4.6.1 Ignition behaviour and flame instability

Ignition behaviour is determined by interactions between complicated factors such as the physical and chemical characteristics of the biomass and the surrounding environment as well as operating conditions. Variation in the composition could enable a longer ignition delay, smaller soot cloud and earlier fragmentation with the instability of the volatile flame. The investigation of ignition delay as a function of certain parameters may provide partial answers concerning optimised particle combustion. Fig. 5-18 shows the onset time of volatile ignition, earlier overlapping combustion and the visible structure of volatile flame in different environmental conditions. There are four observations of burning particle in different environmental conditions. The two different gas temperatures had been performed prior to the moisture and oxy fuel combustion effect. For high mass volume of moisture, particles put in a closed container (20 cm×20 cm) on a

hot plate at 323 K. There was a sponge with high moisture in the bottom of the container, where particles were not touched from the sponge. The group of particles keeps in the container for 4 hours at 95 % of absolute humidity. Consequently, the particles were added 25 % of moisture. The particles, which were out of the container, had to be tested in a min because moisture content was likely to be evaporated in a short time. To compare O_2/N_2 and O_2/CO_2 environments, CO_2 for 21% of O_2 concentration was supplied from the post combustion burner, instead of air. First, the flame instability is found to be related to environmental temperature. A previous study [34] observed a different model of ignition obtained from anisotropy of the thermal properties of large biomass particles and reported that different ignition behaviour was determined by the surrounding gas temperature. Second, moisture content enhanced the ignition delay at the early stage, which caused earlier char combustion with the formation of a thin flame. Kucuk et al. [45] pointed out that the evaporation of moisture leads to an increase in char combustion to be attacked by oxygen due to the formation of an active centre. Lastly, early ignition and flame instability of a particle occur under CO_2 atmosphere due to the high thermal capacity of CO_2 and the high reactivity of char- CO_2 , as reported by Shaddix et al. [22].

Insights into flame formation are essential to understand combustion behaviour, such as flame stability, to better determine the operating conditions and select appropriate biomass. Fig. 5-19 illustrates two types of volatile flames that are observed for a single particle and a pellet of coffee waste. As mentioned before, coffee and sludge particles typically have a thinner volatile flame or an invisible flame compared with torrefied wood particles. At high oxygen concentrations, scattered volatile gases and small particles that escape from parent particles are detected above an invisible or very thin diffusion flame. From the observation, the actual size of the flame can be reduced during the combustion process. To support this flame instability, a pelletised biomass particle is examined at the same gas temperature. The size of diffusion flame at 40 % of O_2 is apparently smaller than that at 20 % of O_2 , and this flame partially detached over an enlarged scattering flame at high oxygen concentration. This phenomenon is attributed to rapid escape of high-volatility matter and particles from a luminous flame without

any reaction. Consequently, the onset of volatile scattering enables the formation of very thin volatile flames with relatively low soot content. These results are consistent with the work of Holtmeyer et al. [46], who studied combustion modes through experimental and numerical methods. The mechanism of this volatile scattering is not clearly defined, but it is frequently experienced by biomass with highly volatile content, anisotropic release and a low-soot flame above a diffusion flame.

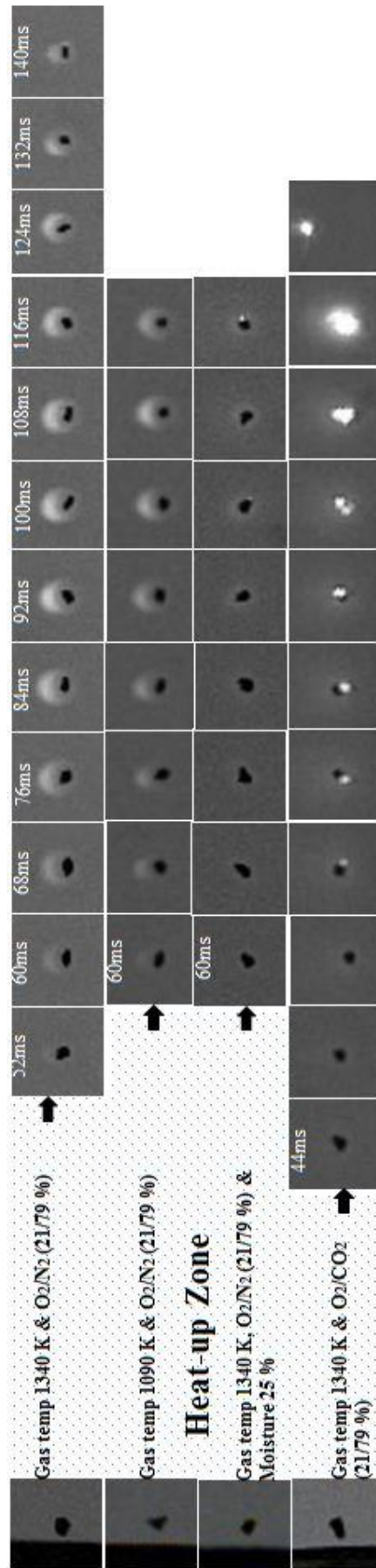


Figure 4-18 Comparison of combustion behaviour on coffee waste particles for four different environmental conditions.

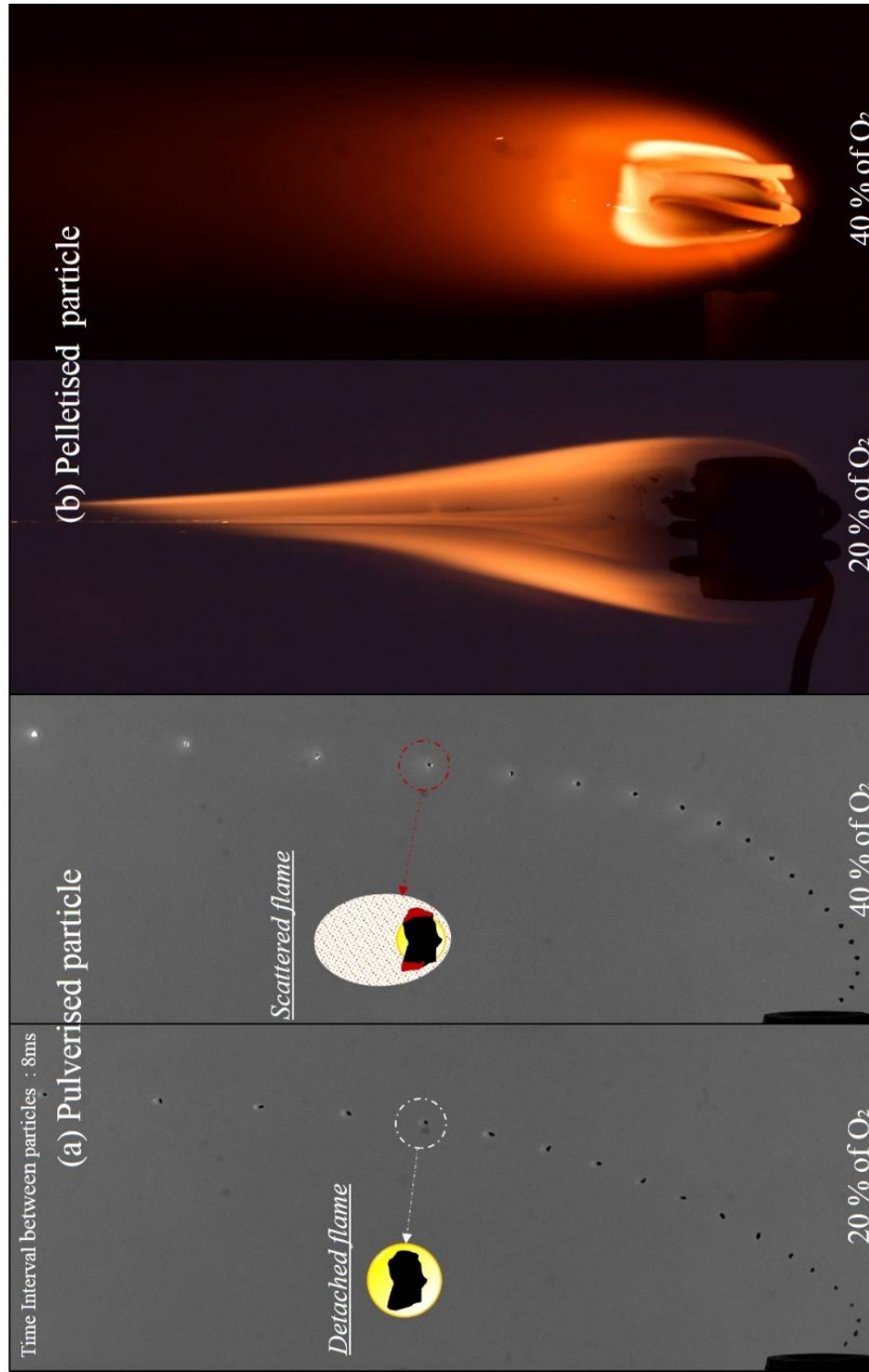


Figure 4-19 Different modes of the volatile flame of coffee waste produced under enhanced oxygen concentration.

4.6.2 Overlapping combustion at an early stage and fragmentation

Overlapping combustion is attributed to low gas temperature, rapid heating rate, small particles and low flame formation. In addition, the shapes of the particle, the different rotational speeds between them and the volatility of the flame may be related to the overlapping combustion shown in Fig. 5-20. Normally, the volatile flame with an O₂ concentration over 21 % has a relatively thin spherical shape for an irregular particle. From the figure, we note that the particle exposed to a hot gas stream starts rotational motion, and then a volatile flame is formed after volatile matter release. In the process, the different rotational speeds of the particle and volatile flame are detected after volatile ignition. Then, an edge of the irregular particle is suddenly exposed in a hot gas stream without a surrounding volatile flame. This exposed edge is directly heated by the surrounding hot gas. The different rotational motions between a particle and volatile flame can change the datum of irregular objects. Sequentially, the opposite edge of the particle is rapidly ignited and char combustion is extended over the surface since the volatile flame shrinks as a function of the residence time. This earlier overlapping combustion and a fast devolatilisation at high temperature and a rapid heating rate enhance the thermal stress and internal pressure inside the particle, leading to a high probability of fragmentation. Only coffee waste particles occasionally experience this phenomenon for oxygen concentrations over 30% and in the size range of 150–255 µm.

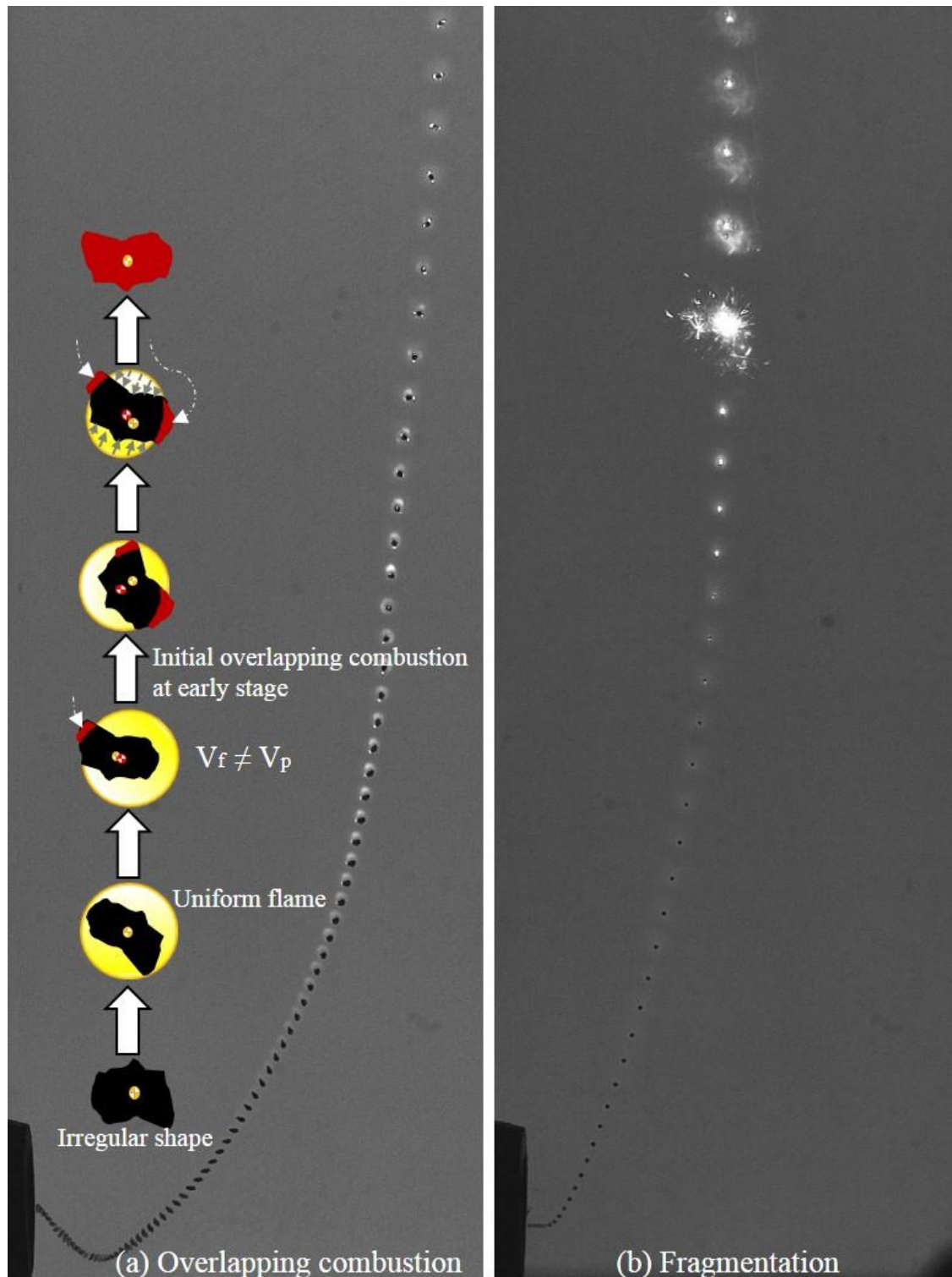
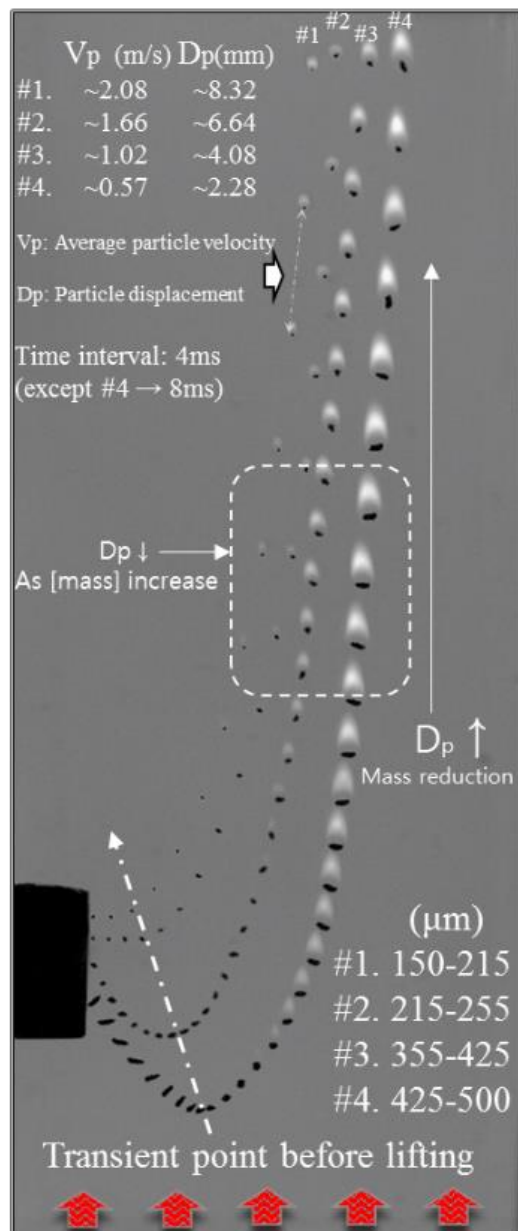


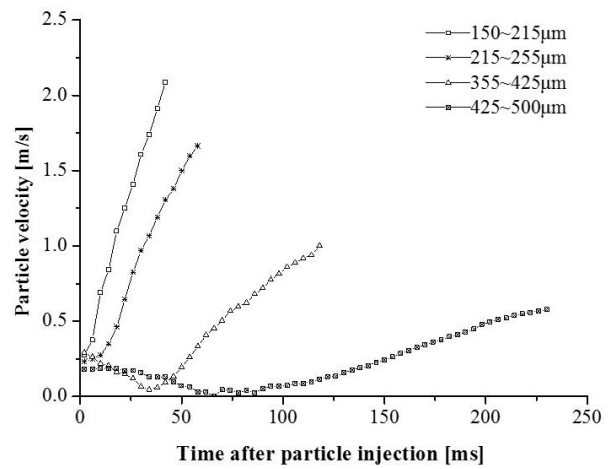
Figure 4-20 Overlapping combustion and fragmentation occurring in the coffee waste particle.

4.6.3 Trajectories of small to large biomass particles for optimisation of burnout

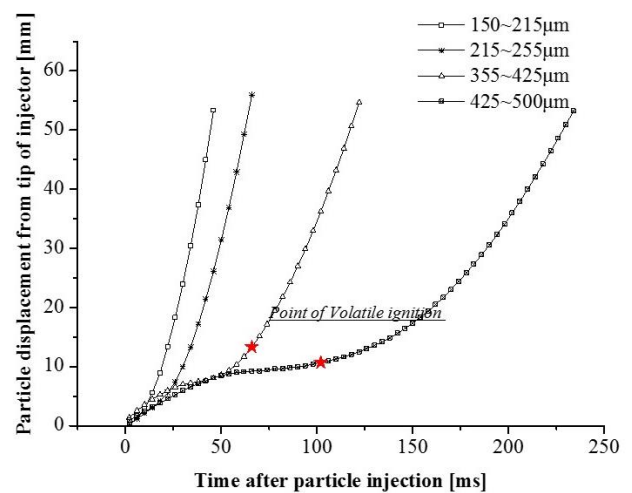
The particle size of biomass is expected to be larger than that of coal for pulverised combustion because of its low density and fast reaction rate. However, large particles injected into a burner can be incompletely burned as they may drop to the bottom of the furnace without combustion. Hence, determination of the particle size for complete burning is essential to achieve a high level of utilisation for pulverised combustion. Saastamoinen et al. [17] also analysed the possible trajectory of particles to be burned virtually and suggested an optimised particle-size for biomass. Fig. 5-21 shows clearly how realistic trajectories of biomass particles (i.e. torrefied wood) in the cross-sectional configuration develop with regard to size variation. From this, the maximum particle size that can be completely burned is suggested experimentally. Small particles, which range from 150 to 255 μm in diameter, move in the direction of the hot gas stream, regardless of gravity force, as particle velocity increases. Particles of 355–425 μm drop to the bottom of the furnace and are then lifted toward the top due to buoyancy and drag forces as particle mass decreases. However, Particles of 425–500 μm occasionally drop to the bottom without volatile combustion. The most of particles over 500 μm does not burns in the visualisation field because of excessive particle mass and non-mass reduction in the experiment with the particular environment conditions. E. Karampinis [47] also reported that high volumes of particles may go down to the hopper region, where these particles burn without upward movement



a) Trajectories of burning particles



b) particle velocity



c) Particle displacement

Figure 4-21 Trajectories of small to large biomass particles for burnout, particle velocity and displacement in the combustion process.

4.7 Conclusion

The different burning characteristics of disparate biomass particles were observed because of chemical and physical properties. These observations were carried out in the laboratory scale entrained flow reactor with the cross jet injection using the high speed camera. Combustion behaviours of biomass particles have been analysed as a function of time and characterised in terms of the effects of oxygen concentration, particle size, particle temperature and other environmental conditions. Also, this study was focused on a measurement of the effective size of the flame over the particle with its intensity to clarify its flame stability along with supporting the modelling description.

Observation of burning particles shows that flame volatility is not only highly related to the particle's volatile matter content, but is also attributed to soot formation. Biomass has a relatively more volatile content than coal and yields a less sooty flame, but a stable flame is detected for torrefied wood even at the smallest pulverised particles of size 150–215 μm . However, coffee waste requires larger size of over 255 μm to obtain a flame profile equivalent to that of torrefied wood. Sewage sludge in the same size group as other biomass particles has a highly transparent volatile or invisible flame with a longer ignition delay. The initial volatile ignition of the three biomass particle types occurs differently, as these processes are dominantly determined by their compositions, and different effective radii for the volatile flames are observed for each particle.

Coffee waste and sewage sludge particles in the size range of 155–215 μm undergo char combustion at an early stage and form a flame with low-soot content. This increases particle temperature rapidly and enables a shorter devolatilisation duration compared with torrefied wood. Also, these particles have thin or invisible flame, and scattered volatile flames are detected at high oxygen concentration from the direct observation. To achieve relatively a soot flame, biomass particles are required to be larger but, the size of pulverised particle is limited due to a probability of unburned particles.

The determination of particles size is essential to achieve complete particle burnout in pulverised combustion. From the experimental results, particles with diameters of 150-255 μm , which exposed in a hot gas stream with the particular parameters, move in the direction of the vertical stream, regardless of gravity force. The particle size group of 425–500 μm occasionally falls to the bottom to be incompletely burned without any apparent mass reduction. Consequently, the maximum size of particle that can be burned completely at 1,340 K is in the size range of 355–425 μm . From this result, the optimal biomass particle size would be suggested for a large-scale combustion furnace.

4.8 Acknowledgments

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CHAPTER 5

FLAME STRUCTURES AND IGNITION CHARACTERISTICS OF TORREFIED AND RAW SEWAGE SLUDGE PARTICLES AT RAPID HEATING RATES

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5. FLAME STRUCTURES AND IGNITION CHARACTERISTICS OF TORREFIED AND RAW SEWAGE SLUDGE PARTICLES AT RAPID HEATING RATES

5.1 Abstract

Torrefaction is a promising method for improving the quality of pulverised solid fuel, as it increases the flame stability, radiative heat transfer and energy density of the fuel. Raw sewage sludge contains less fixed carbon and more ash compounds than other biomasses; consequently, it has poor energy quality with a long ignition delay and forms a relatively low, sooty flame. In this study, we directly investigate the combustion behaviours of particles with varying degrees of torrefaction by burning them at 1340 K. The torrefied particles were prepared at different temperatures (473 K or 573 K) for different residence times (10 min or 30 min). The experimental parameters examined were the size range of the particles (150–215 μm and 255–300 μm) and the O_2 percentage (10–40 %). The particles were entrained from a cold carrier gas into a hot gas stream, igniting a volatile flame that was extinguished a few milliseconds later. These temporal variations in the burning particles were detected by in-situ high speed photography (7000 frames/s). The torrefaction degree affected the flame structure and varied the ignition delay, due to the mismatched reactivity and soot formation at rapid heating rates. The most torrefied sludge particles exhibited a relatively luminous volatile cloud and a large flame, while preserving the duration of volatile combustion. These observations confirm the improved pulverised combustion of the torrefied sludge particles. We also obtained valuable flame parameters (radius, intensity and combustion time) of the differently torrefied sludge particles.

5.2 Introduction

The devolatilisation and char oxidation rates, ignition delays and burnout times of burning solid fuel particles largely depend on the surrounding conditions [1, 2]. The hot gas temperature, rapid heating rates and oxygen concentration contribute to discrepant ignition delays and flame intensities [3, 4]. Fast pyrolysis increases the soot production from solid fuel particles, particularly at high temperatures, when soot is relatively more reactive [5, 6]. Such reactivity, along with the high volume fraction of soot particles, greatly influences the combustion performance in industrial applications, because sooty flames radiate large amounts of heat. In general, pulverised solid fuel particles immediately reach high temperatures during combustion, forming a sooty flame with release of volatile matter, tar, soot and ash in the early stages [7, 8]. Moreover, this formation is strongly associated with the physical structures and chemical compositions of the fuels, which vary particularly in their biomass particles [9]. However, the physical properties of volatile flames may not be clearly described in observations, as micron-sized particles burn very quickly in industrial environments.

Utilisation of biomass and waste materials can reduce the environmental problems caused by high carbon dioxide emissions, which are mainly generated from burning fossil fuels. Therefore, clean and renewable energy sources are strongly desired [10, 11] and sewage sludge is currently accepted as a low-cost material for pulverised biomass combustion [12, 13]. For economic reasons, this waste material has been dispensed into landfills or the ocean. However, such waste also contains large quantities of accumulated heavy metals, toxins and dioxin compounds, which contaminate the environment [14]. The direct use of sewage sludge in agriculture could also be risky because of pathogenic transfer to crops [15, 16] and many EU countries have banned the spreading of this waste on land [17]. Since 1993, international treaties have banned ocean disposal of wastes such as sewage sludge. Incineration or combustion might be an alternative option to consume this waste solid and produce electricity and heat energy, although there is arguable regarding the emission of heavy metals [18]. In fact, Cu, Ni, Pb and Cd can be volatilised at a hot gas temperature and dispersed into the atmosphere. The volatility of these heavy metals is enhanced

by particularly chlorine, which exists in the sewage sludge [19, 20]. From this effect, some researches [21, 22] proposed a solution for decontamination of heavy metals during combustion that these heavy metals can be condensed from additional chlorinating agents and electrostatic precipitator ash coarsens them to stable materials.

The combustion behaviour of sewage sludge radically differs from that of general lignocellulose biomass, because sewage contains low hemicellulose and cellulose components and incombustible high ash content [23]. Sludge particles burn with a low luminous flame and have a long ignition delay. Both properties are considered disadvantageous in pulverised combustion. Generally, the heat energy radiated by the highly luminous flame exerts a positive effect, although the release of unburned soot might also generate air pollution [24, 25]. The low-soot flame of raw sludge particles improves with increasing particle size. However, pulverised combustion limits the particle size distribution, as a large particle mass cannot completely burn within a certain time [26]. For this reason, the fuel combustion quality of raw sludge particles needs improvement.

A potential solution is offered by torrefaction, which transforms the sludge particles into coal-like solid fuel particles. In previous research [27, 28], torrefied biomass particles were obtained at surrounding gas temperatures between 473 and 623 K. The thermal treatment chemically converts oxygen to CO and CO₂ and reduces the O/C rate while increasing the energy density and hydrophobicity [29]. In addition, the chemical and physical decompositions in torrefaction alter the reactivity, improve the flame stability and shorten the ignition delay of the fuel particles [30]. The grindability and flowability of the torrefied particles might be improved by deforming the hemicellulose, which exists as fibrous structures in the particles. The effects of torrefaction have been extensively researched, but the analyses have been limited to thermogravimetric analyses, which determine only the reactivity of lignocellulosic biomass materials [31–33]. These studies were limited to investigate the actual flame structures on the torrefied sludge particles.

This study investigates the apparent structure of the soot flame in terms of the boundary of pyrolysis and soot formation. The morphologies of the properties in the flame are also discussed from the captured images. The variations in structural flame properties, such as the dimensions, intensity and combustion time of the soot flame, are demonstrated in a well-controlled single particle reactor. The study also compares the intrinsic ignition delays and combustion times of raw and torrefied sludge particles and discusses the effects of pre-thermal treatment conditions (temperature and residence time) on the burning characteristics of the torrefied particles. Such experimental results enable discussions on describing the modelling of single waste particle combustion.

5.3 Experimental section

5.3.1 Sewage sludge characterisation and particle separation for single particle combustion

The proximate and ultimate analyses of raw sludge particles are shown in Table 5-1. Sludge particles contain a lower volume fraction of volatile matter and more ash content than wood particles. Table 5-2 presents the organic chemical compositions of standard biomass particles. The cellulose and hemicellulose contents are much lower in sludge particles than in wood particles and the lignin content is slightly lower. The sum of these three components in the sludge is approximately 30 % (organic fraction) because of the high proportion of crude protein and ash (inorganic fraction) contained in it. As each of these substances decomposes within a different temperature range, the burning behaviours of sewage sludge and wood particles are expected to be dissimilar. Specifically, hemicellulose and cellulose are thermally degraded at 493–588 K and 588–673 K, respectively, whereas lignin degrades over a wide temperature range (423–1,176 K) [34].

This study explores the effect of torrefaction on raw sewage particles. The surrounding gas temperature and residence time of the thermal treatments are given in Table. 5-3. The volatile matter fraction should decrease with increasing carbon ratio during the torrefaction process. Physically, raw sludge particles

resemble a stiff clay with numerous surface cracks from which the moisture has been previously removed. The particles are brittle and irregularly shaped even after the pulverising process. Therefore, the particle separation is a three-step process of pulverisation, sieving and friction separation. The friction separator contains differently inclined planes that separate out the spherical particles by means of their translational and rotational motions. Shapes such as extremely flat and cylindrical particles, are inappropriate for this experiment because their varying drag coefficients cause random trajectories. Lee et al. [38] reported statistical variations of the particle trajectories in this cross flow mixing configuration, which indicated the probability distribution of the irregular burning particle for the experimental reproducibility. The dynamic motion and trajectories of the particle were influenced by the ignition behaviour.

The sewage sludge particles were prepared in two size groups; 150–215 μm and 255–300 μm . Generally, a biomass particle has a lower particle density, a smaller volatile flame size and less luminosity, compared with a coal particle and, to detect their apparent flame, a biomass particle size over 150 μm is required depending on the type of biomass [35]. Coal particles in pulverised combustion are normally below 100 μm [36]. However, sludge particles of this size burn with barely observable or invisible flames.

Table 5-1 Proximate and ultimate analyses of raw sewage sludge.

Sample	Proximate analysis (wt. % ar) ¹				Ultimate analysis (wt. % da) ²					LHV ^{3&1} (GJ/kg)
	V.M	F.C	Ash	M	C	H	O	N	S	
Raw sewage sludge	61.2	7.89	25.0	5.9	38.6	5.9	20.6	0.9	0.1	17.14
Torrefied sludge (473K, 10min)	55.8	12.2	30.1	1.6	41.2	5.5	18.3	0.9	0.1	-
Torrefied sludge (573K, 10min)	47.4	18.7	32.1	1.7	44.6	5.3	15.2	0.9	0.1	-
Torrefied sludge (573K, 30min)	32.1	28.9	37.3	1.9	47.9	3.5	13.3	0.9	0.1	25.43
Pine Wood (Ref)	81.5	9.7	0.1	8.5	48.5	6.5	43.2	0.15	0.13	18.28

¹as received ²dry, as free ³lower heating value

Table 5-2 Chemical compositions of sewage sludge.

Sample	Organic composition (wt. %)		
	Hemicellulose	Cellulose	Lignin
Raw sewage sludge	5.2	2.1	24.1
Pine wood (Ref)	28.5	40.1	27.7

Table 5-3 Thermal treatment conditions of sewage sludge.

	Torrefaction temperature, K	Residence time, min
#2 torrefied sewage sludge	473	30
# 3torrefied sewage sludge	573	10
#4 torrefied sewage sludge	573	30

5.3.2 Experimental set-up with cross flow configuration at rapid heating rate

The high temperatures and rapid heating rates (10^4 - 10^5 K/s) in this experiment were similar to those of industrial furnaces [37]. The set-up consisted of a pre-heated reactor, a honeycomb burner, a flow straightener and a water-cooled injector (see Figure.5-1). The reactor was a slab of rectangular quartz with dimensions of (45×45×800) mm³, equipped with a guard heater and an insulator. The honeycomb burner produced a high surrounding gas from the bottom with upward flow of 1 m/s. To analyse particle combustion behaviours, the velocities of the upward-flowing and the leftward-flowing streams are constant in all experiments. The ceramic honeycomb flow straightener installed above the burner maintained a laminar gas flow. The water-cooled injector, which maintained a cold carrier gas at 298 K, was placed at the middle and left sides of the quartz. This layout allowed a cross-flow configuration in the reactor. The cold carrier gas was supplied at 2.6 m/s, entraining the particles into the highly mixed main stream in the test section. The particle injection configuration enables a relevant description of a sequential burning process with an apparent flame structure and direct quantitative observations of the burning particles as functions of time and displacement.

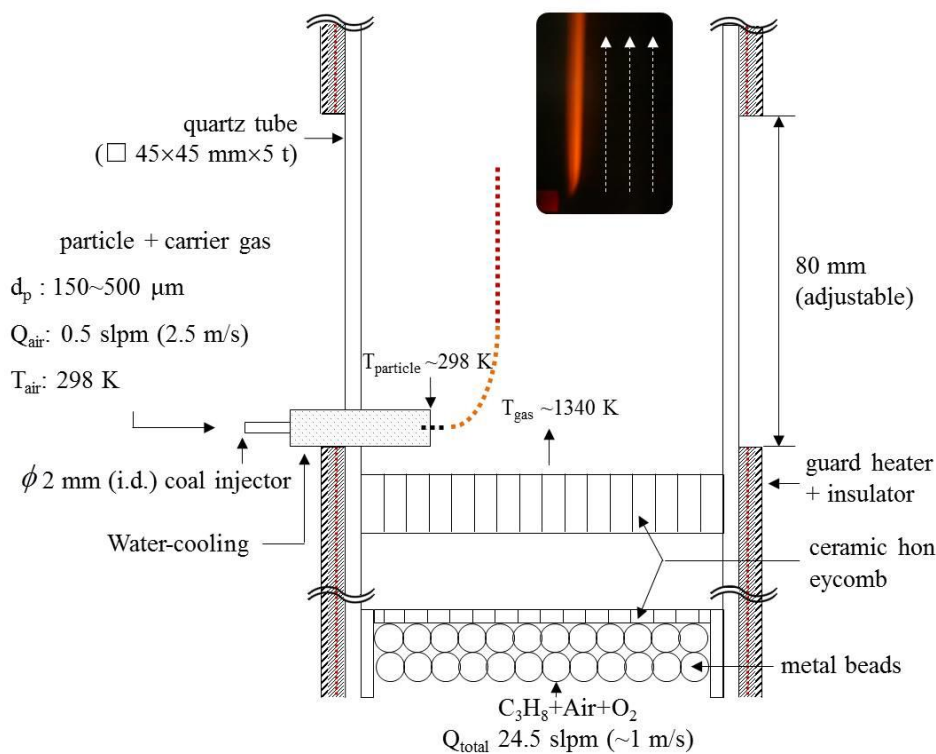


Figure 5-1 Cross-flow configuration in the entrained flow reactor under well-controlled conditions. Single fuel particles are entrained into the 1,340 K zone from the water-cooled injector maintained at 298 K.

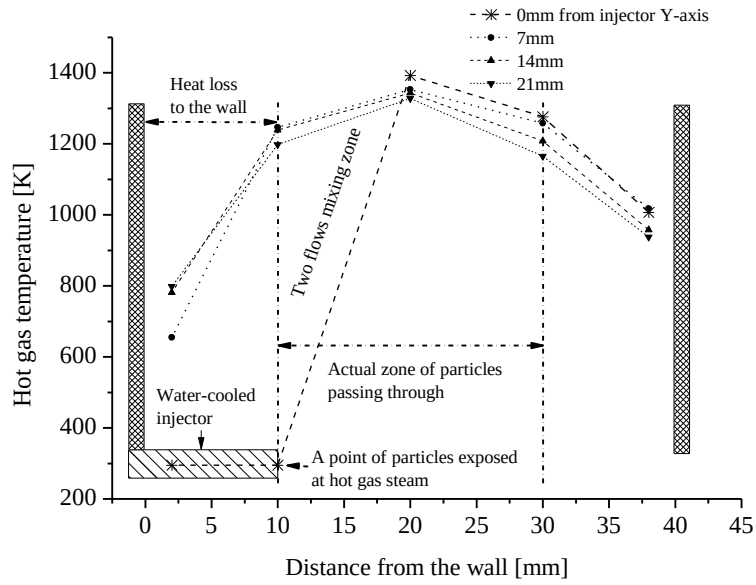
5.3.3 Direct observation of particle combustions

To investigate the combustion events, the burning particles were directly observed by a high speed camera (Phantom V710). The camera records randomly moving particles at 7,000 frames per second in 1,280×800 pixel. The relatively large sludge particles were captured by a 100 mm micro focal lens and the pixel size was measured as 58 μm by calibration. The details of this observational technique are explained elsewhere.

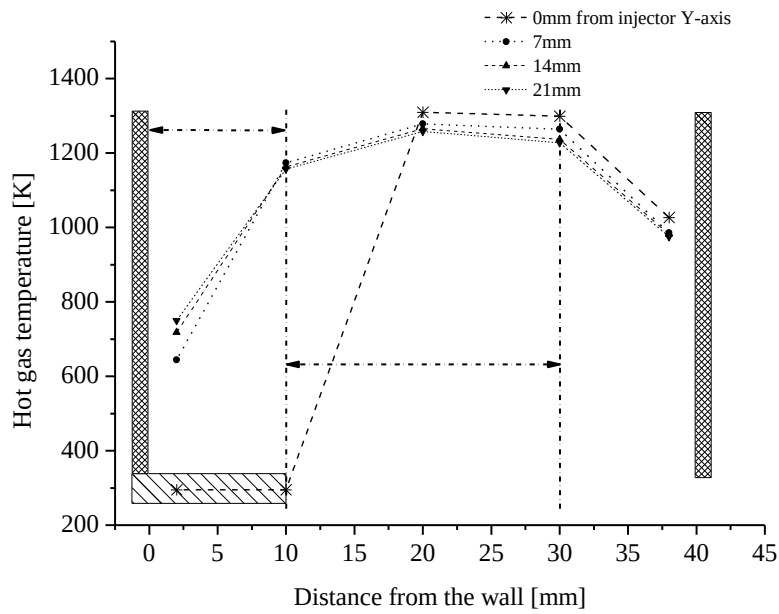
5.3.4 Surrounding environmental conditions and measurement of temperature and velocity profiles

To examine the effect of oxygen diffusion rate, the particles were exposed to O_2 with volume fractions of 10 to 40 %. The post-combustion gas, C_3H_8 , yields flue gases such as N_2 (38.2–67.9 vol%), O_2 (10.4–40.1 vol%), H_2O (12.4 vol%) and

CO₂ (9.3 vol%). The flow rates of the post-combustion gas and the cold carrier gas at the injector were 24.5 and 0.5 L/min, respectively. The particles were heated in the highly-mixed temperature zone created by the markedly different temperatures of the upward- and leftward-flowing streams. Within this zone, the initial combustion behaviour was determined. The gas temperature profiles from the experimental measurement and numerical simulation are plotted in Figure 5-2. In both methods, we evaluated the initial gas temperature and velocity as the particles were heated and investigated the highly-mixed turbulent region. These factors are essential for studying the ignition and combustion times. The numerical simulation, which computed the horizontal and vertical velocities and the gas temperature distribution over a wide range of the visualisation field, was carried out in FLUENT 14.0. Similar results of temperature and velocity in the reactor were shown in ref. [38]. The maximum temperature was 1,340 K at the centre. The sides were uninsulated (and hence experienced large heat losses) because an unobstructed field of view is necessary to allow particle observation. To combat the effect of these losses, the injector was positioned at 10 mm from the x-axis, where the temperature gradient was acceptably small. Therefore, the particles passed through the gas stream between 10 and 30 mm. The temperature profile predicted by the numerical analysis agreed well with the experimental results. Figure 5-3 show the numerically calculated horizontal velocity profile of the flow velocity. The particles gained momentum in the leftward-flowing direction, but their particle velocity in the horizontal direction rapidly decreased when the particles were carried up the reactor.



(a)



(b)

Figure 5-2 Gas temperature profiles obtained by (a) experimental measurement and (b) numerical simulation. The high heat loss at the sides is caused by the exposed field of view. To combat these losses, the injector is placed 10 mm from the wall.

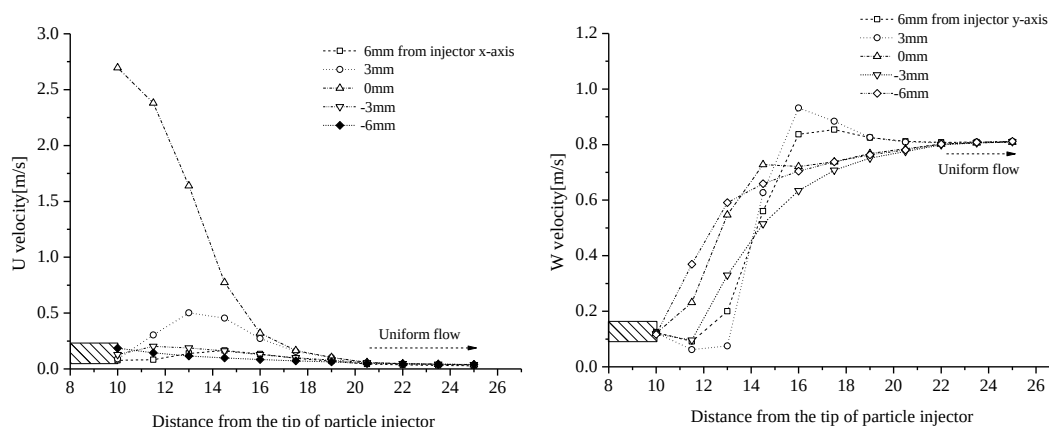


Figure 5-3 Gas velocity profiles around the mixing zone, obtained in the numerical simulation: (a) horizontal velocity (b) vertical velocity.

5.3.5 Formation of standard flame with boundaries of pyrolysis and soot formation

The volatile flame is an elongated formation of sooty cloud several times larger than the particles themselves [39, 40]. It is believed that the detailed mechanism of volatile cloud formation and its flame composition remains questionable because the complicated transport and hundreds of chemical events are difficult to quantify. Particularly, the detailed information of soot formation in phenomenological studies of carbonaceous particles is still being debated, because of the dependency between the particles and the combustion system. To simplify the mechanism, we can regard a soot flame as a collection of volatile matter and submicron soot particles that follow several chemical reactions. During the primary pyrolysis releases, light gases, char and heavy molecular weight hydrocarbons (mainly tar) are released [41]. These liquid-like materials randomly agglomerate into large clusters before cracking and polymerising. During the secondary reaction, tar converts to soot particles, especially at high temperature [25]. Soot particles are composed of 20–50-nm spherules that coagulate and agglomerate [42]. Ma et al. [43] reported soot aggregates of 5- μm diameter in a coal flame. A volatile flame is generally defined by the boundaries

of the pyrolysis and soot formation within the combustion region. These boundaries are described as a simple flame sheet (see Figure 5-4). During pyrolysis, carbonaceous particles of different sizes mix at different rates with organic particles, tar balls and a small number of the initial soot particles [44, 45]. However, the general description of these compositions cannot be elucidated, as it depends on the types and temperatures of the particles. Within the flame sheet, the volatile flame apparently divides into an inner core and an outer shell in the diffusion flame. The primary reaction occurs in the inner core, r_i , a transparent flame region whose dimensions are determined by the devolatilisation rate, oxygen concentration and particle size and temperature. The outer shell, r_s , is a luminous flame region that deposits many aggregates of soot particles through secondary reaction and transport. Finally, the flame edge is a region of secondary combustion driven by oxidation of the volatile phase.

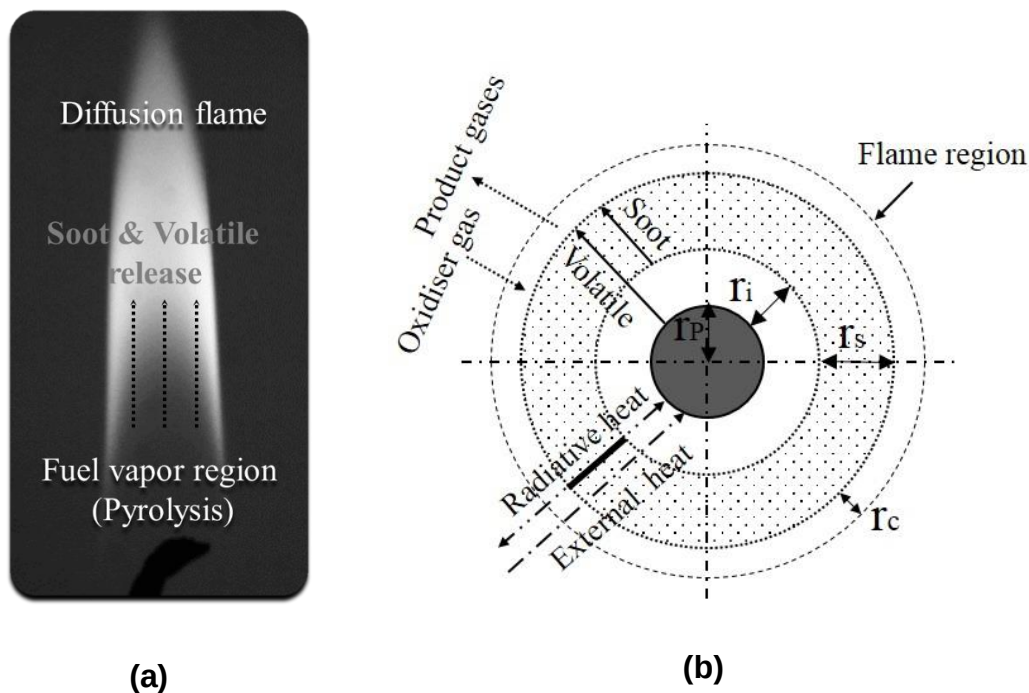


Figure 5-4 General flame structure of a candle: (a) boundaries of pyrolysis and soot formation showing the combustion region (b) representative diffusion flame sheet.

5.4 Results and discussion

5.4.1 Optical carbonaceous particles properties in a flame

To better understand the physical mechanism of flame formation by torrefied sludge particles, we observed the optical flame properties using a manual aerosol collector with a plate. The volatile flame on the pulverised particles was too small for sampling, so we detected the flame of a pelletised sewage sludge particle. The following is an explanation for the procedure. The torrefied sewage sludge particle swiftly departed from the quartz when burned at 1340 K. Within one second, a plate was passed through the pyrolysis zone in the flame. The samples were then transferred to the microscope for particle detection. The transfer needed to be completed within 60 seconds; otherwise, most of the organic particles and tar would evaporate. Several photographic images were acquired under varied displacements of the plate, acquiring different properties of the particles between the pyrolysis and soot formation boundaries. Micron and sub-micron carbonaceous particles were observed under Nikon microscopes (ECLIPSE E200) and imaged by a multi-output digital microscope camera (Moticam 2300).

The sequential images in Figure 5-5 illustrate the development of inorganic, tar and carbonaceous particles in different positions of an elongated flame. The carbonaceous particles are a by-product of gaseous fuel combustion. In general, their particles comprise primary spherules or monomers combined into branched aggregates. The monomers are further composed of black carbon and organic particles, with the ratio of their compositions varying based on the types of particles involved. In our present study, the torrefied sludge particles were tested; however, a detailed mechanism for the soot flame is still questionable. The corresponding images suggest a simple mechanism involving cloud, condensation and agglomeration.

The micrographs in Figure 5-5 show the varying size, shape and brightness of the volatile organic and non-volatile particles, tar balls and aggregates of the soot particles. Agglomerates of non-volatile and soot particles appear very bright, as

these carbonised particles reflect light from halogen (lighting) illumination. The first image, taken in the centre of the pyrolysis boundary, captures a number of organic particles with various shapes and sizes. The bright central regions of these sub-micron particles are probably sourced from sulphur, potassium, silicon and sodium, perhaps introduced through ageing of the organic particles. Consistent with this idea, previous observations [46] revealed no inclusions in the initial organic particles. Novakov et al. [47] reported that these organic particles contribute to cloud nucleation. Cloud condensation nuclei are useful for determining the importance of inorganic components [48]. The second image shows the irregular shapes of non-volatile particles nearby the shrunken organic particles. Older organic particles enhance the formation of tar balls from non-volatile particles. Tar balls form a chain-like arrangement around the organic particles, as also reported by Kennedy [49] and Arora [50]. The third image captures the outer boundary of the pyrolysis. This region contains agglomerated tar balls and non-volatile particles and near-extinct aged organic particles. Interestingly, the tar balls are grey in the previous image, but black in this image. However, the significance of this visual transformation needs verifying in high-resolution images, so cannot be discussed here. The final image also captures the outer pyrolysis boundary, where soot formation produces a very sooty flame. The bright features are highly aggregated soot particles that might have sequentially converted from clusters of tar balls. These aggregates are nearly 1–3 μm across, but appear to be incompletely developed.

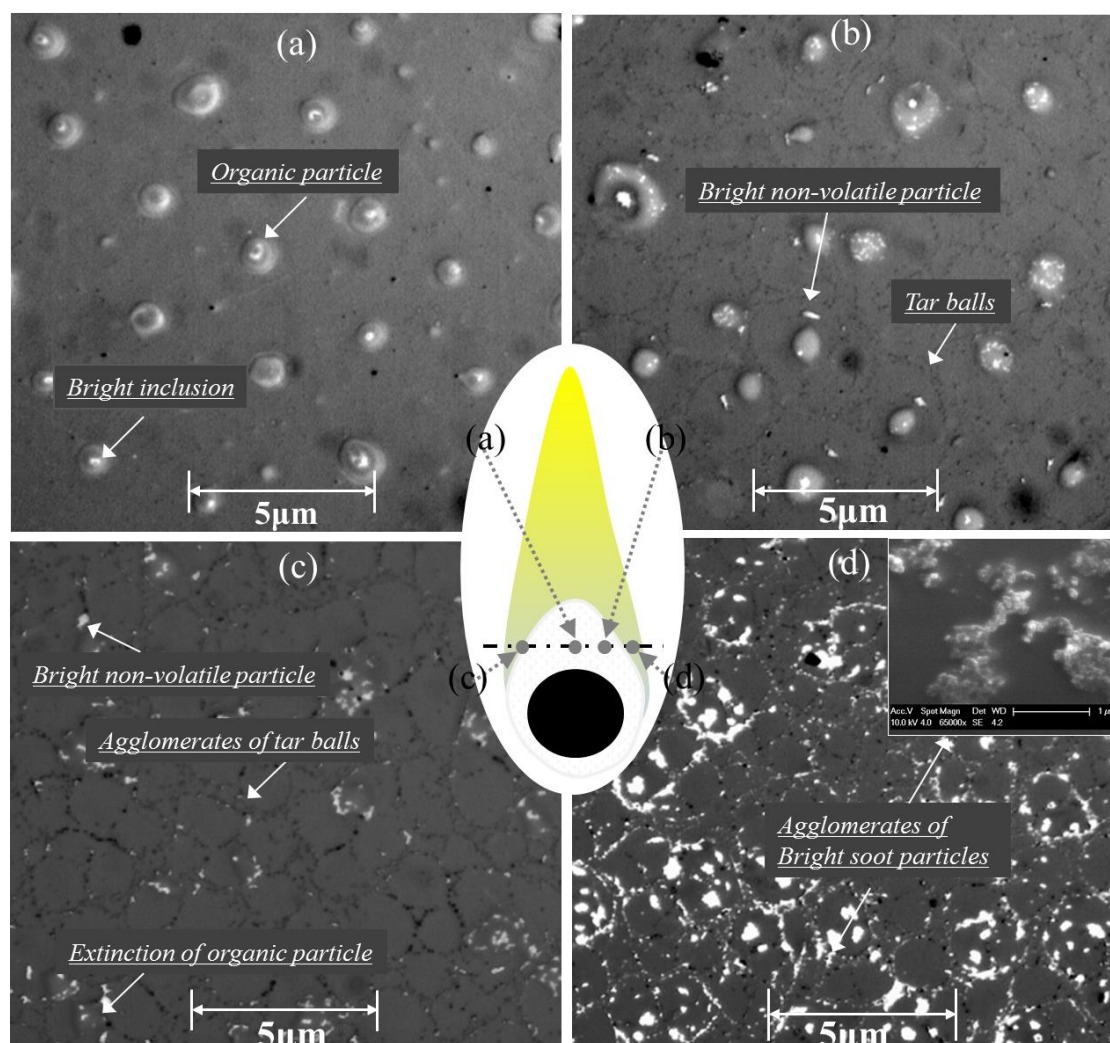


Figure 5-5 Morphology of carbonaceous particles formed in a flame: (a) aged organic particles with inclusions; (b) non-volatile particles with tar balls, (c) agglomerates of tar balls with extinct organic particles and (d) agglomerates of soot particles.

5.4.2 Direct observation of combustion behaviours of raw and torrefied sludge particles

The raw and torrefied sewage sludge particles in both size ranges (150–215 μm and 255–300 μm) were burned at the same hot gas temperature but different oxygen concentrations. The sequential combustion process of a burning pulverised biomass particle is described in the superimposed images in Figure 5-6. The particle is immediately heated up in the hot gas flow and a volatile flame appears within a few milliseconds, followed by the release of volatile matter on the surface and subsequent char combustion. As the oxidising environment was increased, the particles ignited faster with a shorter duration of volatile combustion and a higher probability of overlapping combustion before the flame extinguished.

The surrounding environment clearly affected the flame shape and luminosity between the particles. In the small particle group (150–215 μm), the raw sludge particles burned with an invisible flame or an apparently low luminous volatile cloud. The flame appearance can be explained by the low tar content in the small particle group, the H/C ratio in devolatilisation [51] and the high hydrogen-to-carbon ratio ($\text{H/C} = 1.5$) with a small amount of volatile phase. In contrast, the H/C ratio of coal ranges from 0.2 to 0.8, depending on the rank of the coal. Consequently, the small raw sludge particles exhibited an invisible flame. However, the complex and varied mechanisms of tar formation preclude a clear explanation of the tar formation process [52].

In the larger particle group (255–300 μm), the flame was elongated with a moderate intensity, but still might generate insufficient radiative heat for combustion systems. It has been found that the soot flame intensities and flame sizes generated by the most torrefied sludge particles were remarkably distinct from those of burning raw particles. In the following results, the quantitative combustion characteristics of the raw and torrefied sludge particles are compared. In the images, apparent soot flames are observed only on the torrefied particles, even in the small particle group. This might indicate that torrefaction greatly improves the fuel combustion quality of the particles, but reduces the duration of

volatile combustion by removing the volatile matter. The result is contrary to expectation, as also explained in the next results. The flames became larger with decreasing O₂ concentration, as reported in previous studies [37, 53].

Figure 5-7 presents the normalised optical intensity, measured from the centre of the particle along the y-axis and the representative combustion characteristics of burning particles for the model and design of the furnace. The lower oxygen concentration here contributes to increasing the radiation heat transfer from the increased flame intensity; however, there is a trade-off between the radiation heat transfer and flame size. The energy is described by time-averaged radiation, i.e. $Q_r = \sigma \epsilon_T T_f^4 A_f$, where σ is the Stefan–Boltzmann constant (i.e. 5.67×10^{-11} kW/m²K⁴), ϵ_T is the flame emissivity, T_f^4 is the average flame radiation temperature and A_f is the flame surface area. Figure 5-7 presents the normalised optical intensity, measured from the centre of the particle along the y-axis. The flame of the burning torrefied particle comprised a transparent inner core and an outer shell with possible sooty formations. The inner flame was observed only under the 10 % and 21 % O₂ conditions. The outer flame increased with decreasing O₂ concentration; this trend was attributed to slower soot oxidation. The soot particles with volatile matter tended to lift in an elongated formation under buoyancy and transport. High-luminosity spherical flames appeared at oxygen concentrations above 21 %. The highest luminosity was observed in the presence of 21 % O₂. As the O₂ concentration increased from 21 % to 40 %, the flame intensity decreased rapidly to approximately 0.5.

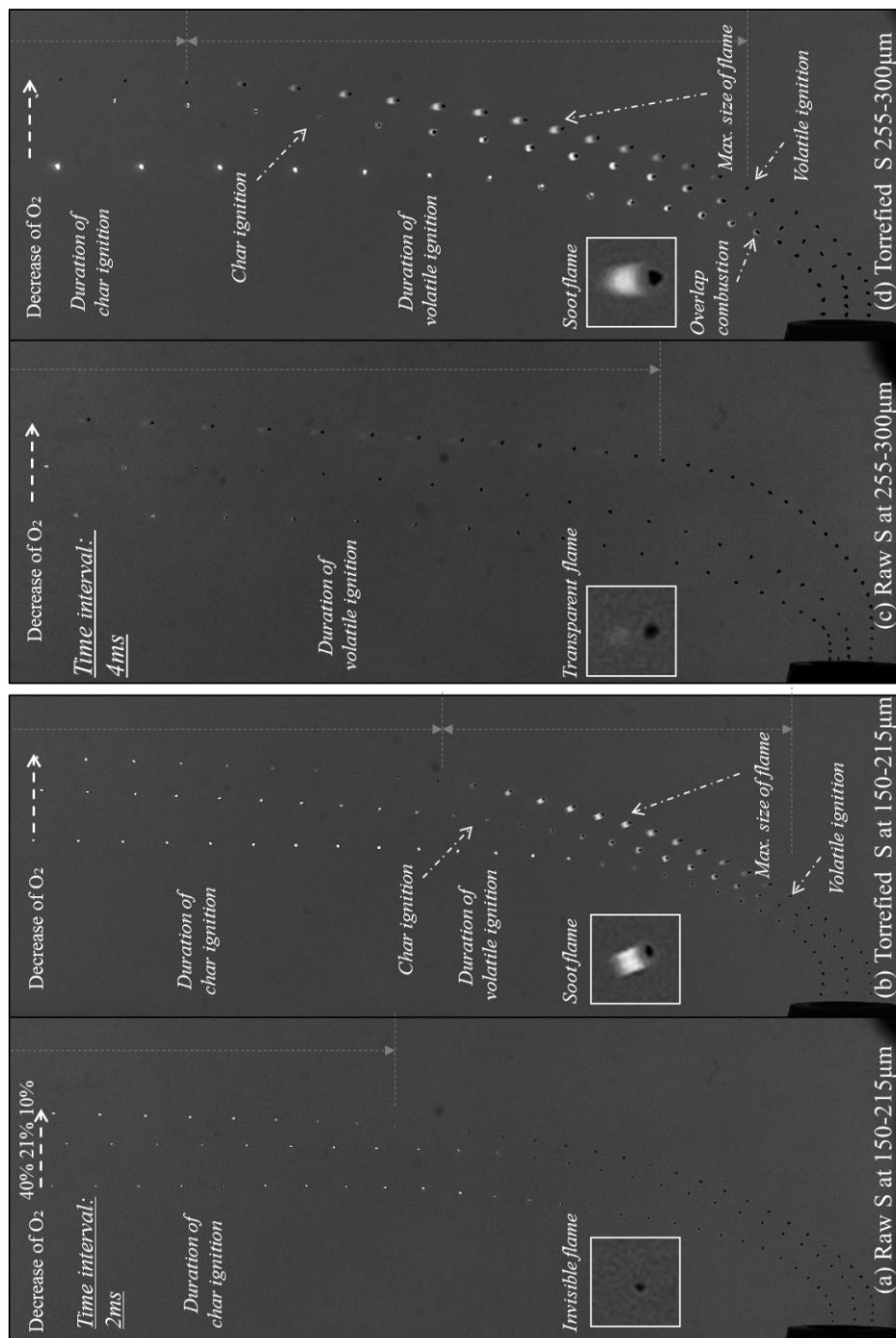


Figure 5-6 Sequential combustion on burning raw and torrefied sludge particles at oxygen concentrations of 10–40%: (a) Raw sludge particles (150–215 μm), (b) Torrefied sludge particle (150–215 μm), (c) Raw sludge particle (255–300 μm) and (d) Torrefied sludge particle (255–300 μm).

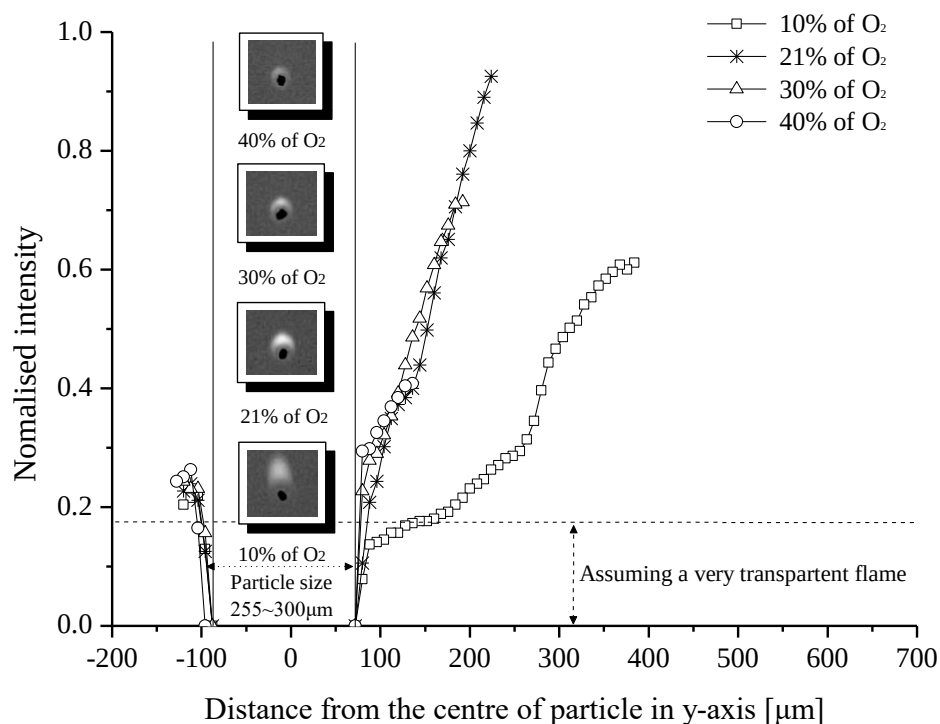


Figure 5-7 Optical normalised flame intensity versus y-axis distance from the centre of 255–300 μm -diameter torrefied sludge particles. The most intense flames are spherical and appear at 21% oxygen concentration.

5.4.3 Comparative combustion behaviours on three torrefied sludge particles under different thermal treatment conditions

According to the temperature and residence time of the thermal treatment, the chemical compositions of the fuel particles are varied. In particular, the degree of torrefaction will affect the combustion behaviours of the particles. The change might be remarkable in sewage sludge. In fact, the low fixed carbon and high ash contents of raw sludge particles degrade the combustion quality and lengthen the ignition delay. Figure. 5-8 is a photographic series of three small-sized (150–215 μm) torrefied sludge particles, showing the histories of the volatile flames in a 21 % O_2 atmosphere. The onset times of gaseous and char combustions are also shown. The luminosity was the highest on sewage particles torrefied at 573 K for

30 min and was relatively low on particles torrefied at 573 K for 10 min. The ignition of particles in both treatments was almost equivalent at 26 ms. However, the particles torrefied at 473 K for 30 min exhibited an invisible flame until the onset of char combustion. Interestingly, all of the particles were ignited at the same onset time (46–48 ms after the extinction of volatile combustion).

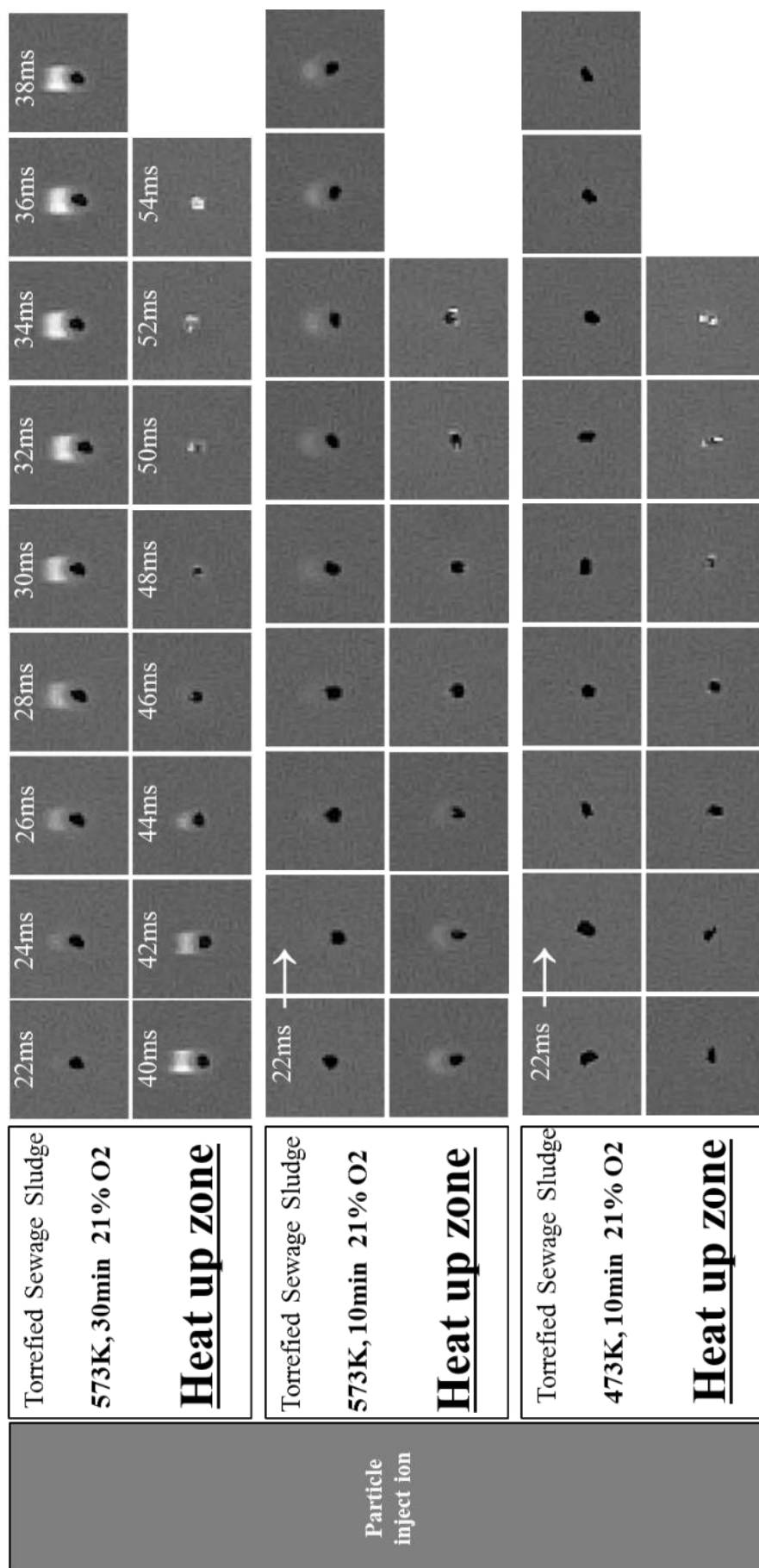


Figure 5-8 Photographic series of torrefied sewage sludge (diameter = 150–215 μm) burning in a 20 % O₂ atmosphere: (a) Sewage sludge torrefied at 573 K for 30 mins, (b) sewage sludge torrefied at 573 K for 10 mins and (c) sewage sludge torrefied at 473 K for 30 mins. The luminosity of the flames depends on the torrefaction degree of the particles.

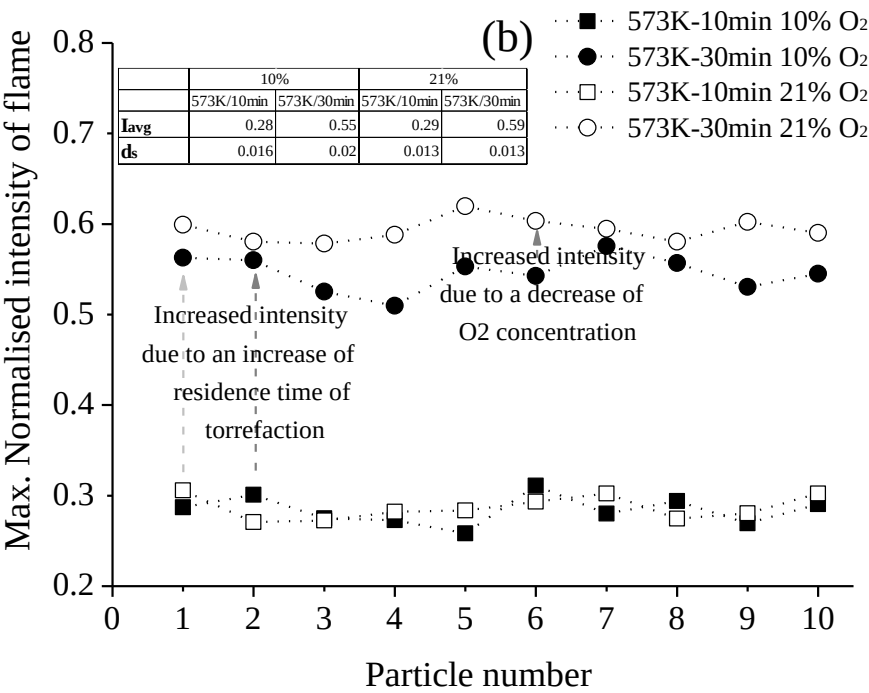
Figure 5-9 plots the maximum radii of the volatile flame and the normalised intensities during the burning of sludge particles torrefied under two conditions (10 min and 30 min; 573 K). For each torrefaction treatment, we analysed 10 samples with the standard deviation. For the flame sheet model, we assumed and calculated the concentric flame as the spherical flame. The volatile flame area (A_f) was calculated by summing the corresponding area (dA_{pixel}), which was obtained from the pixels in the flame image. The effective flame radius (R_{eff}) is calculated from the following equation, where R_p is the particle radius

$$R_{\text{eff}} = \sqrt{\frac{1}{\pi} \cdot (A_f + \pi R_p^2)}, \quad \text{where } A_f = \int dA_{\text{pixel}} \quad (1)$$

The intensities of volatile flames for the four particles were analysed by image processing, which was measured from an averaged value of a grayscale image. The image was converted into the grayscale image from a numerical data matrix. In the process, each pixel in the image has different values in a range of 0 to 255 and numerical background values, which were more or less than 65, are extracted from the images. Finally, the intensity of the flame was divided by the maximum value of grayscale (255).

The profiles confirm variability in the flame structures, which may explain the discrepancy in the burning characteristics. Under the same conditions of particle size (255–300 μm) and O_2 concentration (10%), the maximum apparent effective diameter of the flame was approximately 500–600 μm for the more torrefied particles (30 min at 573 K) and 370–420 μm for the less torrefied particles (573 K at 10 min). As the O_2 concentration increased to 20%, the effective flame diameters of the more torrefied particle (573 K at 30 min) and the less torrefied particle (573 K at 10 min) decreased by approximately 110 μm and 70 μm , respectively. The residence time is an important influencer of the flame diameter, because an appropriate torrefaction time enhances the chemical conversion for the reaction rate and soot formation. The flame intensity, which might be strongly related to the soot volume fraction, was lower on the more torrefied sludge

particles than on the less torrefied particles (0.51–0.62 vs. 0.27–0.3 at O₂ concentrations of 10–21%).



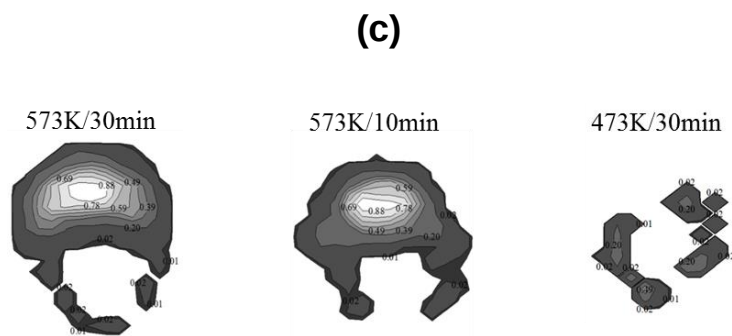
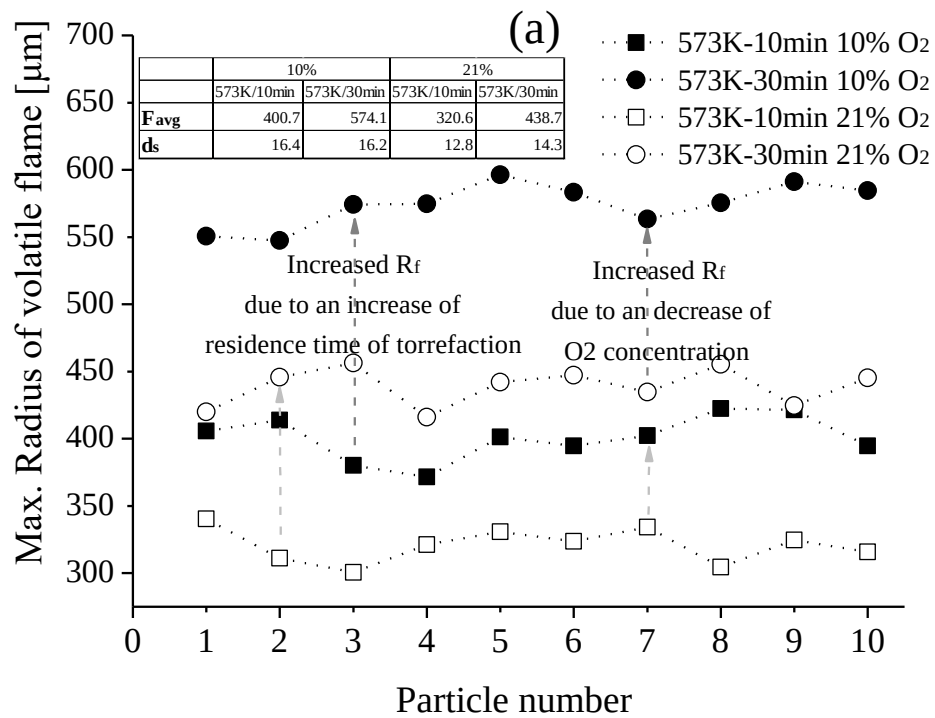


Figure 5-9 Volatile flame structure on torrefied particles in O₂ atmospheres of 10 % and 20 %: (a) Maximum radius of volatile flames (b) Normalised intensity of flames (c) Image analysis of volatile flames. Each panel shows the variation in flame size and intensity on sludge particles torrefied under different conditions.

5.4.4 Discrepancy of volatile flames-time histories on the most and least torrefied particles

From our results, we can quantify the development of the burning particles associated with their volatile flames from initial ignition to flame extinction. We might also understand how the chemical reactions of the differently torrefied particles contribute to the ratio of the effective flame radius to particle size. Figure 5-10 shows the histories of the burning behaviours of 5 particles in the larger size group (255–300 μm). Generally, the physical structure of the volatile flame is determined by the volume fraction of the gaseous phase and soot particles. The reaction rates of these phases depend on their chemical compositions and the particle temperature. Here, the particles torrefied by different treatments differed in their torrefaction temperatures, but were identical in size.

Beyond the peak in Fig. 5-10, the ratio of the effective flame radius to particle size narrows between the differently torrefied particles. The discrepancy appears before the peak; the radius of the less torrefied particles, with a low soot flame, decreases by up to 0.75. This phenomenon might be related to the early-stage presence of soot particles, because the more torrefied sludge particles (573 K at 30 min) have a higher fixed carbon than the less torrefied particles (573 K at 10 min). The flame intensity of the less torrefied particles reduced over the combustion duration. However, these particles contained more volatile matter than the highly torrefied particles, which would have enlarged their flames. Consequently, the variable radii and flame intensities are dominated by the different reaction rates with soot formation in the early stage. In turn, the variable rates reflect the different chemical and physical compositions of the particles. However, this physical phenomenon requires validating in quantitative analyses of the soot volume fraction, which is beyond the scope of this study. The diffusion flames of the raw and strongly torrefied particles (473 K for 30 min) were not clearly detected in the volatile-flame time histories. In other words, the raw sludge particles and those torrefied under inappropriate pre-thermal conditions might be unsuitable for biomass fired combustion.

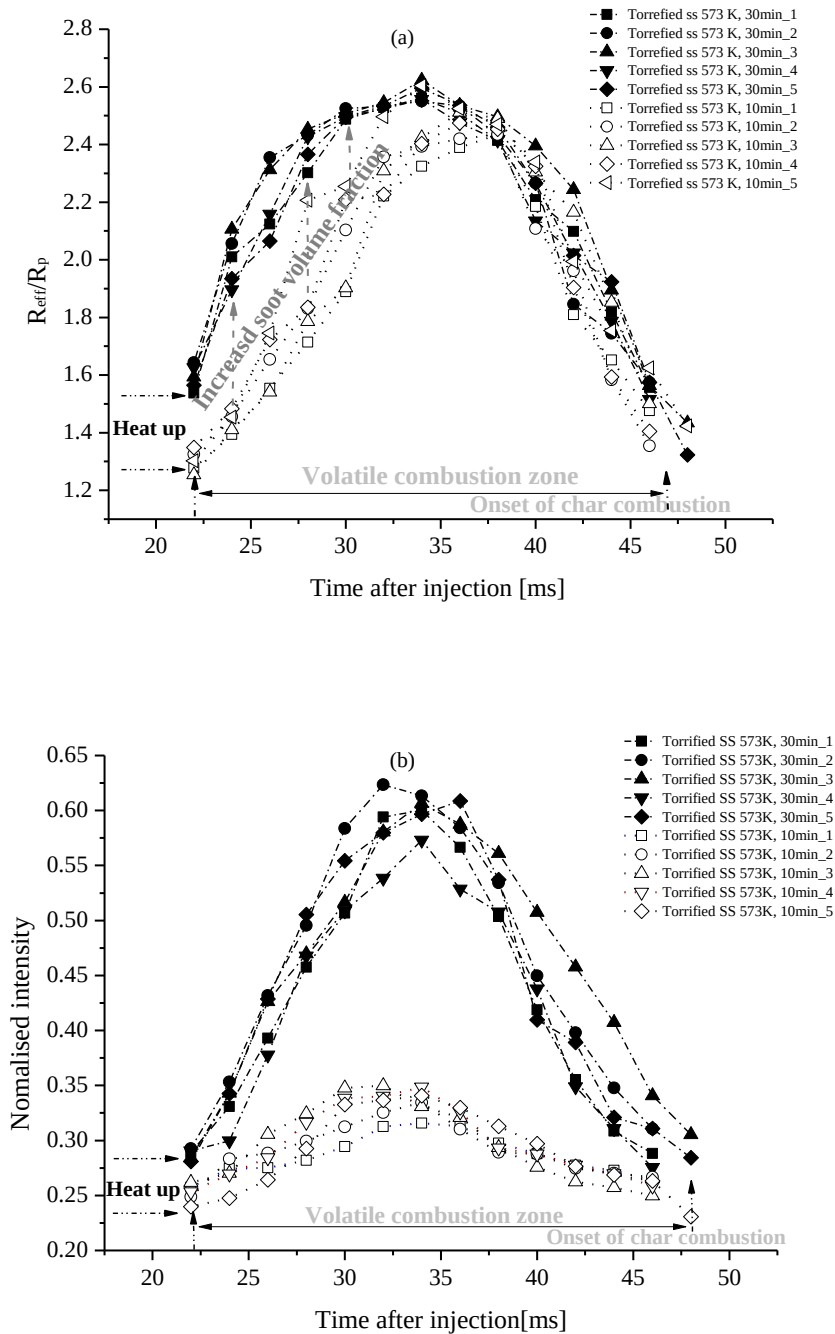
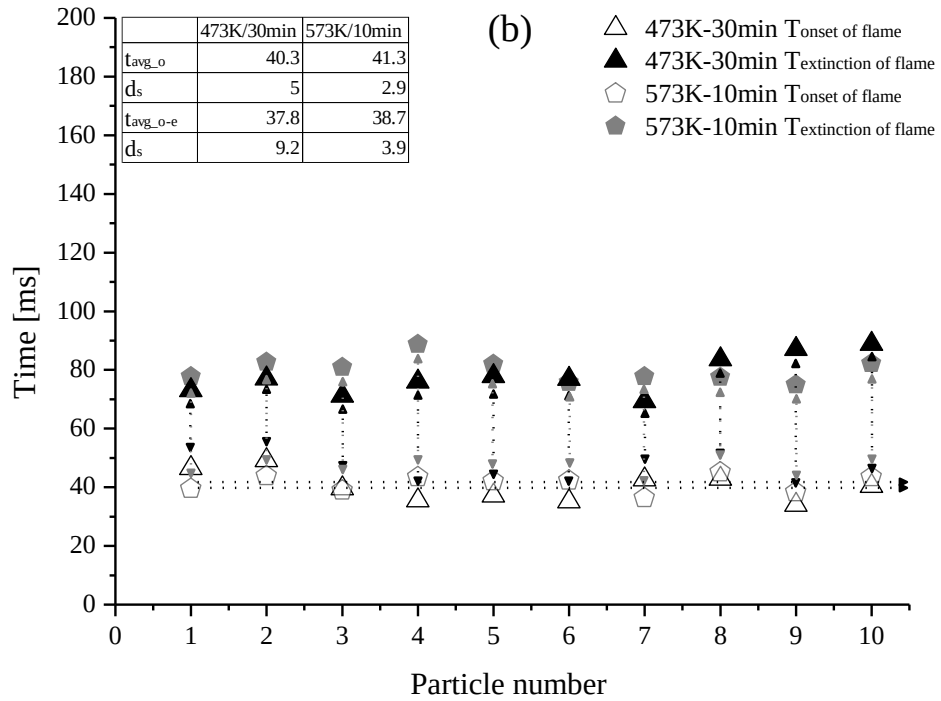
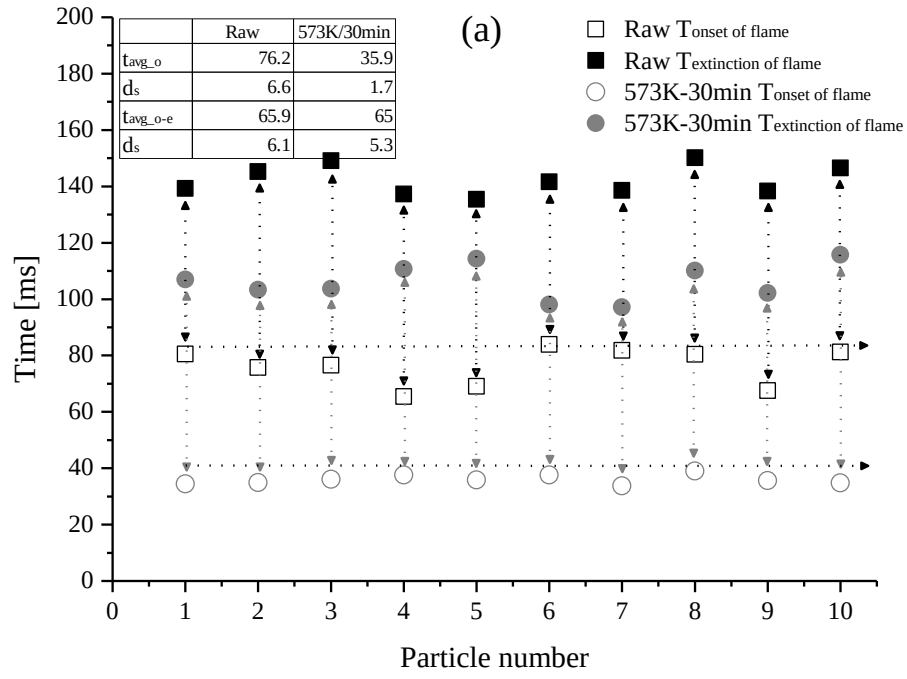


Figure 5-10 Apparent volatile flame structures of torrefied sewage sludge particles at 1340 K: (a) Radii of effective volatile flames relative to the particle diameter (255–300 μm) and (b) normalised flame intensities of differently torrefied particles at 21% O_2 concentration. The graphs illustrate the early-stage discrepancy in the volatile flames between the differently torrefied sludge particles.

5.4.5 Ignition delay and duration of volatile combustion on raw and torrefied sludge particles

Figure 5-11 presents the dissimilarity in the onset of initial ignition and the volatile combustion duration among the three torrefied particles and raw particles of the same diameter (255–300 μm). By discussing the discrepancy among the time parameters in particles torrefied to different degrees, we can evaluate the combustion quality of the torrefied particles. The standard deviation of the volatile combustion duration of each particle was 1.7–9.2, sufficiently small for quantitative analysis. This statistical analysis is significant for verifying the flame structure and combustion behaviours. The three torrefied particles nearly coincided at approximately 35–40 ms after the average onset of volatile ignition, but the raw sludge particles exhibited a longer ignition delay (almost 76.2 ms). Consequent to the extended ignition delay, the flame of the raw particles was extinguished at 140 ms. However, the volatile combustion duration scarcely differed between the raw and the most torrefied particles, despite the different volume fractions of volatile matter in the two particles. Conversely, the volatile combustion time was approximately 26 ms longer in the less torrefied sludge particles than in the more torrefied particles. It appears that appropriate torrefaction can improve the quality of solid fuel particles and increase the radiative energy from the soot flame without reducing the combustion time.



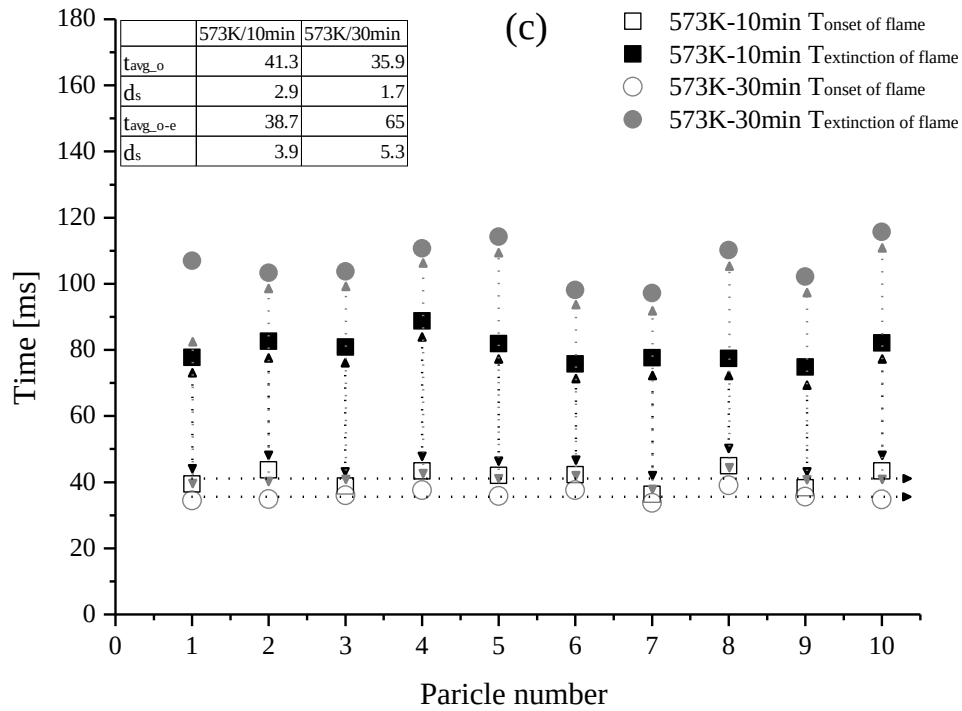


Figure 5-11 Ignition delays and durations of volatile combustions for four different sludge particles of the same diameter (255~315 μm): (a) raw and sludge particles torrefied at 573 K for 30 mins, (b) particles torrefied at 473 K and 573 K for 30 and 10 mins and (c) sludge particles torrefied at 573 K for 10 and 30 mins. The ignition delay is longest on the raw particles, but the duration of volatile combustion is identical on the raw and the more torrefied sludge particles.

5.4.6 Flame structures obtained from the effect of particles size and oxygen concentration

The improved flame structures of the most torrefied sludge particles also enable high radiative heat transfer for combustion applications. According to the radiative heat transfer equation, this energy is proportional to the flame size and to the fourth power of the flame temperature. Figure 5-12 shows the structural changes of the inner core and outer shell in the most torrefied particles of both particle sizes. Here the O_2 concentration was varied as 10, 21 and 40 %. For both particle sizes and below 21 % O_2 concentration, the inner core was extended in the flame and the R_f/R_p rose steeply toward the peak. At 21% O_2 concentration, the R_f/R_p depended on particle size, being 3.6 and 2.7 for particles in the 150–215 μm and 255–300 μm ranges, respectively. The area of soot formation was larger at the higher particle diameters (255–300 μm). The normalised intensities of the flames of 150–215 μm were most similar at low O_2 concentrations (10 and 21 %) and dramatically decreased to below 0.1 at 40 % O_2 . On the other hand, the flame intensities of the 255–300 μm particles increased as the O_2 concentration increased from 10 % to 21 %, where they peaked at 0.65, then reduced to 0.52 at 40 % O_2 . The discrepancy in the intensity profiles of the 150–215 μm and 255–300 μm particles might be related to the soot volume fraction, as the higher carbon contents in the larger particles form a more luminous flame.

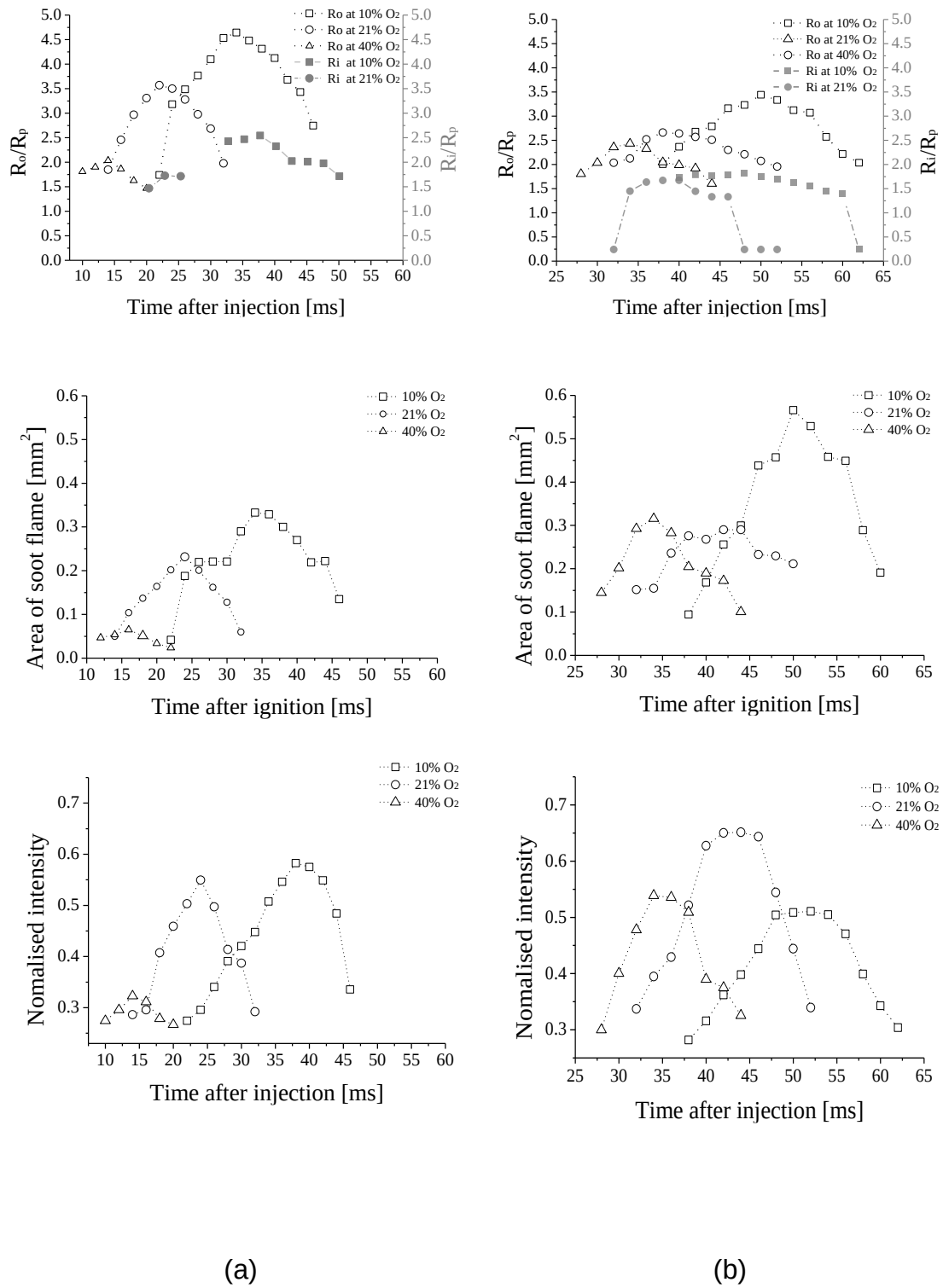


Figure 5-12 Parametric physical flame parameters of the most torrefied sludge particles exposed to different oxygen concentrations. The particle size is (a) 150–215 μm and (b) 255–300 μm .

5.4.7 Burnout characteristics derived from the particle size and oxygen concentration effects

In very small pulverised particles, the ignition delay is shortened by the uniform temperature gradient throughout the particle. Intra-particle temperature gradients establish in particles sized over 200 μm [54]. In fact, the particle's surface temperature determines the heat flux generated to the centre of the particle. The temperature difference induced by the particle size increases the heating time and reduces the devolatilisation rate. The most torrefied sludge particles were investigated only for their size effect, as a clear soot flame was scarcely formed in small-diameter (150–215 μm) raw and less torrefied sludge particles. Figure 5-13 compares the average heat-up and volatile combustion durations of both size groups burning under O_2 concentrations of 10–40 %. The standard deviation of the 20 samples was computed with the standard error (max. 0.3) using the rudimentary statistical analysis. The ignition delay and combustion time of the larger particles was almost double that of the smaller particles at the same oxygen concentration. We surmise that the particle temperature gradient plays an important role in these time parameters. The intra-particle effect requires further investigations on larger particle sizes.

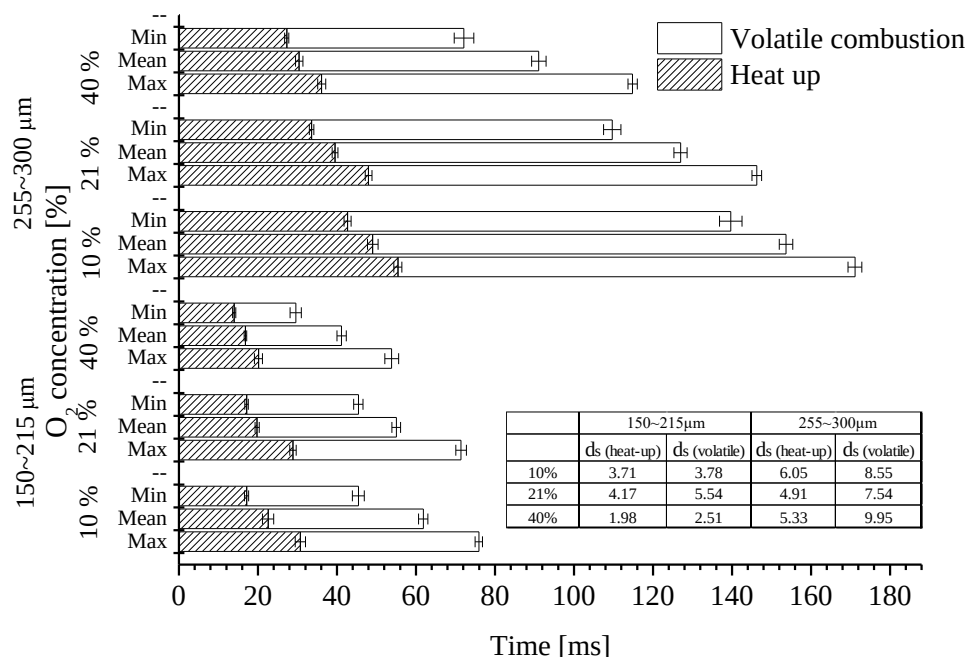


Figure 5-13 Effect of particle (573 K/30 min) size and oxygen concentration on ignition delay and volatile combustion duration.

5.5 Conclusion

The flame structures of torrefied sewage sludge particles were experimentally observed in an environment of a hot gas stream and oxidising gases. The flames were compared with those of raw sewage sludge, which is generally regarded as a solid fuel particle with low combustion quality. The particles were burned at rapid heating rates and high temperatures that typify actual volatile flames. The sludge particles were torrefied to different degrees and their ability to improve the combustion quality was assessed. From the results, it is believed that torrefaction improves the flame size and intensity, which plays a significant role in radiative heat transfer and flame stability. These flame structures such as their size and intensity were determined by the torrefaction degree. These flame parameters were significantly discrepant only in the early stages of particle combustion, when the reaction rates and soot formation were non-synchronous. The most torrefied sludge particles (prepared at 573 K for 30 min) yielded verysooty flames with a

fast ignition time even in the small diameter range (150–215 μm). The duration of volatile combustion (~ 70 ms) was almost equal in the raw and the most torrefied particles, despite the reduced volatile matter in the latter. For a comparative analysis of the torrefaction treatments, a sufficiently high torrefaction temperature and an appropriate residence time are required. The difference in onset of volatile ignition between the raw and strongly torrefied samples might be attributable to lignin, which decomposes over a wide temperature range. Finally, when the oxygen concentration in the combustion was varied from 10 to 40 %, the highest flame intensity was obtained on torrefied particles at 21 % O_2 concentration; moreover, the effective flame was enlarged in the smaller particle group. This experimental result enables valuable discussions for improving the flame structures of torrefied particles under rapid heating rates and may also provide a modelling description of single torrefied particle combustion.

5.6 knowledgments

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CHAPTER 6

Burning characteristics of single particles of coal and wood mixtures for co-firing in a upward-flowing hot gas stream

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6. BURNING CHARACTERISTICS OF SINGLE PARTICLES OF COAL AND WOOD MIXTURES FOR CO-FIRING IN A UPWARD-FLOWING HOT GAS STREAM

6.1 Abstract

This study presents the comparative burning behaviours of single solid particles of coal and biomass mixtures for co-firing. In this experimental investigation, a direct observation approach was used to investigate the ignition, flame characteristics and combustion times by means of high-speed photography at 7,000 frames per second. Single particles were entrained into a hot gas stream at 1,340 K and a rapid heating rate at 10^4 - 10^5 K/s. The apparent volatile flames from the prepared particle size groups were observed within 20-50 milliseconds. To assess the effect of oxygen concentration, particles were burned for their flame characteristics in a range of 10%–40% O₂. The test particles were sieved into three size groups (215–255 µm, 255–300 µm and 300–350 µm) to assess the effect of particle size. Special particles for the co-firing effect were collected individually from two types of mixed pellet: 20:80 and 50:50 coal/wood. Pure sub-bituminous coal and wood particles were also prepared in order to compare their combustion behaviours. In the experimental setup with a cross-injection configuration, sequential combustion processes were effectively and clearly described in terms of particle displacement with time. The experimental results showed distinguishable flame characteristics from single particles of coal, 50:50 coal/wood, 20:80 coal/wood and wood, including soot flame size and intensity. The impact of high coal-blending ratio caused an increase in the flame size and intensity and the ignition time was close to that of pure coal particles. Quantitative measurements of combustion events on co-firing particles were also discussed in relation to significant impacts of the particle size and the oxygen concentration.

6.2 Introduction

Co-firing is a promising technique with several benefits, the most important of which are environmental ones. Simultaneous burning of coal and biomass emits low NET carbon dioxide [1, 2] and the sulphur oxide (SO_x) and nitrogen oxide (NO_x) emissions from this combustion are generally lower, compared with the coal-fired combustion [3–6]. The economic benefits of this type of combustion are fuel price stabilisation, fuel flexibility and low-risk costs of retrofitting coal-fired plants with fuel-blending control systems for biomass particles [7, 8]. The main challenges with co-firing come from the characteristics of biomass particles in relation to chemical composition, fibrous shape and relatively large particles (~3 millimetres for biomass, ~150 μm for coal in p.f. boiler) [9, 10] with relatively low energy density [11, 12]. Their irregular shape and wide particle size range during combustion play a significant role in burning behaviours such as ignition, volatile flame and char combustion [13]. The significant differences between biomass and coal are the wide disparity in volatility and the fixed carbon content of different types of biomass. The volatile matter content of biomass is greater than that of coal and the fixed carbon content is less, which contributes to their different burning behaviours regarding volatiles and char combustions [14–16]. From a previous study [17], pulverised biomass particles are known to exhibit flame characteristics that are associated with a small flame and low intensity during homogeneous combustion. Besides, the volatile matter in biomass is released earlier than that in coal because of the different ignition temperatures of their organic compositions [18–20]. Consequently, the burning behaviour in co-firing is attributed mainly to the biomass type and its mixtures.

Soot loading in volatile flames plays an important role in generating radiation heat transfer, because of soot luminosity, as illustrated by the equation: $q_{\text{radiation}} = \epsilon 4\sigma T^4 \Delta t$, where $\epsilon = 1 - (1 + k_f v_L T / c_2)^{-4}$ [21, 22]. There have been studies on average soot volume fraction from different types of coal [15]. It is believed that biomass has less flame luminosity, where gas is the major phase in the flame. Atiku et al. [24] measured soot particles, which consist of elemental carbon (EC) and organic carbon (OC), between biomass and coal. During flaming combustion,

eight times as much elemental carbon was collected from burning coal. In the experiment, the apparent volatile flame would be discussed for comparative soot intensity between co-firing particles and pure solid particles.

An in-depth understanding of the thermal decomposition and combustion in co-firing would certainly be beneficial. Several studies [2, 7, 18–20, 24–28] have reviewed technical considerations and conducted biomass combustion with coal in extended experimental investigations. In thermogravimetric analysis (TGA), the devolatilisation of biomass–coal has been investigated extensively at low heating rates, with focus on the ignition characteristics [18], kinetic analysis [19] and primary reactions [25]. However, the experimental results of such studies have not been adequately explained in the context of practical combustion behaviour. This is because the actual pulverised solid-fuel particles in power plants are generally burned rapidly and are accompanied by complicated reactions and events. Gani et al. [26] investigated the co-combustion of coal with biomass in relation to ignition, NO_x emission and ash formation in a drop-tube furnace at 800°C. They plotted the temperature profile along the furnace during biomass, coal and co-combustion and showed that co-combustion yields the highest temperature of the three. Lu et al. [27] reported that adding biomass can prolong ignition in co-firing because of the large particles and high moisture content of the biomass. They also investigated flame characteristics such as brightness, temperature and ignition in industrial-scale coal combustion. However, there were uncertainties such as the loading of particles, their sizes and environmental conditions; these limited the extent to which they were able to explain the flame parameters. Therefore, for a comparative analysis to clarify the combustion behaviour of solid-fuel particles with clearly defined physical properties under well-controlled conditions, it is necessary to burn one particle at a time.

In previous studies [17, 29], we investigated the combustion of single coal and biomass particles in a lab-scale entrained-flow reactor. The experiments were carried out under rapid heating rates and a high gas temperature in order to describe the particle combustion process and investigate the flame

characteristics. Khatami, Levendis et al. [30–32] also observed the behaviour of single particles of individual coal and biomass in a drop-tube furnace. However, the observations of flame structure from these experiments are neither fully understood nor explained in relation to co-firing. Different physical and chemical events can occur in co-firing because of a mixture of solid fuel particles. Unfortunately, no experimental research has been reported on single particles of pulverised coal and biomass mixtures.

This paper reports an investigation of burning single particles, which were produced from a mixture of pulverised coal and biomass, using direct observation. Sequential combustion processes such as heat-up, devolatilisation and char combustion are described in detail. The effects of having single particles with different blending ratios, sizes and oxygen concentrations are also discussed. Given the statistical uncertainties related to single particles of homogenous fuel mixtures (20:80 and 50:50 mixtures of coal and wood), there was a clear need for particle definition from sub-experiments such as scanning electron microscopy (SEM), fuel properties and TGA, prior to the main experiment. The experimental results are compared to discuss their ignition and combustion time and flame parameters with pure wood and coal single particle burning behaviours through quantitative analysis.

6.3 Methodology

6.3.1 Experimental apparatus

The experimental combustion study of solid fuel particles was performed in a lab-scale entrained-flow reactor as shown in Fig. 6-1 with optical access to the burning single particles. The square-shaped quartz tube is 45 mm in length and width and 800 mm in height, and a honeycomb burner is located at the bottom for an upward flow of post-combustion gas. An electrical guard heater shields the quartz to minimise the temperature drop of the post-combustion gas except across the optical access section. Particles are injected at ambient temperature (298 K) via a water-cooled injector made of stainless steel double tubes: an outer tube for cooling water and an inner tube for the carrier gas and particles. This

injector is positioned above a porous flow straightener in the cross-flow configuration in which single particles are entrained from the horizontal cold carrier gas into the vertical hot gas stream. The injector is also placed 20 mm from the interior wall to minimise temperature and flow differences between the hot gas stream and the wall. To support the temperature environment, the temperature gradient in the optical access section is shown in Fig. 1 by a simulation image (Fluent 13.0) that includes a prediction of particle displacement during burning. The carrier-gas flow rate is 0.5 slpm in all experiments and the particles are injected at 25–30 particles/min by a micro-syringe injector.

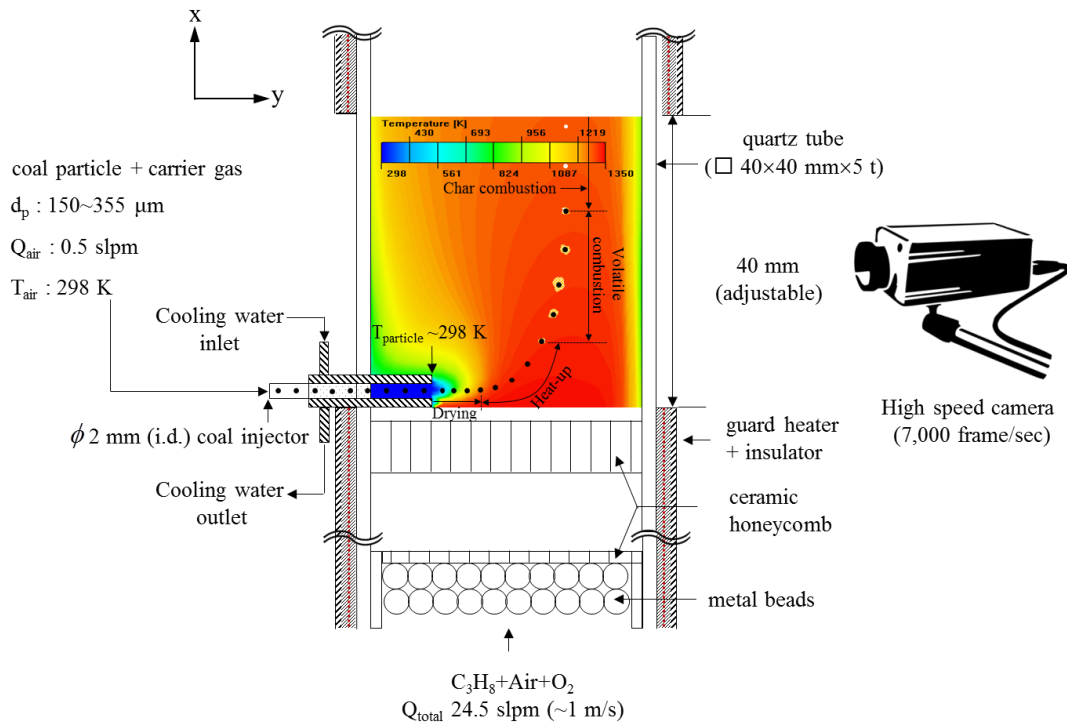


Figure 6-1 Schematic diagram of the lab-scale entrained-flow reactor for a few hundred micron-sized single solid particles. Also shown are the temperature fields of the hot gas stream (red) and cold carrier gas (blue), which explain the temperature gradient and the predicted sequential combustion processes of burning particle in the optical access section.

6.3.2 Environmental conditions

The variable-supply gas inputs of C_3H_8 , O_2 and air into the honeycomb are controlled for 10%–40% oxygen concentration, whereas the flow rate of these gases is maintained identically at 24.5 slpm for the experiments. The following main flue gases are produced: N_2 (38.2%–67.9%), O_2 (10.4%–40.1%), H_2O (12.4%) and CO_2 (9.3%).

The gas temperatures were measured on the basis of radiation loss of the probe of an R-type thermocouple at 21 locations in x- and y-axis: 0, 7, 14, 21 and 50 mm from the injector along the y-axis and 2, 19, 20, 30 and 39 mm along the x-axis. To obtain a mean value, temperature was averaged over 30 seconds. The variation in adiabatic flame temperatures from the post-combustion was approximately 140 K from 10 % to 40 % oxygen concentration. The mixing zone of the leftward-flowing cold carrier gas and the upward-flowing hot main gas stream is shown in Fig. 6-2. As particles pass through this zone, their temperature increases up to the devolatilisation or ignition temperature. The highly interacting flow zone at 0 mm along the y-axis is also sufficient to affect particle motion and combustion. Khatami et al. [31] discussed the change in combustion behaviour of a particle between quiescent gas conditions (no flow) and active gas flow. Therefore, the environment with the mixing zone and cross injection configuration enables an exclusive description of sequential combustion processes such as drying, heat-up and volatile combustion regimes that accompany particle motion.

The velocities of post-combustion gas and cold carrier gas in a cross-jet apparatus have been discussed by Lee et al. [33]. The particle velocities during the release of volatile matter vary according to these physical quantities, so all experiments were performed under identical vertical and horizontal velocities: ~1 m/s for the post-combustion gas and 2.5 m/s for the cold carrier gas.

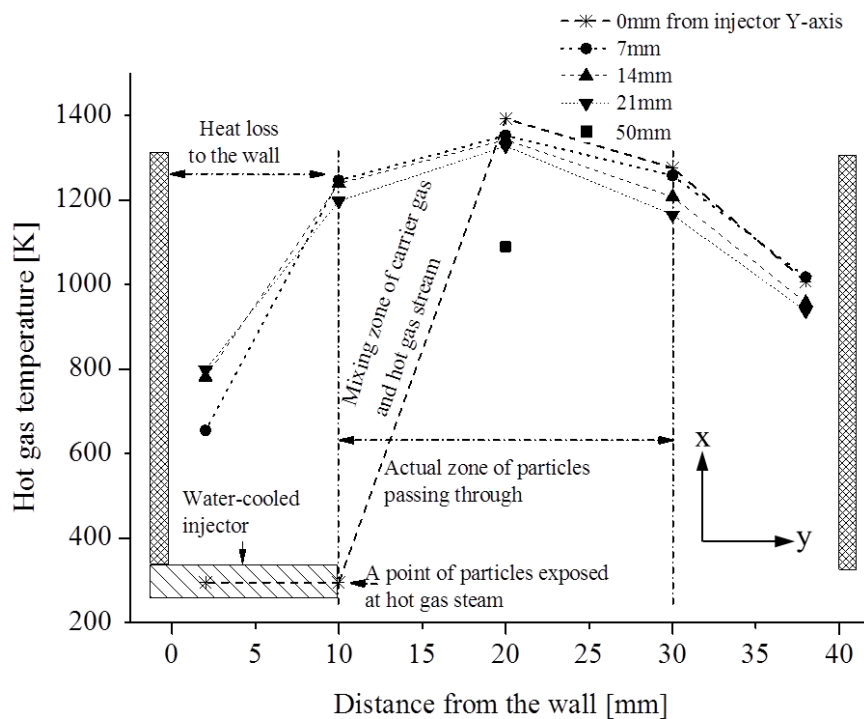


Figure 6-2 Experimental measurements of surrounding gas temperatures in the optical access section. This shows the actual zonal temperatures of particles passing through and the predicted initial particle temperature before heat-up.

6.3.3 Particle properties

The coal used in this study was a sub-bituminous type mined by Adaro Energy in Indonesia; the biomass was pine wood logged in Gyeongsang Province, South Korea. These materials were used for making a few-hundred-micron-sized single particles with a coal-to-wood fuel ratio of either 50:50 or 20:80. To produce these special particles, we first created pellets in a pellet factory through a sequence of pulverising and sieving the raw coal and wood (step 1), mixing the resulting powders (step 2) and compressing the mixture into pellets (step 3), as shown in Fig. 6-3. In step 1, particles are milled separately by species and sieved to under 100 μm ; anything larger can spoil a homogeneous mixture. Step 2 is an initial fuel mixing process in which the same volume (500 mL) of coal and wood or 200 mL and 800 mL, respectively, are added to a container before being shaken and then sieved for 20 min. The final step is the pelletizing process, which involves another

mixing process with the addition of 2 kg of water per 1 m² of particles. This water content plays an important role in the physical bonding of different solid fuel particles as an adhesive source; this particular level of water loading was determined through repeated tests of pellet stability/integrity.

Two types of pulverised co-firing particles were obtained from several separation methods that have been described in detail previously [17]. Some of the collected particles inevitably have irregular shapes with high aspect ratio because of the fibrous wood particle structure, but these can be separated using an inclined plane. The particles were separated into size groups (215–255 µm, 255–300 µm and 300–355 µm) using seven testing sieves with different mesh diameters: 215, 255, 300 and 355 µm. Repeated tests with uncoated paper on an inclined plane allowed the particles to be sorted by shape, e.g., flat, cylindrical, or spherical. In the experiment, only the spherical-like shape is used because the cross-jet injection is limited in burning irregular particle shapes. Flat-like and cylindrical-like particles lead to very random trajectories with non-uniform particle motion in the reactor.

Four particles were subjected to chemical composition analysis on an as-received basis, as shown in Table 6-1. These analysis data were obtained using the thermogravimetric analyser (TGA-701) at the Energy and Environment Research Centre of the Korea Advanced Institute of Science and Technology (KAIST). The changes in volatile matter and fixed carbon mass fraction for the 50:50 blended particle were approximately +15% and –16.6%, respectively, compared with coal particles, whereas for the 20:80 blended particle they are +26.7% and –27.7%, respectively. The blended particles have higher moisture content because of the water added during pelletising. However, the moisture differences between the four particles after the pulverising process are too small to noticeably affect their combustion behaviours.

The bulk densities of the four particles were measured using a simplified bulk density technique that involved filling a bottle with pulverised particles. This method allows the density of each packed-bed particle to be calculated based on $\rho_p = (m_{b,p} - m_{b,e}) / V_{b,w}$, where ρ_p is the particle density, $m_{b,p}$ is the mass of the bottle

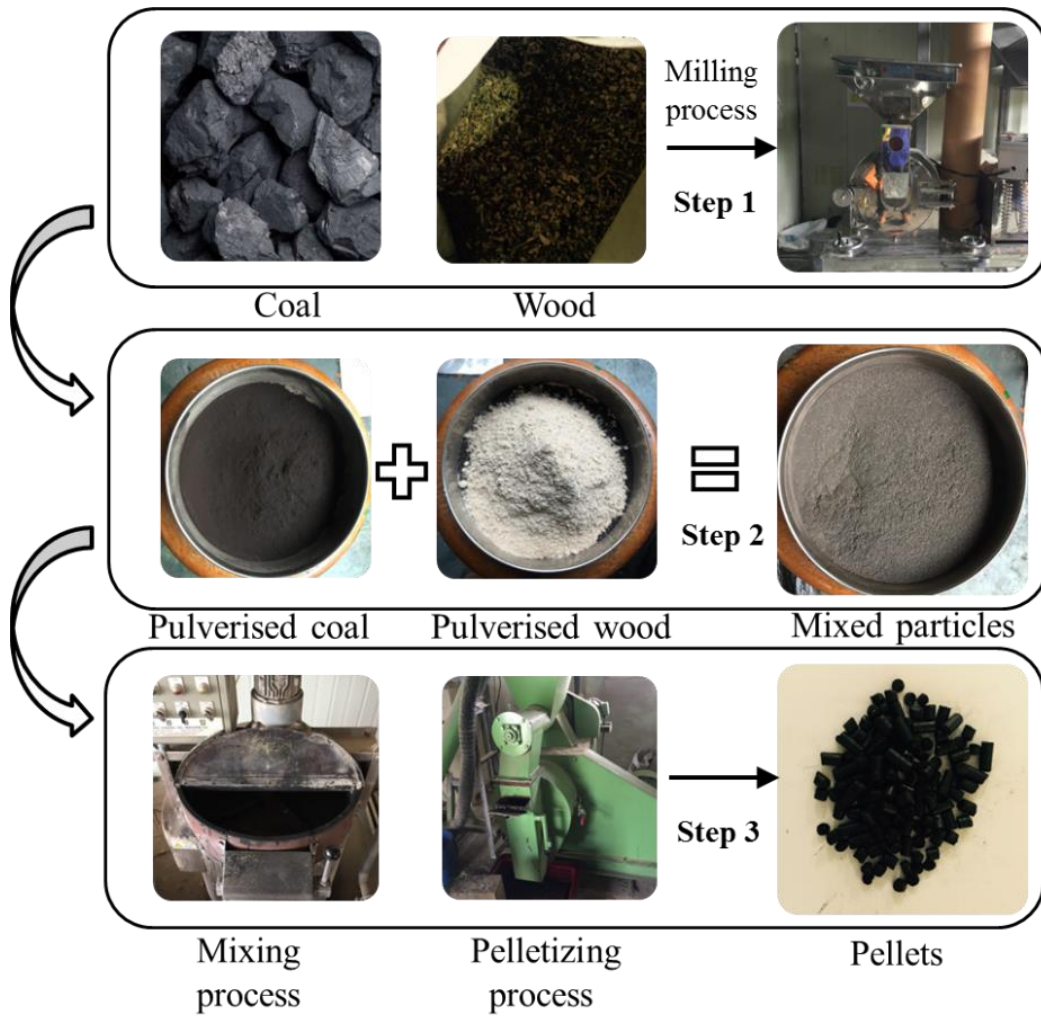
filled with particles, $m_{b,e}$ is the mass of the empty bottle and $V_{b,w}$ is the volume of the bottle determined from water filling. Using coal for the reference bulk density, the relative bulk densities of 50:50 coal/wood, 20:80 coal/wood and wood are 570 kg/m³, 430 kg/m³ and 340 kg/m³, respectively. From measuring these particle densities, the energy densities were calculated as 19.581 GJ/m³ for coal, 12.490 GJ/m³ for 50:50 coal/wood, 8.530 GJ/m³ for 20:80 coal/wood and 6.215 GJ/m³ for wood.

The difference in chemical composition between coal and wood particles is shown in Fig. 6-4 in a Van Krevelen diagram that indicates the relationship between the hydrogen/carbon (H/C) and oxygen/carbon (O/C) ratios. Coal particles have the lowest H/C (0.73) and O/C (0.28) ratios, whereas wood particles have the highest H/C (1.34) and O/C (0.89) ratios. The latter contain highly volatile matter that is high in oxygen and low in fixed carbon. The presence of high oxygen content plays a significant role in the reactivity of the pyrolysis, and the tar yield is proportional to the H/C ratio [34].

Table 6-1 Chemical compositions of four samples

Sample	Proximate analysis (wt. % ar) ¹				Ultimate analysis (wt. % da) ²					LHV ^{3&1} (MJ/kg)	Particle bulk density (kg/m ³)	Approx. energy density (GJ/m ³)
	V.M	F.C	Ash	M	C	H	O	N	S			
Coal	42.0	46.1	1.5	10.4	64.4	4.7	18.1	0.9	0.1	25.43	770	19.581
Coal-Wood (50:50 %)	57.0	29.5	1.3	13.0	58.6	6.2	28.1	0.6	0.1	20.82	570	12.457
Coal-Wood (20:80 %)	68.7	18.4	0.6	11.7	52.3	6.4	35.4	0.4	0.1	17.14	430	8.530
Wood	81.5	9.7	0.1	8.5	48.5	6.5	43.2	0.2	0.1	25.43	340	6.215

¹as received ²dry, ash free ³lower heating value



Step 1: Milling process of coal & wood

Step 2: Mixing process of pulverised coal & wood

Step 3: Pelletizing process of mixed particles

Figure 6-3 Preparation of pellets with 50:50 or 20:80 coal/wood mixtures. This figure shows how the pellets were made with fuel blending for co-firing, prior to being pulverised into a few hundred micron-sized particles.

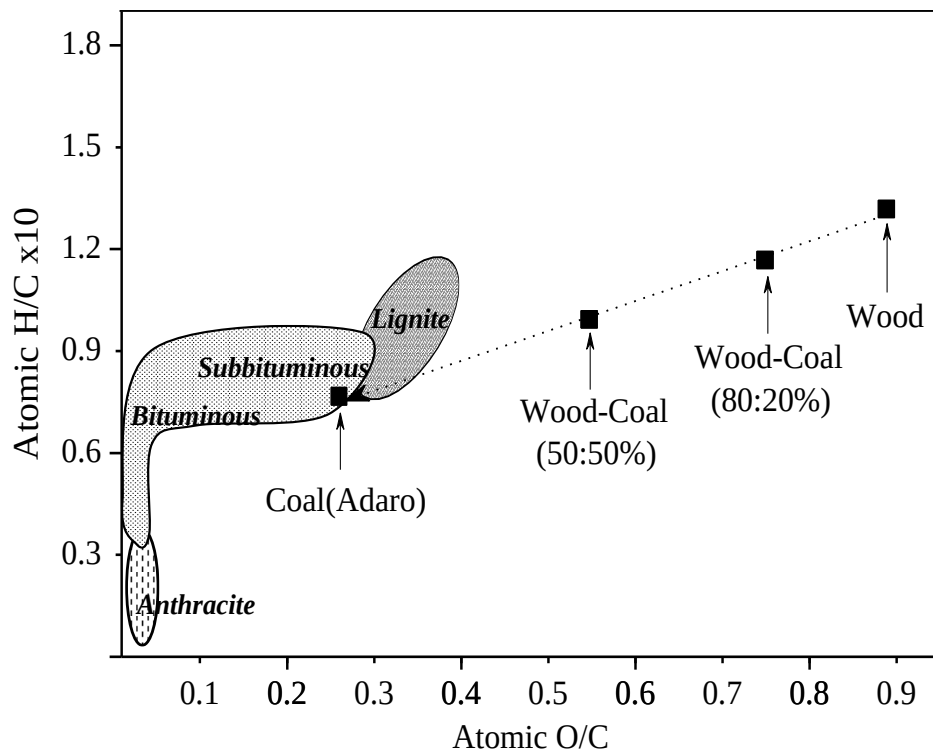


Figure 6-4 Van Krevelen diagram for the four different solid-fuel particles.

6.3.4 Direct observation of burning particles

A high-speed camera (Phantom V710) was used for direct observation of the burning particles. It can record at 7,000 frames per second and is fitted with a micro-lens (Nikon Micro-NIKKOR 105 mm f/2.8) as shown in Fig. 6-5. The magnification of the microscope lens was determined through repeated tests with 30-mm and 200-mm micro-lenses to record clear images of the soot flame in the maximum range of combustion regimes. The complementary metal oxide semiconductor (CMOS) image sensor in the camera was 25.6 mm × 16.0 mm and a resolution of 1,280 × 800 pixels was selected to provide a quantitative analysis of the burning particles. Lee et al. [29] introduced the calibration method with minimal observation errors wherein the pixel size was calibrated using circle and line-scale reticle shapes, fitted inside the field of view of the camera. Without a backlight, the flame intensity on a particle's surface was too bright to allow char particles to be captured simultaneously. The flame intensity varied according to the type of solid particle; for example, a coal particle burns with almost twice the

intensity of a biomass particle [17]. Therefore, determining the backlight intensity played an important role in comparing the flame structures of the four particles. A controllable-brightness, light-emitting diode (LED) backlight with uniform luminescence and high intensity was adapted identically at 5,600 K for all experiments and was located at 50 mm from the quartz window.

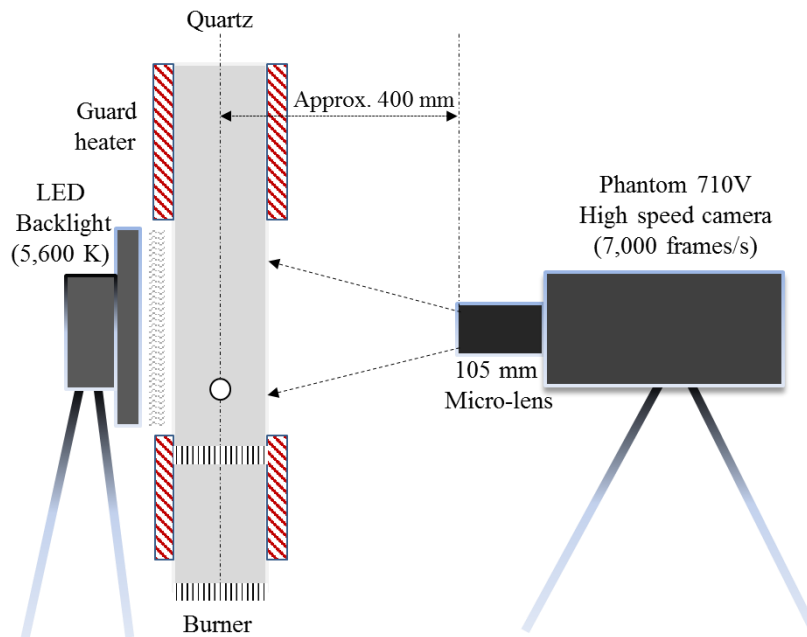


Figure 6-5 Configuration of high-speed camera and LED backlight. This enables the observation of particle ignition and volatile and char combustion on a few hundred micron-sized surfaces.

6.3.5 Physical formation of the four particles from SEM images

To explain the particle structures of the fuel mixtures, pulverised particles were examined using a NOVA 230 SEM. The resulting images shown in Fig. 6-6 were taken under the following conditions: accelerating voltage 10.0 kV, spot size 3.0, magnification 650–800 $\times$. The pure wood and coal particles were compared with the two co-firing particles. First, the raw wood particle had a remarkably fibrous structure with a high aspect ratio, and the external physical structure of the coal particle was an irregular blocky shape with angular transitions. These appreciably different shapes can play an important role in particle motion, temperature gradient and ignition [33, 35].

They may also exert a strong influence on differences in combustion behaviour, such as flame structure, release of volatile matter and combustion mode. The blended particles were physical mixtures of coal and wood fragments, and the small coal particles could appear inside or on the particles. The fuel blending ratios (50:50 or 20:80) were fairly constant according to the volume fractions of coal particles used in the pelletising process. However, it is difficult to guarantee a homogeneous mixture of pulverised particles. Repeated tests showed remarkable differences in the apparent flame structures of each particle group but similar combustion behaviour in identical particle groups. The standard deviation was less than 10% in all experiments. We analysed the thermal decomposition of the four particles to support whether the particle mixtures were homogeneous or not, as discussed later in section 6.3.6.

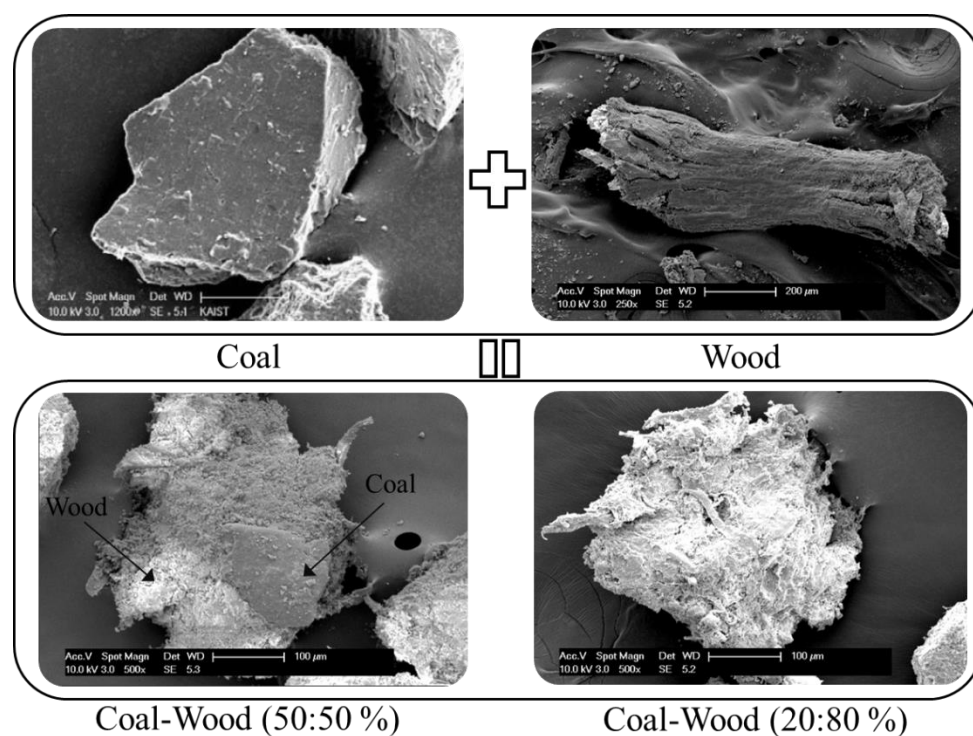


Figure 6-6 SEM images of coal, wood, 50:50 coal/wood and 20:80 coal/wood particles.

6.3.6 Characterisation of volatile flame on pulverised coal and raw wood particles

Flames comprise pyrolysis and luminous regions in which a gas phase and a solid phase (as submicron soot particles) are released by the chemical reactions. The luminous region is occupied in a flame and the high radiative energy is generated mostly from the soot particle fraction. The fixed carbon content plays an important role in the formation of an elongated soot cloud, because this content is equivalent to elemental carbon, which is one of the elements that produce soot particles [36]. Here we discuss the physical appearance of flames due to coal and wood particles prior to the investigation of single particles with different fuel mixtures. As shown in Fig. 6-7, the different size and shape in volatile flames for both sub-bituminous coal and wood particles at 1,340 K were observed under 10-40 % O₂. The diffusion flame of coal was found to be several times larger than the wood flame under all oxygen concentrations. Increasing the coal particle size under low O₂ concentration enhanced the elongated flame. This result is consistent with previous research [29, 37]. The attached flame is formed where the rate of volatile release is balanced by the rate of oxidation, but this fast oxidation rate decreases the radius of the volatile flame and enhances the detached flame depending on biomass species, particle size and particle heating rates. Especially, biomass particles have thin volatile flames under high oxygen concentration because of their turbulent dispersion of gas-phase, which is the major species in a flame. Coal particles under low O₂ concentration have an elongated flame with a soot tail. This tail is formed by the effect of thermophoresis (force and velocity) between the solid phase and surrounding gas and low availability of oxygen [38–40]. The differences in this soot tail are less pronounced at higher oxygen concentration [41].

The flame characteristics of pure coal and wood particles offer a meaningful comparison for the flame parameters of the two co-firing particles with different fuel-blending ratios. In the experimental results, the intensities of volatile flames for the four particles were analysed by image processing, which converts a flame image into a grayscale image. In the process, each pixel in the image has

different values in a range of 0 to 255, and numerical background values, which were more or less than 65, are extracted from the images. After that, the intensity of the flame was divided by the maximum value of grayscale (255). The intensity-weighted values in the flame boundaries were fluctuating, which means that it might be considered a flame threshold. To minimise their fluctuation and verify the minimised variation of the flame size, we have carried out the sensitivity analysis with varying back-lighting intensity until the rate of change in the flame size was minimised.

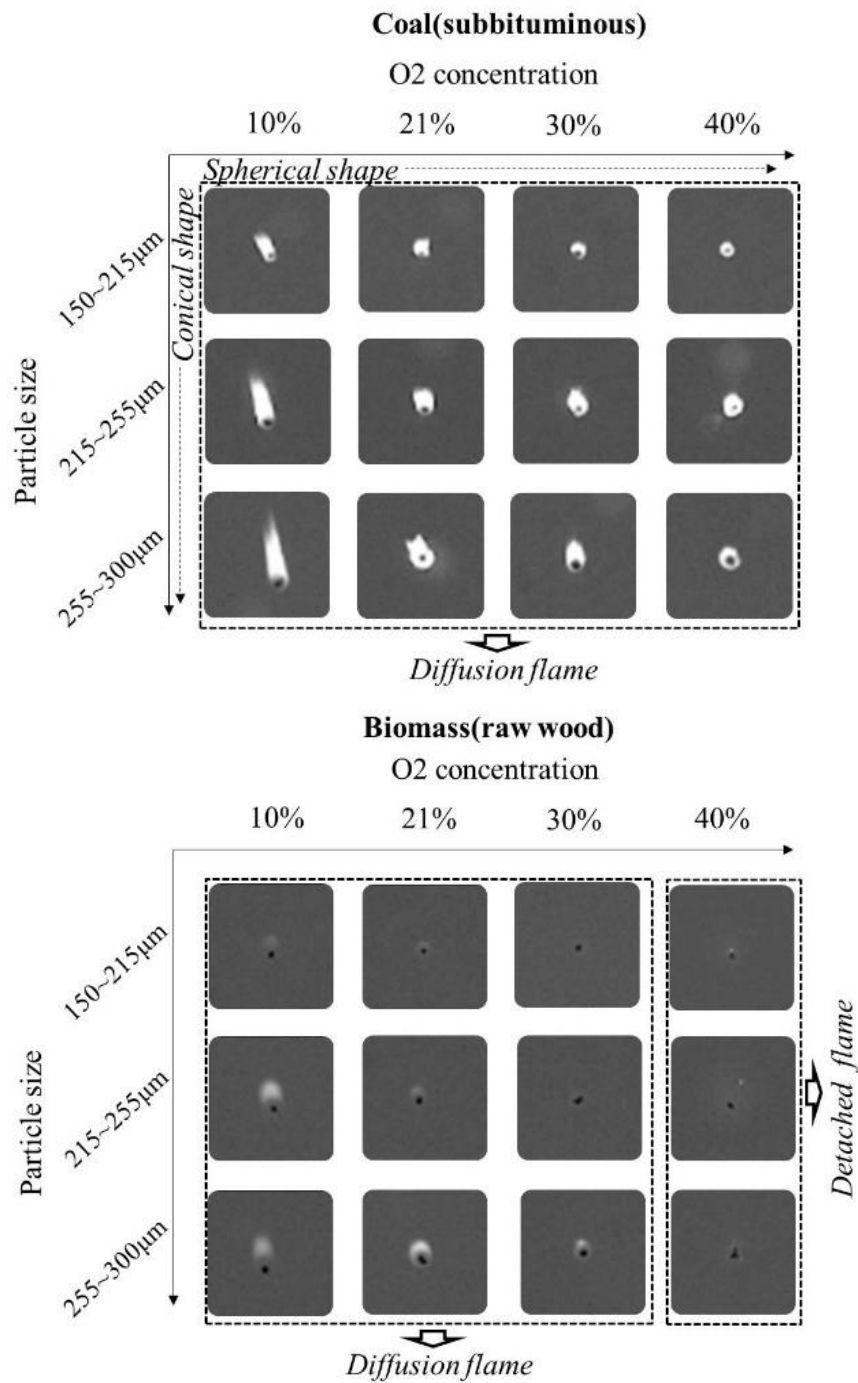


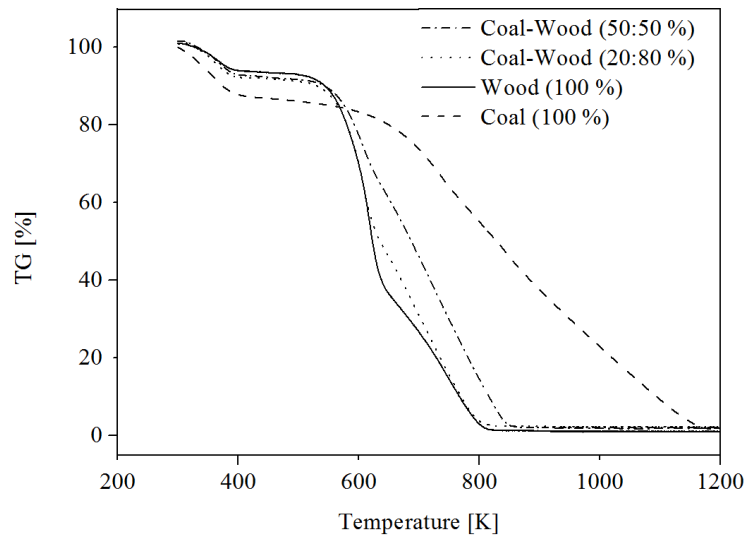
Figure 6-7 Typical flame structures of pure coal and wood in relation to shape and size under 10–40% O₂ and at 1,340 K. This illustrates the physical changes due to particle size and O₂ concentration, and explains the corresponding volatile combustion modes of attached, diffusion and detached flames.

6.4 Results and discussion

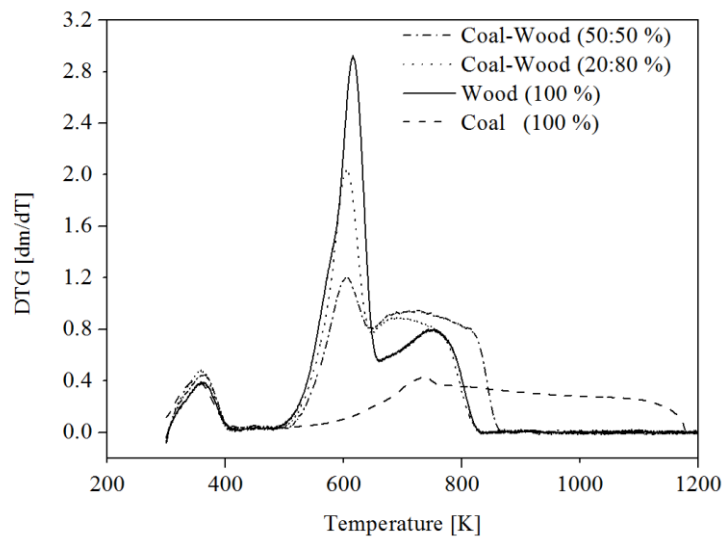
6.4.1 Sequential combustion processes under slow heating and thermal decomposition for different fuel-blending ratios

It is generally accepted that the impact of co-firing sub-bituminous coal (Adaro) with biomass (pine wood) contributes to rapid devolatilisation, fast ignition and low emission of carbon dioxide because of the chemical and physical characteristics of wood. Thermogravimetric analysis, TG/DTA 92-18, was used to investigate the characteristics of co-firing particles with different fuel blending ratios compared to raw wood particles. Each sample was prepared at 8 ± 0.5 mg from pulverised particles in the range of 150–215 μm , and the samples were heated at 20 K/min to 1,273 K under air conditions. The results explained the thermal decomposition and how the mass of these samples reduces differently as a function of temperature over time. The main experiment was carried out under rapid heating, but the TGA here was done under slow heating that is not representative of practical conditions in an industrial furnace. In spite of this limitation, the different thermal decompositions of 20:80 and 50:50 coal/wood and wood particles can be discussed in relation to the impact of co-firing combustion and by comparing the combustion behaviour with that under rapid heating rate. Thermogravimetric (TG) plots and derivative thermogravimetric (DTG) curves, which are obtained from the derivatives of the TG profiles, are shown in Fig. 6-8. The results show unequal TG and DTG curves, with the first and second peaks of mass reduction followed by fluctuations between 50:50 coal/wood, 20:80 coal/wood and raw wood. In relation to the combustion processes, the first peak is due to the drying process that occurs at 300–400 K, after which the particle is heated up with negligible mass reduction. Sequentially, the volatile release starts at approximately 520 K and the peak reaches almost 610 K because pure wood particles have three components: *lignin*, *cellulose* and *hemicellulose*. A fluctuation then occurs because of lignin decomposition. Generally, hemicellulose decomposes in a range of 493–588 K, cellulose does so at 588–673 K and lignin does so over a wide range of 433–1173 K [42]. Finally, the particle mass decreases at constant mass loss rate, which is associated with char combustion.

The second peak and degree of fluctuation magnitude were obviously different between the three particles, which is attributed to either the volume of wood particles or the volatile mass fraction in a particle. Coal particles have a moderate peak and the char combustion regimes are extended because of their high carbon content. Consequently, under slow heating, the highest peak for devolatilisation occurs for the raw wood particle, and the co-firing particles also have higher peaks at relatively low temperatures. However, the flame ignition and combustion behaviours under this slow heating rate does not correspond with those of a single burning particle under rapid heating rate. This aspect is discussed in section 6.4.2.



(a)



(b)

Figure 6-8 Thermal decompositions of 50:50 coal/wood, 20:80 coal/wood and pure wood obtained from TGA at a heating rate of 20 K/min: (a) TG, (b) DTG. These graphs explain the distinction between mass reduction associated with homogeneous and heterogeneous combustion between the two prepared co-firing particles, coal particles and pulverised wood particles.

6.4.2 Sequential combustion processes under rapid heating and development of volatile flames for different blending ratios

The sequential combustion processes of a pulverised solid-fuel particle are explained in the superimposed images in Fig. 6-9. Single particles of coal, 50:50 coal/wood, 20:80 coal/wood and wood in size ranges of 215–255 μm and 300–355 μm were burned under 10% oxygen concentration and at 1,340 K. Particles are heated rapidly by the drying process after particle injection at 298 K. The release of volatiles then starts within a few milliseconds, followed by volatile combustion. Char combustion starts after extinction of the volatile flame, but this regime is not shown because of limited optical access. Under rapid heating rates, volatile combustion presents changes in the flame size, following volatile ignition. Comparative flame size and intensity with sequential combustion processes can be explained as a function of time. In contrast, TGA, which is operated under slow heating rates, shows the fluctuated profile with a peak for the regime of volatile combustion, providing a range of particle temperature for volatile and char combustion and a different rate of devolatilisation between the four particles. The similar tendency of volatile combustion was shown in the results, but there are more complex physical and chemical events in a flame around a particle under rapid heating. Generally, high soot formation in a flame is associated with tar reacting to become submicron-sized soot particles at high temperatures. This affects the volatile combustion associated with highly luminous flames [43, 44]. From this result, the four burning particles differed in apparent homogeneous ignition and apparent flame structures. The pure coal particle (215–255 μm) ignited after 30 ms, whereas the wood particle ignited after 48 ms. The single particles with fuel mixtures ignite in almost the same way as does the coal particle, which is attributed to the coal ignition characteristics. To see this in more detail, the results for ignition and combustion times are discussed in Fig. 12–15, where it can be seen that increasing the coal blending ratio has an impact on large elongated flames with their high intensity.

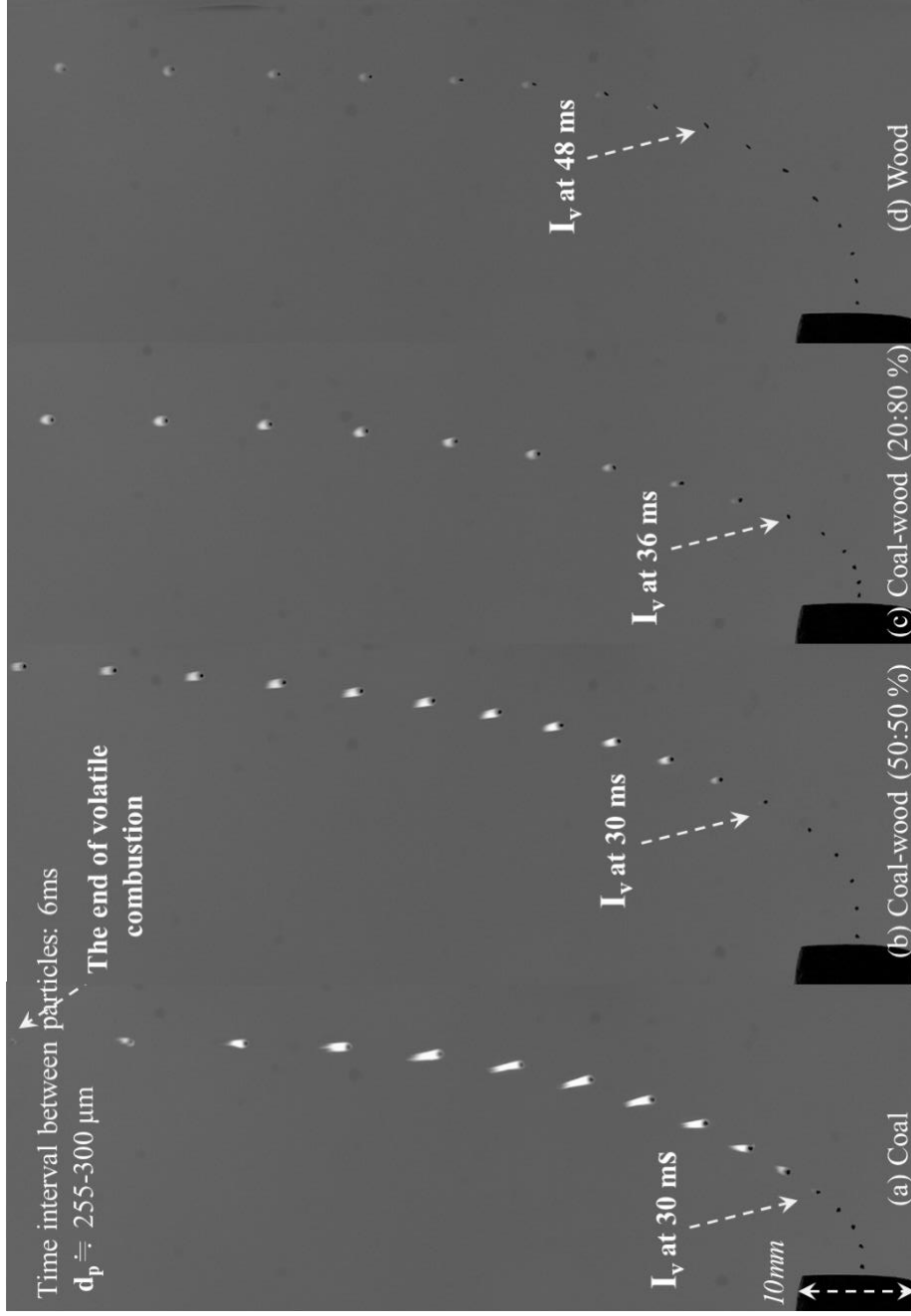


Figure 6-9 Sequential combustion-process images of four solid particles ($d_{255-300 \mu m}$, $T_g = 1340 \text{ K}$ and $10\% \text{ O}_2$ concentration). After leaving the tip of the injector, each single particle is marked at intervals of 6 ms as it forms an apparent volatile flame from initial ignition.

6.4.3 Ignition delay, volatile combustion and flame characteristics

Figure 6-10 shows the average heat-up (or ignition) and volatile combustion durations for the four particles from 20 of each particle under different oxygen concentrations at 1,340 K. The standard deviation of each test is less than 10% of the mean values from the quantitative analysis. The heat-up time is measured from when the particle is injected until the apparent volatile ignition. This ignition might be different from homologous ignition, because a light gas phase emits a very weak light. Therefore, this experiment presents only the apparent volatile ignition with soot luminosity. The results show that, under 10% oxygen, the coal particle and the two co-firing particles have shorter ignition delays (26–30 ms) than that of the wood particle (40 ms).

Under all oxygen levels, the differences in apparent volatile ignition between particles (except for the pure wood particles) are not significant because of early ignition, based on apparent volatile ignition of the coal particle. The volatile combustion time of the co-firing particles is almost the same as that of wood. In other words, the different ignition and volatile combustion times of the co-firing particles can be attributed to both coal and wood, respectively.

The apparent flame characteristics of the four particles at 215–255 μm are explained under 10, 21 and 30% O_2 as shown in Fig. 6-11. Overall, the size of the volatile flames decreases with the shorter combustion time as the oxygen concentration increases. This result shows that the four particles have distinguishable flame structures in terms of size and intensity under all oxygen levels. Their flame size and intensity are explained by a quantitative analysis in section 6.3.4.

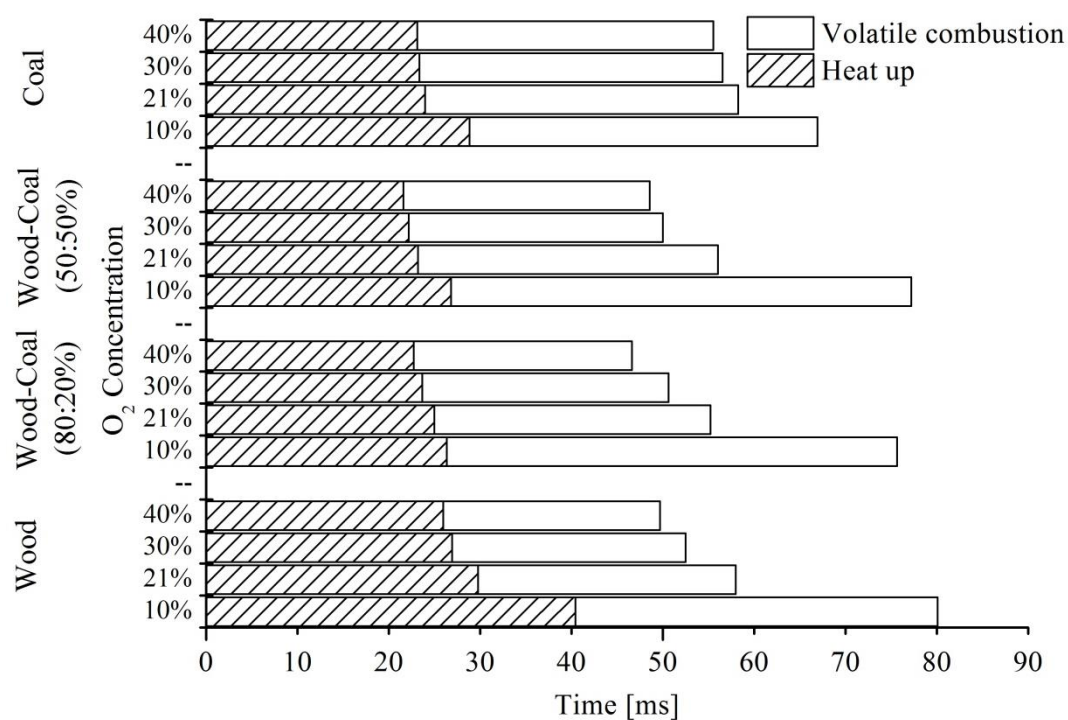


Figure 6-10 Measurement of average duration of heat-up and volatile combustion, obtained from four particles (255–300 μm) under different oxygen concentrations at 1,340 K. This figure shows different burning characteristics between the wood and coal particles and the two mixed particles.

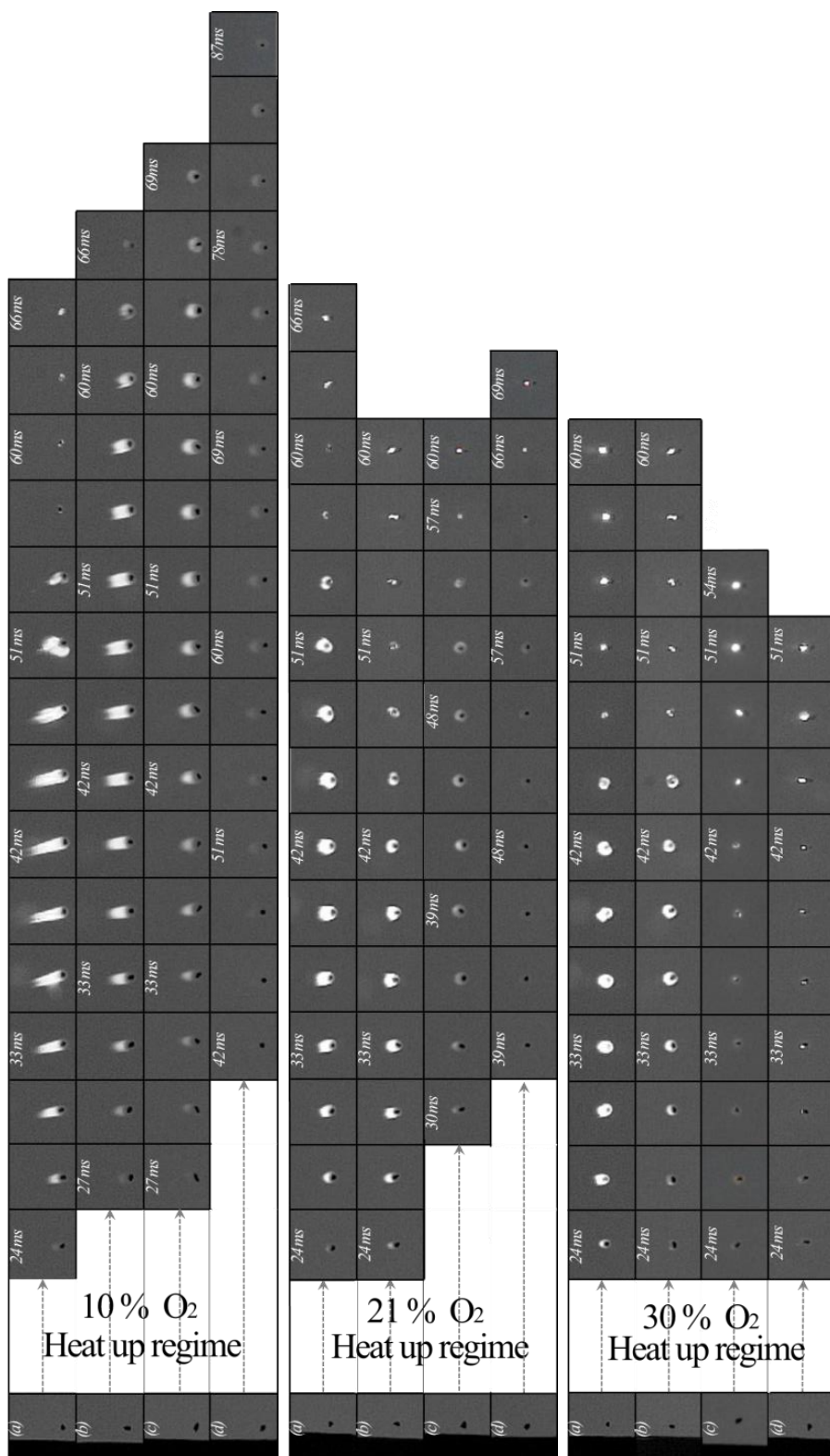


Figure 6-11 Burning particles at 215–255 μm under 10%–30% O_2 concentrations at 1,340 K: (a) coal, (b) 20:80 coal/wood, (c) 50:50 coal/wood and (d) wood. The particles are captured over time intervals of 4 ms. The coal particle has the largest and brightest flame of the four.

6.4.4 Effect of particle types over time

The results shown in Fig. 6-12 suggest that increasing the coal blending ratio under 10 and 21% oxygen concentrations has a significant effect on the enveloped flame of each particle in the time domain. The size and intensity of the flames around particles (215-255 μm) were measured from volatile ignition to flame extinction. However, we cannot detect the whole volatile combustion in particles (300-350 μm) as explained before. Particle combustion events are associated with a high peak when the maximum volume of volatiles and soot particles are in the flame. This can also be seen in the nearly symmetrical profile during combustion [17]. From this result, the profiles of the two particles with fuel mixtures are seen to lie between the coal and wood profiles. The peak flame size does not correspond entirely with the peak flame intensity, although they have similar tendencies over the same period. The peak of volatile flame area occurs marginally before the intensity peak.

Figure 6-13 shows the variation in maximum flame area and intensity under 21% O_2 at 1,340 K with the wood-coal blending ratio. The imagined line between wood and coal particles is drawn in order to compare their measured magnitudes. To obtain the results, the flame parameters were averaged over 20 particles for each test. The flame area of the 50:50 coal/wood particle differed from the prediction of the imagined line by 0.03 mm^2 . Both the 20:80 and 50:50 coal/wood particles have a higher intensity compared with the trend in flame area. Also, there was little difference in intensity between the 50:50 coal/wood and pure coal particles under 21% O_2 .

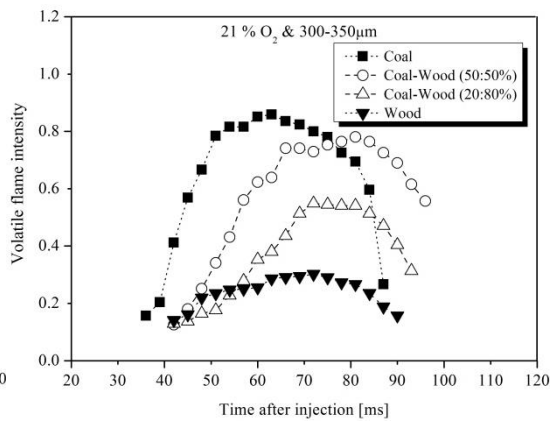
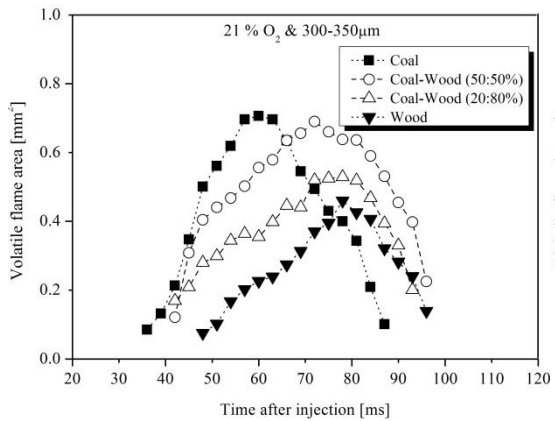
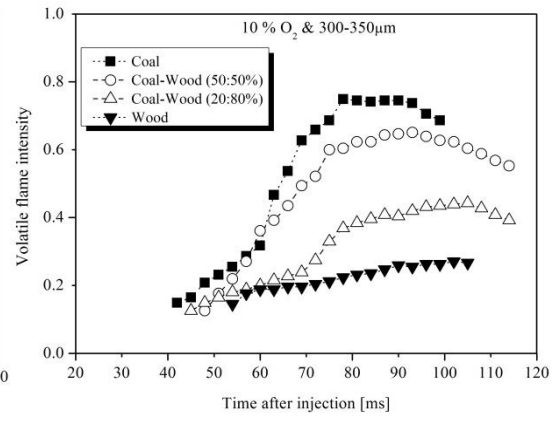
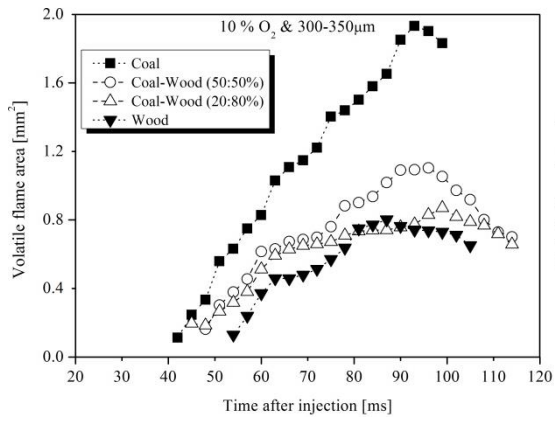
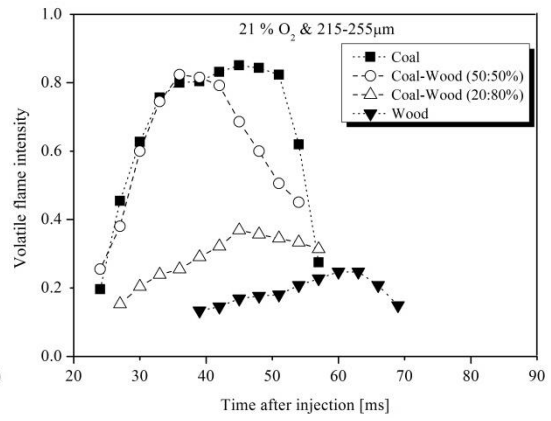
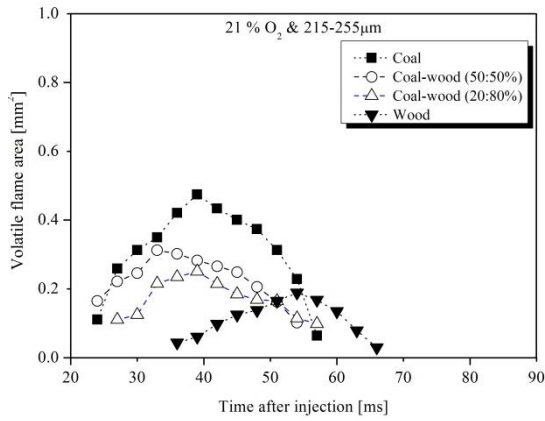
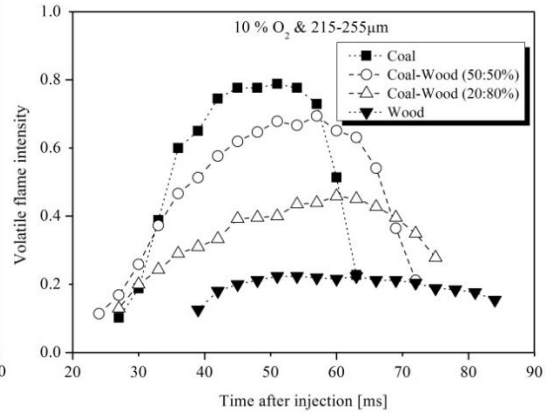
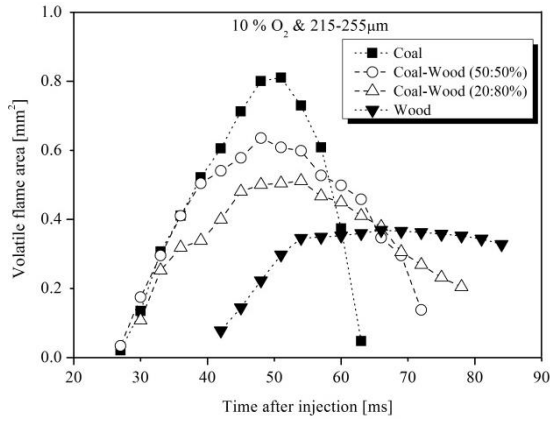


Figure 6-12 Effect of particle type on flame development under 10 and 21% O₂ 1,340 K. The figures show a peak in the flame parameters as a function of time, and distinguishable flame size and intensity between particles are measured at 215–255 μm and 300–300 μm .

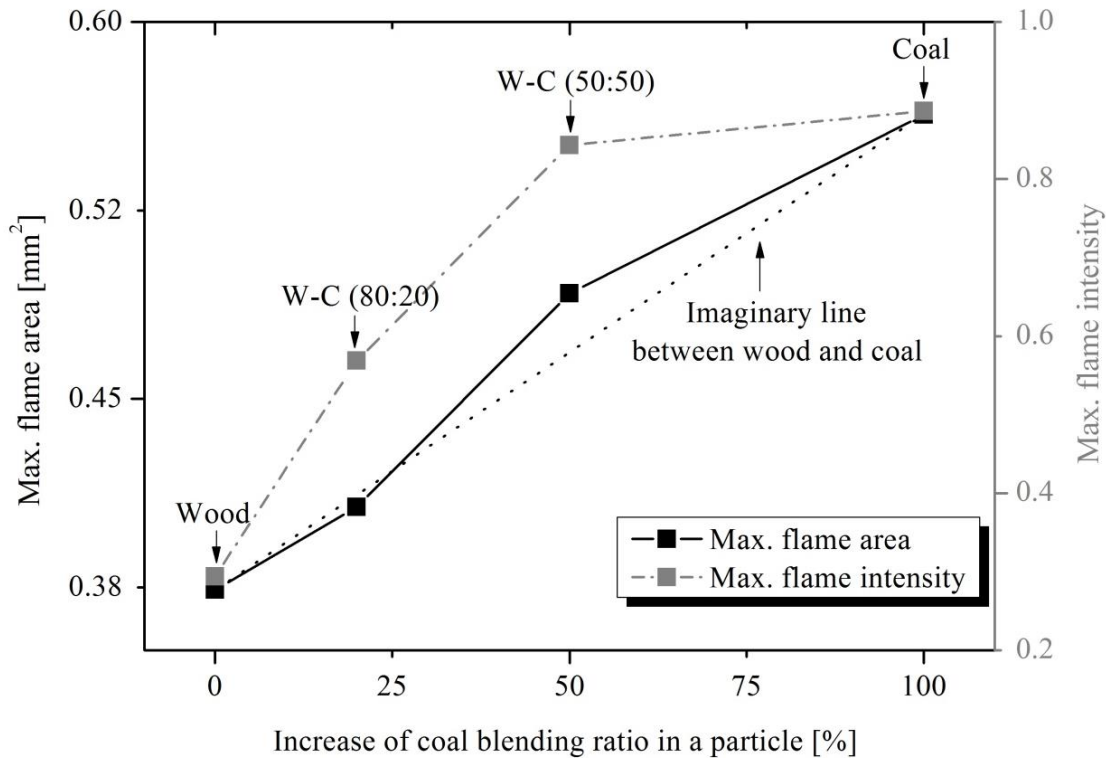


Figure 6-13 Overall profiles of average flame parameters with particle coal-blending ratio (255–300 μm) under 21% O₂ at 1,340 K. This figure shows how flame intensity and area increase with reference to an imagined line between wood and coal.

6.4.5 Effect of oxygen concentration with particle type as a function of time

The four different types of particle in the particle size group of 215–255 μm were burned under 10%–40% O₂. Fig. 6-14 shows the temporal flame profiles for the effect of oxygen concentration. The flame area decreased with shorter volatile combustion time as the oxygen concentration was increased. A dramatic decrease of this flame parameter for particles at 255–300 μm was observed

between 10 and 21 % oxygen, as shown in Fig. 15(a). Particles burning under low oxygen concentration have an elongated flame. The flame areas of coal, 50:50 coal/wood, 20:80 coal/wood and wood under 21%–30% O₂ decreased by approximately 44, 40, 59 and 79%, respectively. As for the combustion mode, particles containing 80% or more of wood have imperceptible volatile flames with low luminosity at high oxygen concentrations, and simultaneous homogeneous and heterogeneous combustion occurs on the surface. Hence, coal blending plays an important role in stable flame structures and sequential combustion processes even under high oxygen concentrations.

Overall, the flame intensity of the four particles at 255–300 µm present the effect of oxygen concentration as shown in Fig. 15(b). The flame intensities on all the particles were comparatively high under 21% oxygen. However, the peak flame intensity of the coal particles was reached at 30% oxygen concentration, whereas the pure wood particle and particles with wood mixtures have their highest flame intensities at 21% O₂. This phenomenon is likely attributable to the volume fraction of soot in the flame. The normalised flame intensities of particles with high wood mixtures decreased dramatically between 21 % and 30 % O₂. Khatami et al. [15] reported that the highest peak soot volume fraction of bituminous coal occurred in 40 % O. The different profiles between two results are related to the particle size, environmental conditions and reaction rate.

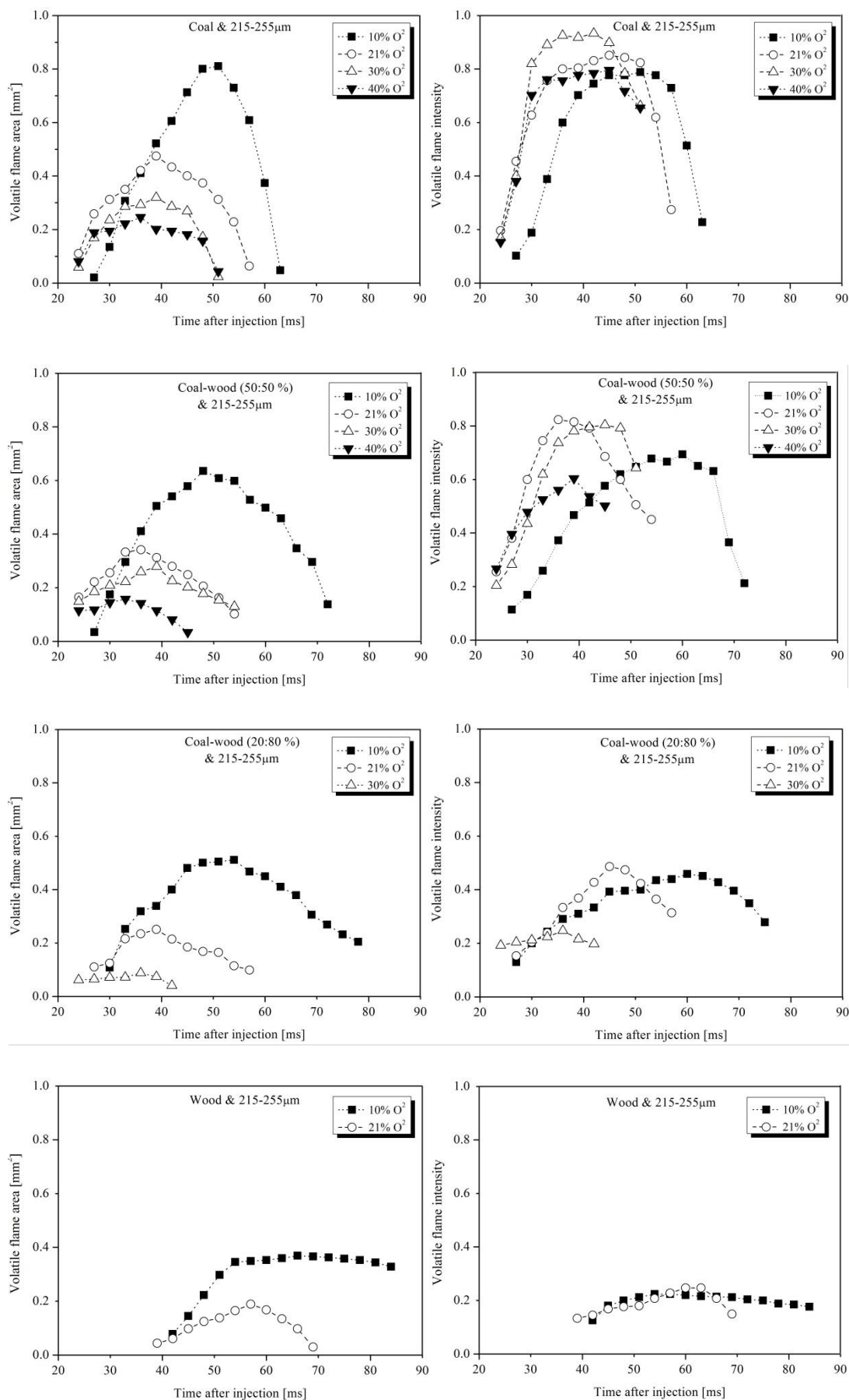
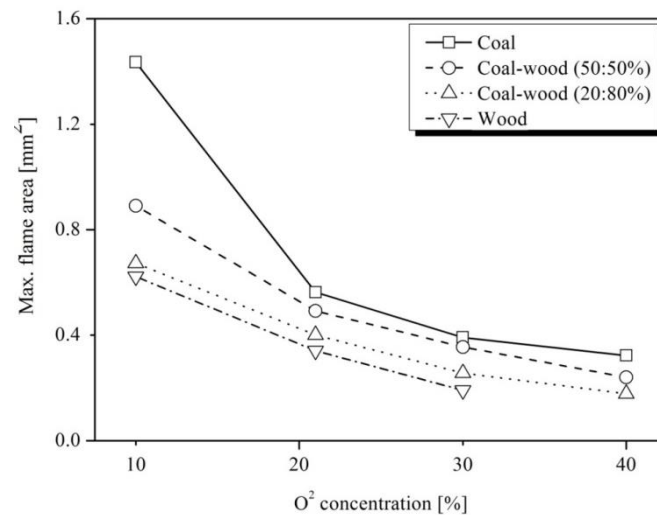
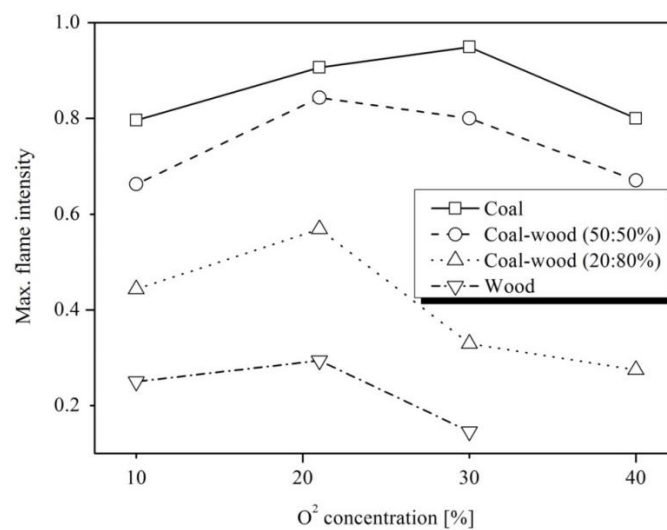


Figure 6-14 Effect of oxygen concentration (10%–40%) on the flame characteristics of the four particles (215–255 μm) at 1,340 K. The graphs illustrate the variation of volatile flame area and intensity with surrounding O_2 .



(a)



(b)

Figure 6-15 Overall profiles of average flame area and intensity of the four particles (255–300 μm) with O_2 concentration. These graphs show a wide variation in flame area for the four particles under 10% O_2 ; wood and blended particles (not coal particles) have a peak flame intensity at 21% O_2 .

6.4.6 Effect of particle size

Figure 6-16 shows superimposed visible flame appearances for particle sizes in the ranges of 215–255 μm and 300–350 μm . All the experiments were performed under 10% oxygen concentration at 1,340 K. After injection, the burning particles were captured at 4-ms time intervals. The increase of approximately 100 μm in the size of the four particle types clearly affected the ignition delay. The trajectories of the 300–350- μm particles dropped slightly after injection and then went upwards until burnout because of the relatively high particle mass. In the experiment, the particle size group of 355–425 μm dropped slightly after injection and then lifted toward the top until burnout. Larger particle sizes fall to the bottom to be incompletely burned without volatile combustion, which was explained by Mock et al. [17].

Figure 6-17 shows the average flame parameters for 20 particles of 215–255 μm and 300–350 μm under 21% oxygen concentration. This shows that the increase in flame size for all particles was very steady between the two particle-size groups. However, the increased flame intensity is a little different between coal particles and particles with a high coal-blending ratio. The coal and 50:50 coal/wood particles also show very similar flame intensity variations with particle size, which may be attributed to a sufficiently high soot particle volume fraction in the particles.

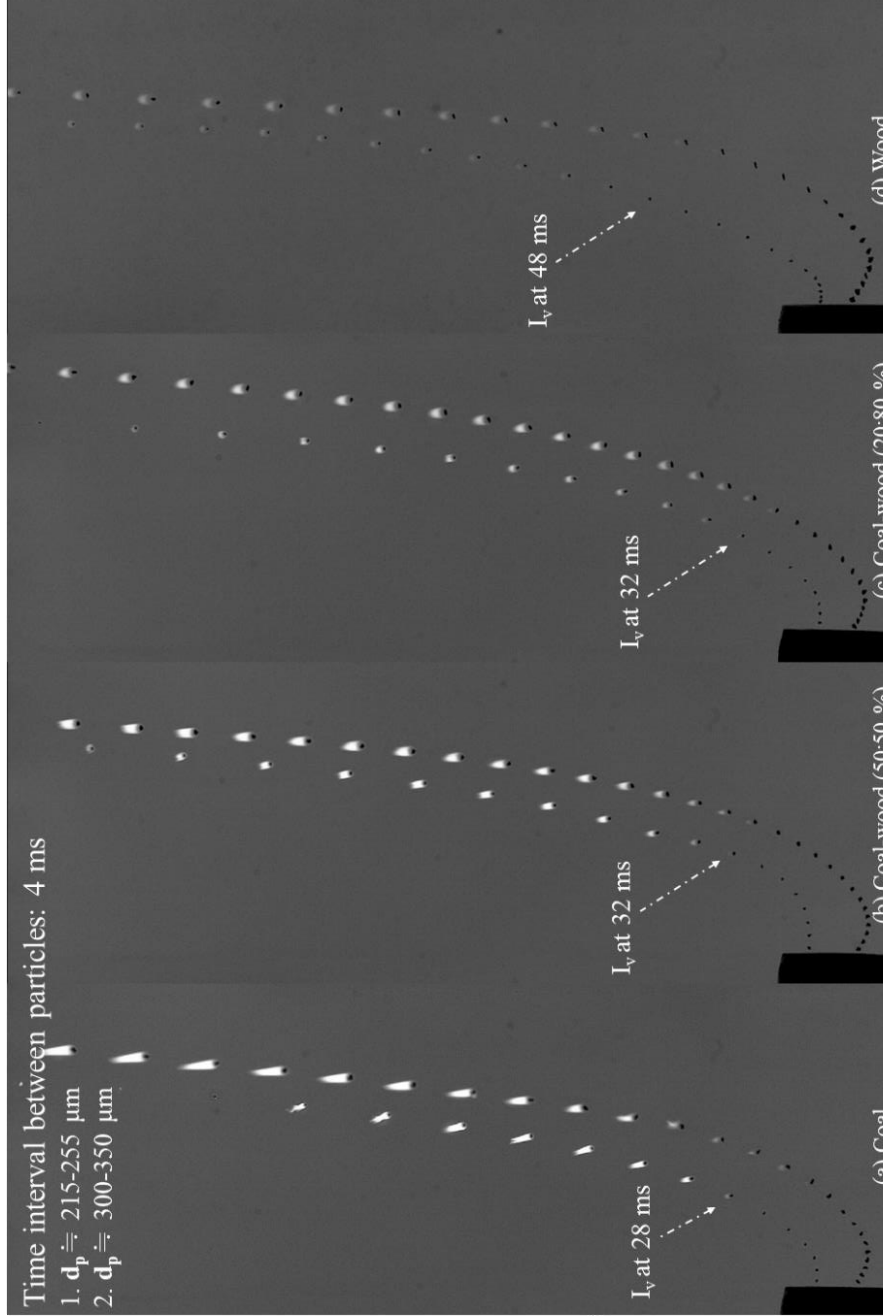


Figure 6-16 Superposition of four different particles of 215–255 μm and 300–350 μm at time intervals of 4 ms entrained in hot gas streams of 1,340 K under 10% oxygen concentration. The tendencies of particles of different sizes are similar between the two particle-size groups. However, the flames on the 300–350 μm particles grow because of the longer ignition delay.

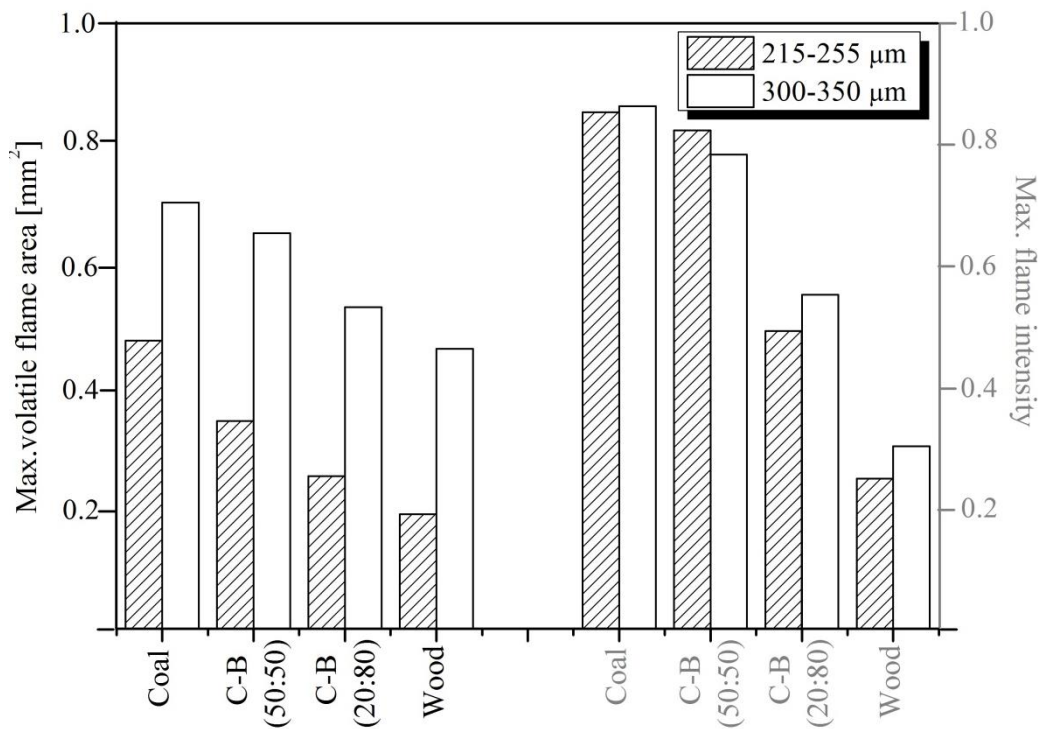
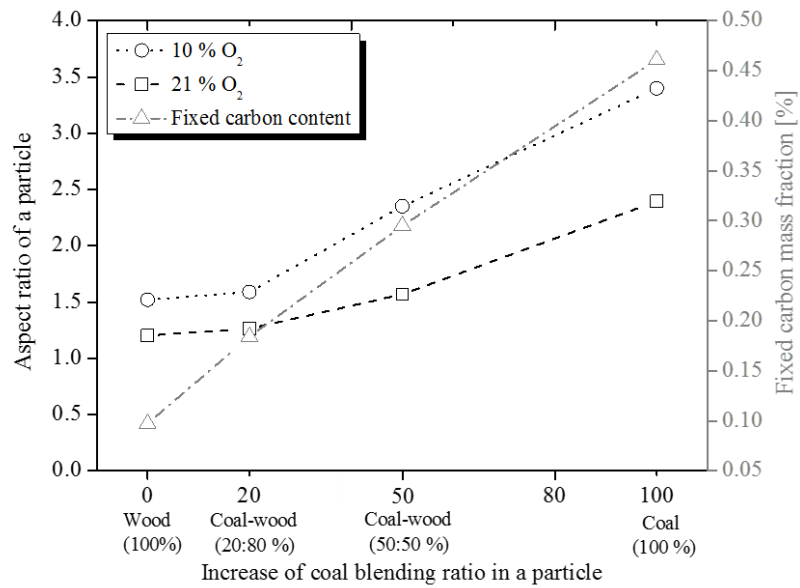
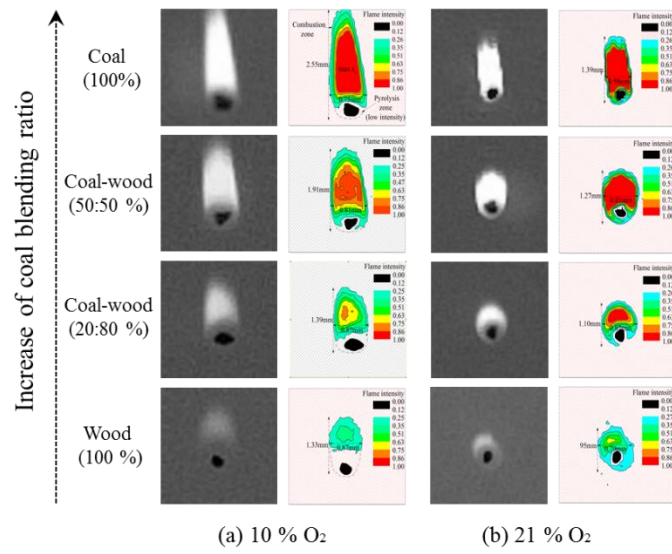


Figure 6-17 Average flame area and intensity of four different particles with particle size (215–255 μm and 300–350 μm) under 21% O_2 concentration. The graphs show a regular decreasing trend in volatile flame area.

6.4.7 Flame aspect ratio of co-firing particles

The shapes of the flames on the four particle surfaces under 10 and 21% oxygen concentrations can be represented in terms of the flame aspect ratio. Figures 6-18(a) and (b) illustrate the measurement of flame height, length and intensity after image post-processing, which may be an effective way to define the characteristics of flame shape. One of the results is that a relatively large pyrolysis zone for fuel vapourisation and reactions was observed clearly under low oxygen concentration, showing a transparent coloured boundary layer. The flame aspect ratio increases rapidly for burning particles with a 50% coal blending ratio. However, wood and 20:80 coal/wood particle have aspect ratios of approximately 1.2, which suggests a more spherical flame. An elongated flame can be attributed to soot phase in a particle. Coal particles, which contain more fixed carbon and less volatile matter, have the highest visible flame aspect ratio of 3.4 under the lowest oxygen concentration.



(c) Flame aspect ratio

Figure 6-18 Flame structure in terms of aspect ratio obtained from volatile flames of four particles under 10 and 21% O₂ concentrations by image post-processing.

6.5 Conclusions

In the study, pulverised single solid-fuel particles with different fuel mixtures were burned in a lab-scale entrained-flow reactor. These were compared with the burning of pure coal and wood particles under identical environmental conditions. The four particles differed in relation to their chemical and physical characteristics, which in turn affected the flame characteristics. The main objectives were to assess the burning behaviours of mixed single particle for co-firing, focusing on ignition, flame area and intensity, and combustion time from direct observation. Quantitative analysis of these combustion parameters was presented along with a description of the sequential combustion process of the particles under various oxygen concentrations and for different particle sizes.

The burning of particles under both slow and rapid heating was also discussed in relation to the similarities and differences of their combustion behaviours. The significant conclusions of this study are as follows:

1. Single particles were observed in sequential combustion processes such as heat-up, ignition and volatile and char combustion. Simultaneous volatile and char combustion has been observed in a particle with high wood mixture under enhanced oxygen concentrations.
2. The conical flame shape on co-firing particles was affected by an increase in the coal mixture ratio. This was because the high fixed carbon content and H/C ratio of coal generate a large soot flame with a high aspect ratio and flame intensity.
3. The pulverised particles are burned out in a few hundred milliseconds under rapid heating; coal particles ignited sooner than the apparent ignition of wood particles. As a result, the ignition of pulverised co-firing particles is attributed to the coal ignition characteristics. However, the volatile combustion time plays an important role in the high volatile matter content of the wood mixtures.
4. Of relevance to co-firing combustion is the fact that particles with coal/wood mixtures improve the radiative heat energy from the flame

parameters compared with wood flames: +9% and +32% for the size and 93% and 187% for the intensity of 20:80 coal/wood and 50:50 coal/wood, respectively, under 21% O₂. This may affect the stable diffusion flame, the fast homogeneous ignition and the flame stability to the boiler efficiency.

6.6 Acknowledgments

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CHAPTER 7

CONCLUSIONS AND FUTURE WORK

7. CONCLUSIONS AND FUTURE WORK

7.1 Conclusions

This experimental study used a laboratory-scale entrained flow reactor in the cross-jet configuration and with a rapid heating rate of 10^5 K/s. We first focused on combustion of pulverised biomass particles, and the results provide a description of a burning particle as a function of time and particle displacement. To extend our understanding of burning-biomass processes, combustion, ignition and combustion times in subbituminous coal were analysed by direct observation. To assess other burning characteristics, the effect of particle size, gas temperature and oxygen concentration were considered as experimental parameters. Direct observation was also implemented to understand combustion and the physical structure of volatile flames from three particle groups: biomass and waste material, torrefied sewage sludge and special solid fuels for co-firing.

Compared with coal particles, all biomass particles yielded less sooty flames with smaller flame sizes, which we attribute to more volatile content, less fixed carbon and lower particle density. Torrefied wood, coffee waste and sewage sludge particles had different combustion characteristics. Among these particles, only torrefied wood particles form a stable flame for particle sizes in the range 150–215 μm , and 150–215 and 215–255 μm sewage sludge particles form a highly transparent volatile flame with a longer ignition delay. These characteristics are determined primarily by particle composition and the accompanying physical and chemical properties.

The results of the experiments suggest a maximum particle size for complete burnout: Particles in the size range of 150–255 μm burn completely in the direction of the hot gas stream, but particles in the size range of 355–425 μm drop to the bottom of the reactor and are lifted in the burning process. Particles over 425–500 μm occasionally drop to the bottom without undergoing volatile combustion.

The torrefied sewage sludge particles provided better combustion quality than the raw sewage sludge particles. The degree of torrefied particles presented various

flame sizes as a function of intensity, and these physical flame structures differed significantly in the early combustion stage. The raw and torrefied sludges had different onsets of volatile ignition, which we attribute to lignin, which decomposes over a wide temperature range. Consequently, the torrefaction process is a feasible option for yielding even brighter soot flames and faster ignition, which were obtained from our single particle combustion results. The combustion characteristics here directly improve the radiative heat transfer for the pulverised combustion furnace. Therefore, the disadvantages of biomass combustion, i.e. less energy density and shorter combustion time, can be overcome using this promising method.

Special particles for co-firing were also assessed for their burning characteristics, and a quantitative analysis yields the desirable magnitudes of the combustion parameters to demonstrate the effect of co-firing. Mixed particles containing significant amounts of wood undergo simultaneous homogenous and heterogeneous combustion under enhanced oxygen concentration. Increasing the fraction of coal in a particle leads to a conical flame shape because the high fixed carbon content and H/C ratio contribute an enlarged sooty flame with a high aspect ratio. Consequently, for co-firing, these particles release more radiative energy because of the improved flame structure, which in turn affects the flame stability and the performance of boilers with fast homogenous ignition.

The colour-scale imaging process was used to analyse the physical structure of the elongated flame given different environmental conditions. The flame intensity was also quantitatively analysed as a function of time and displacement. Unfortunately, the proxy temperature of the flame was not calculated because pyrometry with different colour filters was not applied to the test rig. Pete B et al. [x] reported a compact temperature and soot volume fraction diagnostic technique based on a thin-filament pyrometry using a colour digital camera. In a future study, their diagnostic technique will be adapted to predict the soot temperature and soot loading.

Digital image processing for the burning particle is one of the novel aspects of our experiments given that their volatile flames and characteristic particles are

clearly observed. In our present study, we evaluated the combustion quality and radiation heat transfer with their flame structures, which were obtained from different particle types. Further, our valuable information can contribute to the theory of flame sheet and the code of commercial dynamic fluid for pulverised solid combustion. The single particle combustion method might be a feasible option given that group and bulk particles combustion do not have the same quantitative particle loading and shape.

7.1 Future work

Further research is possible without modifying the current experimental setup.

- The combustion obtained as a function of biomass particle shape can be of interest for the combustion of pulverised biomass. For such an experiment, the particle-shape separator, which was introduced in Chapter 2, may help to separate particles into three groups according to shape.
- Wet coal particles present a problem for various combustion characteristics such as ignition delay and fragmentation, which are key factors for designing the particle injector and furnace. By using a humidified container, coal particles can be prepared in a poorly wetted or strongly wetted condition. This combustion is discussed in the first publication, but more experimental results are required to analyse and explain the combustion events.
- Plastic particle can be burned in furnaces as an energy source unless they emit toxins. Recently, plastic combustion (Tang et al., 2015; Asamany et al., 2017) has been studied. The present experimental setup can be also of used for this type of combustion research.

Furthermore, slight modifications of the current experimental setup (e.g. using the surrounding hot gas stream from the kantar heater instead of the post-combustion gases) would allow the single particle combustion to be studied by considering the effect of high gas temperature, environmental CO₂, a wetted environment and two flow velocities.

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APPENDICES

Stoichiometry combustion of propane from the balanced equation, are described by the following equation:

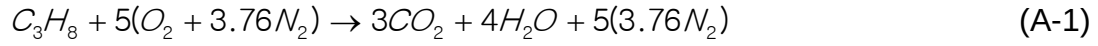


Table A- 1 Buner gas input and Equilibrium post-combustion gases (24.5 slpm)

Equivalence ratio	O ₂ (%)	C ₃ H ₈ (slpm)	MFC Air (slpm)	Air (slpm)	MFC O ₂ (slpm)	O ₂ (slpm)
0.57	0.09	0.6	21.27	23.60	0.1715	0.30
0.54	0.10		20.97	23.28	0.4835	0.62
0.52	0.11		20.67	22.96	0.7954	0.94
0.50	0.12		20.37	22.65	1.1074	1.25
0.48	0.13		20.08	22.33	1.4193	1.57
0.46	0.14		19.78	22.01	1.7313	1.89
0.44	0.15		19.48	21.69	2.0432	2.21
0.43	0.16		19.18	21.37	2.3552	2.53
0.41	0.17		18.88	21.06	2.6671	2.84
0.40	0.18		18.59	20.74	2.9791	3.16
0.39	0.19		18.29	20.42	3.2910	3.48
0.37	0.2		17.99	20.10	3.6030	3.80
0.36	0.21		17.69	19.79	3.9149	4.11
0.35	0.22		17.40	19.47	4.2269	4.43
0.34	0.23		17.10	19.15	4.5388	4.75

0.33	0.24	0.6	16.80	18.83	4.8508	5.07
0.32	0.25		16.50	18.51	5.1627	5.39
0.31	0.26		16.21	18.20	5.4747	5.70
0.31	0.27		15.91	17.88	5.7867	6.02
0.30	0.28		15.61	17.56	6.0986	6.34
0.29	0.29		15.31	17.24	6.4106	6.66
0.28	0.3		15.02	16.93	6.7225	6.97
0.28	0.31		14.72	16.61	7.0345	7.29
0.27	0.32		14.42	16.29	7.3464	7.61
0.27	0.33		14.12	15.97	7.6584	7.93
0.26	0.34		13.83	15.65	7.9703	8.25
0.25	0.35		13.53	15.34	8.2823	8.56
0.25	0.36		13.23	15.02	8.5942	8.88
0.24	0.37		12.93	14.70	8.9062	9.20
0.24	0.38		12.64	14.38	9.2181	9.52
0.23	0.39		12.34	14.07	9.5301	9.83
0.23	0.4		12.04	13.75	9.8420	10.15

Total flow rate (slpm)	O ₂ , %	N ₂ , %	H ₂ O, %	CO ₂ , %
	0.09	0.74		
	0.1	0.73		

24.5	0.11	0.72	0.10	0.07
	0.12	0.71		
	0.13	0.70		
	0.14	0.69		
	0.15	0.68		
	0.16	0.67		
	0.17	0.66		
	0.18	0.65		
	0.19	0.64		
	0.2	0.63		
	0.21	0.62		
	0.22	0.61		
	0.23	0.60		
	0.24	0.59		
	0.25	0.58		
	0.26	0.57		
	0.27	0.56		
	0.28	0.55		
	0.29	0.54		
	0.3	0.53		
	0.31	0.52		

24.5	0.32	0.51	0.10	0.07
	0.33	0.50		
	0.34	0.49		
	0.35	0.48		
	0.36	0.47		
	0.37	0.46		
	0.38	0.45		
	0.39	0.44		
	0.4	0.43		