DESIGN AND OPERATING PARAMETERS OF A FLUIDIZED BED FOR THE COMBUSTION OF MUNICIPAL SOLID WASTE USING STANDPIPES AIR DISTRIBUTORS

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Dedicated to human race;

“Look towards those who rank below you (so that you may get used to being thankful) and do not look who rank above you, lest you should despise the favours of Allah upon you”

(Muhammad S.A.W. – The prophet of Islam)

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ABSTRACT

Hydrodynamic studies and combustion of simulated and actual municipal solid waste were carried out in a fluidized bed system. A wide range of parameters was investigated in hydrodynamic study after which the optimum parameters were implemented in the combustion studies. A newly fabricated standpipes air distributor (primary air inlet) was designed based on findings of the optimum orifice diameter, orifice distance and distance between pipes. Orifice diameter, orifice distance and distance between pipes of 3 mm, 10 mm and 70 mm were used in the hydrodynamic studies of circular and rectangular columns (CHS and RHS). The operating parameters investigated in the CHS and RHS included the effect of sand sizes and aspect ratios on the fluidization profile. Standpipes air distributors having the same orifice diameter and distance but with a wider pipe distance of 200 mm were used in the hydrodynamic studies of a bigger rectangular (big scale) column. Different air flow strategies were implemented to ensure good mixing between sand and samples and to investigate the penetration of the incombustibles into the sand bed. Parameters studied in the combustion of municipal solid waste included the effect of fluidizing velocity and air factor on the combustion profile in the bed as well as the freeboard region with standpipe air distributor design and dimension established from the hydrodynamic studies of a bigger scale rectangular column. Findings from the CHS and RHS showed that sand particles with mean size of 0.34 mm performed good fluidization profile compared to other coarser sand sizes. The ratio of the bed height over diameter of column (D_c) for good fluidization was determined at $H = D_c$ for the circular column whereas the ratio of the bed height (H) over the length (L) of column was observed at H<L for the rectangular columns. A two side air flow was seen as the best air flow strategy for good mixing in a bigger rectangular column. The range of fluidization number and air factor for the combustion of simulated municipal solid waste in a rectangular fluidized bed combustor was 5 – 7 U_{mf} in which 5 U_{mf} was found to be the optimum with air factor of 0.8 (primary air). Air factor of 0.4 (secondary air) was observed to show good temperature profile in the freeboard region for the combustion of municipal solid waste. The optimum total combined air factor for the combustion of municipal solid waste was 1.2 in which inlet primary air factor and inlet secondary air factor were 0.8 and 0.4, respectively.

ABSTRAK

Kajian hidrodinamik dan pembakaran sisa pepejal perbandaran simulasi buatan dan sisa pepejal perbandaran sebenar telah dijalankan di dalam sistem turus terbendalir. Pelbagai parameter telah dikaji dalam kajian hidrodinamik yang mana keputusan yang diperolehi digunapakai di dalam kajian pembakaran di dalam turus terbendalir. Penyalur udara (penyalur udara utama) direka berdasarkan kepada keputusan optimum yang didapati setelah menjalankan kajian berkenaan diameter orifis, jarak antara orifis dan jarak antara paip. Diamter orifis, jarak antara orifis dan jarak antara paip yang digunakan di dalam kajian hidrodinamik turus terbendalir bulat dan segiempat (CHS dan RHS) adalah 3 mm, 10 mm dan 70 mm. Parameter operasi yang dikaji dalam kajian hidrodinamik CHS dan RHS bagi turus terbendalir bulat dan segiempat adalah kesan saiz pasir dan nisbah aspek ke atas profil terbendaliran. Penyalur udara yang mempunyai diameter orifis dan jarak antara orifis yang sama digunakan dalam kajian hidrodinamik turus terbendalir segiempat yang lebih besar tetapi jarak antara paip dibesarkan kepada 200 mm untuk mengkaji profil terbendaliran. Pelbagai strategi masukan udara digunakan untuk mengkaji profil terbendaliran di dalam turus terbendalir ini. Parameter yang dikaji di dalam kajian pembakaran termasuklah kesan nombor halaju udara dan pekali udara ke atas profil terbendaliran di dalam turus terbendalir. Hasil dari kajian hidrodinamik menggunakan turus terbendalir bulat dan segiempat (CHS dan RHS) menunjukkan bahawa purata saiz pasir 0.34 mm memberikan profil terbendaliran yang baik berbanding dengan saiz pasir lain. Nisbah yang optimum bagi ketinggian (H) pasir di dalam turus terbendalir kepada diameter turus terbendalir (D_c) adalah $H = D_c$ untuk turus berbentuk bulat. Manakala nisbah yang optimum bagi ketinggian (H) bendalir di dalam turus terbendalir kepada panjang (L) turus terbendalir adalah H<L bagi turus berbentuk segiempat. Keputusan kajian menunjukkan julat nombor halaju udara bagi pembakaran simulasi buatan sisa pepejal perbandaran adalah 5 – 7 U_{mf} di mana nombor halaju udara 5 adalah yang paling optimum dengan nilai pekali udara 0.8 (pekali udara prima). Pekali udara yang menunjukkan kesan yang baik bagi pembakaran di atas pasir adalah 0.4 (pekali udara sekunder). Pekali udara keseluruhan yang optimum bagi pembakaran sisa pepejal perbandaran adalah 1.2 di mana pekali udara prima adalah 0.8 dan pekali udara sekunder adalah 0.4.

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A_t , A_v	Cross-sectional area of bed, (m^2)
A_D	Area of distributor plate per hole, (m^2)
Ar	Archimedes number, $Ar = \frac{\rho_f(\rho_p - \rho_f)g d_m^3}{\mu_f^2}$ (dimensionless)
Bi	Biot number (dimensionless)
C_{Pa}	Average heat capacity of air (J/g^{0}C)
C_{Pv}	Average heat capacity of volatiles (J/g^{0}C)
$C_{p\,ca}$	Average heat capacity of char and ash (J/g^{0}C)
C_{Pds}	Average heat capacity of dry waste (J/g^{0}C)
C_{Pwv}	Average heat capacity of water vapour (J/g^{0}C)
C_xH_y	Hydrocarbon
D_c	Column diameter, (m)
D_b, d_b	Bubble diameter, (m)
D_G	Binary molecular diffusion coefficient of oxygen in air, (m^2/s)
d_{bo}	Initial bubble formed near the bottom of the bed, (m)
d_i	Diameter of the spherical fuel particle, (m)
d_m, d_p	Mean particle diameter (m), particle diameter (m)
d_t	Bed diameter, (m)
d_*	Dimensionless particle size, $d_* = d_{sph}\left[\frac{g\rho_f(\rho_s - \rho_f)}{\mu^2}\right]^{1/3}$
g	Gravitational acceleration, (9.81 m/s^2

g_c	Conversion factor, $\left(\frac{1kgm/s^2}{N}\right)$
$\hat{H}_i$	Specific enthalpy of the ith component at 25^{0}C, (kJ/kg)
h	Heat transfer coefficient, $\left(\frac{W}{m^2K}\right)$
k	Thermal conductivity, $\left(\frac{W}{mK}\right)$
L_{mf}	Height of bed at minimum fluidization, (m)
L_p	Pyrolysis endothermicity, (kJ/kg)
M	Mass of solid in bed, (kg)
M_a	Mass flow rate of air (g/min)
M_{ca}	Mass flow rate of residual char and ash (g/min)
M_{ds}	Mass flow rate of dry waste (g/min)
M_f	Mass flow rate of fuel (g/min)
M_v	Mass flow rate of volatiles (g/min)
M_w	Mass flow rate of water (g/min)
n_d	Total number of orifices
n_i	Moles of the ith component in the feed or product
p_s	Partial pressure of oxygen at the carbon surface, (atm)
Q_{rad}	Radiative heat loss (W)
q, q	Heat flux $\left(\frac{W}{m^2}\right)$, heat liberated (J/g)
Re	Reynolds number, Re = $\left(\frac{\rho_f U d_p}{\mu_f}\right)$ (dimensionless)
T_a, T_a	Inlet air temperature (^{0}C), temperature of flame (K)
T_0	Temperature of particle (K), temperature of the surroundings (K)
T_b	Bed temperature (^{0}C)
T_{ad}	Adiabatic flame temperature, (^{0}C)
T_s	Burning char particle surface temperature, (K)

T_v, t_v	De-volatilization time, (s)
t_b	Burn-out time, (s)
U, u	Fluidization velocity, $\left(\frac{m}{s}\right)$
U_b	Bubbles velocity in a bubbling fluidized bed, $\left(\frac{m}{s}\right)$
U_{br}	Single bubble velocity, $\left(\frac{m}{s}\right)$
U_0, u_0	Fluidization velocity at the distributor, $\left(\frac{m}{s}\right)$
U_{mf}, u_{mf}	Minimum fluidization velocity, $\left(\frac{m}{s}\right)$
U_t, u_t	Terminal-fall velocity, $\left(\frac{m}{s}\right)$
u_*	Dimensionless gas velocity, $u_* = u_t\left[\frac{\rho_f^2}{g\mu(\rho_s - \rho_f)}\right]^{1/3}$
z	Distance above the distributor, (m)
z_{b0}	Height of initial bubble formation, (m)
ΔP_t	Pressure drop across the bed, $\left(\frac{N}{m^2}\right)$
$\Delta \hat{H}_c$	Heat of combustion of the fuel at reference temperature 25^{0}C, $\left(\frac{kJ}{mol}\right)$
$\Delta \hat{H}_v$	Heat of vaporization of water at 25^{0}C, $\left(\frac{kJ}{mol}\right)$

Greek Letters

α	Thermal diffusivity $\left(\alpha = k\rho^{-1}C_p^{-1}\right)$
λ	Amount of heat required to raise the moisture from ambient conditions to the boiling point and to evaporate the moisture, (J/g)
σ	Stefan-Boltzmann constant (5.67x10^{-8} $\frac{W}{m^2K}$)
ε , ε_{mf}	Bed voidage, bed voidage at minimum fluidization
ε_m	Emissivity of the bed surface, (dimensionless)
ϕ_s	particle sphericity, (dimensionless)
μ_f , μ_g	fluid viscosity$\left(\frac{kg}{ms}\right)$, gas viscosity, $\left(\frac{kg}{ms}\right)$
ρ_b	Bulk density, $\left(\frac{kg}{m^3}\right)$
ρ_c	Carbon density of a char particle, $\left(\frac{kg}{m^3}\right)$
ρ_g	Density of fluidization gas, $\left(\frac{kg}{m^3}\right)$
ρ_p	Particle density, $\left(\frac{kg}{m^3}\right)$
ρ_f	Fluid density$\left(\frac{kg}{m^3}\right)$, gas density$\left(\frac{kg}{m^3}\right)$
ρ_i	Density of the initial fuel particle, $\left(\frac{kg}{m^3}\right)$
η_{CU}	Carbon utilization efficiency, (%)
η_{CQ}	Combustion quality efficiency, (%)
η_{TE}	Thermal efficiency, (%)

Abbreviation

2D	Two-dimensional
3D	Three-dimensional
AF	Air Factor
ASEAN	Association of South East Asian Nations
BFB	Bubbling Fluidized Bed
CH	Centre High
CFB	Circulating Fluidized Bed
CHS	Circular Hydrodynamic Studies
EF	Equal Flow
GI	Galvanized Iron
HHV	High Heating Value, (MJ/kg)
ITA	Investment Tax Allowance
LHV	Lower Heating Value, (MJ/kg)
LDPE	Low Density Polyethylene
LPM	Litre Per Minute
MSW	Municipal Solid Waste
OSH	One Side High
PS	Pioneer Status
PAH	Polycyclic aromatic hydrocarbon
ppm	part per million
RC – 1	Rectangular column – 1
RC – 2	Rectangular column – 2
RDF	Refused Derived Fuel
RHS	Rectangular Hydrodynamic Studies
SEM	Scanning Electron Microscope
SPP	Small Power Producers
SREP	Small Renewable Energy Programme
TDH	Transport Disengaging Height
TSH	Two Side High
UK	United Kingdom

APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter discusses the thermal treatment of the municipal solid waste in a fluidized bed combustor. It also discusses the background of the research activities, selection and justification for the proposed study. Brief description on the reason for the utilization of fluidized bed for waste incineration is included and focus is given on the Malaysian energy scenario. The objectives of the research and the scope of work are also pointed out.

1.2 Research Background

Literatures on the utilization of the most suitable combustion technology for reduction of wastes (biomass, coal and municipal solid waste) are reviewed. It gives information and basic guidelines for the overall current research activities. This includes the selection of type of fuel to be used, thermal treatment method, combustion technology and design of air distributor.

1.2.1 Selection of Fuel for Combustor

Fuel for combustor may vary as it depends on the purpose of the burning itself. In the case of municipal solid waste, the waste itself is regarded as a fuel. Ruth (1998) has given a thorough review on the combustion technology using municipal solid waste as its feed. Another source of fuel is the biomass waste and becomes one of the promising sources of fuels for energy generation. Experimental investigation on the combustion of biomass in a pilot scale fluidized bed has been carried out by Saenger *et al.* (2001) and Natarajan *et al.* (1997) on the combustion of coffee husk and Armesto *et al.* (2002) on the combustion and gasification of rice husks. These two sources of fuels are readily available and many research and commercial activities have been done especially on the aspect of energy conservation via the integrated power plant operation system. Coal as a fuel has been another source of energy generation as commonly practised decades ago. Extensive research activities on the combustion of coal are still being carried out. Saxena *et al.* (1997) used a fluidized bed of 0.154 m in diameter and an overall height of 3.5 m on their research on the combustion of coal.

Looking into Malaysian perspective, municipal solid wastes are abundant and cause a challenging effort for the authorities to dispose it off. As a matter of fact, the increase in municipal solid waste is an indication of the progress of Malaysia towards developed nation. Solid waste generation in major urban area in peninsular Malaysia is shown in Figure 1.1.

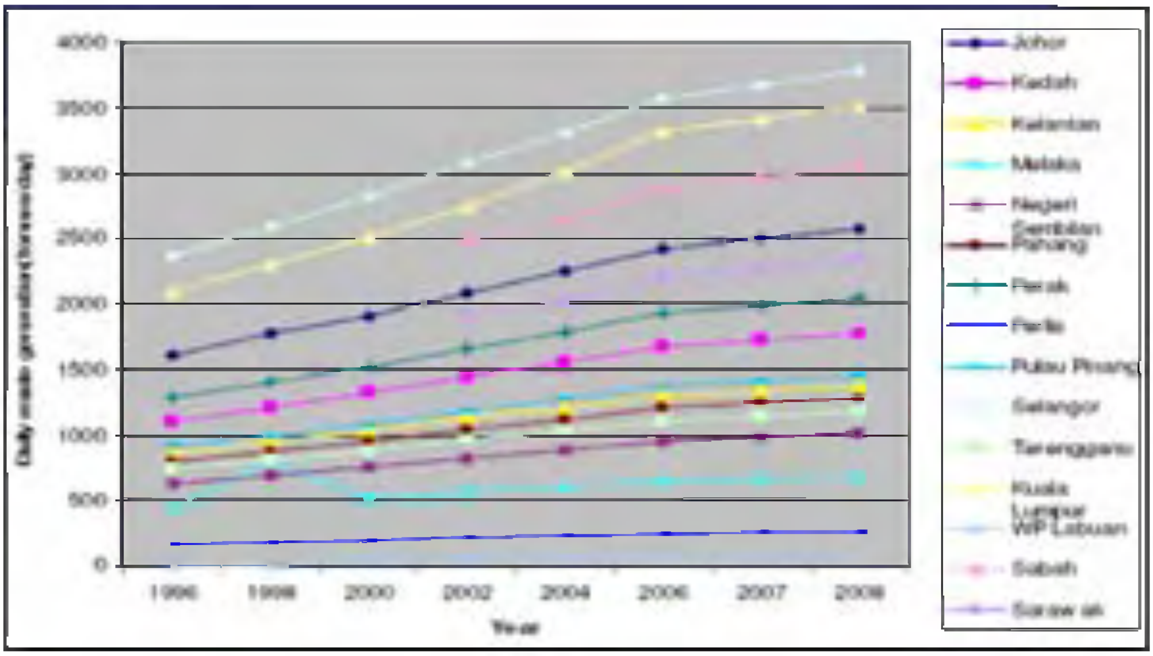

Figure 1.1: Solid waste generation in states in Malaysia (Agamuthu, 2008)

Data clearly show an increment in waste generation in states in Malaysia, so does the problem of disposing it. Currently the most widely used method of waste disposal in Malaysia is land-filling. However, with tremendous increment in waste generation annually, the Malaysian government has looked into several alternatives in reducing the disposal problem such with the possible use of thermal treatment method.

On a larger picture, the cheapest and widely used method of waste disposal in the world is land-filling. However, with a steady increase of municipal solid waste generation annually due to human activities and population growth, alternative method of solid waste disposal system is in need. Thus, combustion or gasification of municipal solid waste comes into the picture. Of the three sources of fuels stated above (municipal solid waste, biomass and coal), municipal solid wastes are heterogeneous in nature, therefore, investigating the combustion of municipal solid waste in the laboratory scale fluidized bed is very difficult. Municipal solid waste has been successfully burnt in a grate combustion system or mass burn combustion system (Ruth, 1998). On the other hand, refuse derived fuel (RDF) which is fuel originated from municipal solid waste after segregation and separation of municipal solid waste components has been used in a fluidized bed combustor (Piao *et al.*, 2000; Hernandez-Atonal *et al.,* 2007).

The compositions of the municipal solid waste vary with geographical location, social and economic status. For example, the amount of moisture in municipal solid waste is low in industrialised countries, whereas wastes in developing countries especially in ASEAN region contain high moisture content. Typical distribution of components in municipal solid waste for Thailand and the United Kingdom is shown in Table 1.1.

Table 1.1: Waste components of municipal solid waste for Thailand and the UK (Patumsawad and Cliffe, 2002)

Component	Thailand	United Kingdom
Paper	13%	31%
Food waste	39%	25%
Plastics	10%	8%
Textile, rubber, leather and wood	23%	5%
Metal Glass Other	15%	8% 10% 13%

Karthirvale *et al.* (2003) conducted municipal solid waste characterization on the medium income residential areas in Kuala Lumpur in 2001. Table 1.2 shows the summary of the waste composition from the medium income residential areas generated in Kuala Lumpur.

Table 1.2: Compositions of municipal solid waste generated from residential medium income in Kuala Lumpur (Karthirvale *et al*., 2003)

Component	Weight percent (%)
Food/organic	38.42
Mix paper	7.22
Newsprint	7.76
High grade paper	1.02
Corrugated paper	1.75
Plastic (rigid)	3.57
Plastic (film)	14.75
Plastic (foam)	1.72
Diapers	7.58
Textile	3.55
Rubber/leather	1.78
Wood	1.39
Yard	1.12
Glass (clear)	2.07
Glass (coloured)	2.02
Ferrous	3.05
Non-ferrous	0.00
Aluminium	0.08
Batteries/hazardous material	0.18
Fine	0.71
Other organic	0.00
Other inorganic	0.27
Others	-
TOTAL	100

With regards to the varying composition of wastes in the municipal solid wastes, efforts have been made to simulate the municipal solid wastes compositions according to its major compositions. This is the first step towards understanding the burning behaviour of the actual municipal solid wastes. The operating parameters of the fluidized bed combustion of municipal solid waste will be based on findings from the combustion of the simulated municipal solid waste. The formulation of the simulated municipal solid waste used in the current research activities is based on the data gathered from the municipal solid waste characteristics study conducted in Kuala Lumpur (Rozainee, 2001). The simulated municipal solid waste is made of four major categories; namely, food waste, plastics, paper and vegetable wastes. Proximate analysis was conducted to investigate the simulated municipal solid waste compositions in terms of four constituents; namely moisture content, volatile matter, ash and fixed carbon. Ultimate analysis was carried out to determine the chemical elements that make up the sample namely carbon content, hydrogen content and oxygen content. The percentage compositions of these waste categories are shown in Table 1.3. Appendix A shows the detail calculation and formulation of simulated municipal solid wastes.

Table 1.3: Compositions of simulated municipal solid waste

Simulated municipal solid waste	**Percentage (%)**
Rice waste	27
Shredded paper	19
Plastic film (LDPE)	25
Vegetable waste	29

Other researchers have conducted various experiments with simulated waste but the samples were not representative to the Malaysian scenario. Patumsawad and Cliffe (2002) used pre-dried chicken manure pellets. Water was added to generate the required percentage of moisture content as their objective was to demonstrate the technical feasibility of a fluidized bed for burning high moisture municipal solid waste. Thipse *et al.* (2002) investigated the chemical and physical characteristics of a synthetic fuel to represent the collective composition of municipal solid waste in the United States. The majority of fuel consists of paper and wood whilst low density polyethylene was chosen to represent the plastic polymer and iron represented the metal content. Animal feed and water simulated the waste food organic contents and the inert component silica made-up the rest of the fuel. The fuel is made in three stages: (i) mixing the components, (ii) size reduction by shredding, (iii) compaction into cylindrical pellets of 2.5 cm diameter and approximated length of 5 cm.

Yang *et al.* (2003) presented another technique for the formulation of the simulated municipal solid waste. The major fuel in the simulated waste consists of cardboard and vegetable and the weight ratio between the cardboard and vegetable was 1.85:1 which is in accordance to the ratio between paper and food content in a typical United Kingdom municipal solid waste. Knowing the waste characteristics enable researchers to simulate the feed into the combustor. The majority of the combustible materials in the municipal solid waste derived from paper and plastics. These materials if it were to be separated or sorted out from the bulk of the municipal waste could be used as a potential fuel for the combustor as they yield high calorific values. Salvador *et al.* (2004) studied the combustion of substitution fuels that were made from compressed mixes of cardboard and polyethylene. These two materials represent the two classical classes of waste components.

Municipal solid waste disposal has always been seen as a burden but with good solid waste management, the municipal solid waste is actually an asset. Having known the waste compositions in the municipal solid waste enables the separation of combustible and incombustibles prior to the combustion of the wastes. The municipal solid waste could be turned into resources of energy and electricity generation through the implementation of the state of the art thermal decomposition method such as demonstrated by the fluidized bed combustion or gasification system.

One advantage of thermal conversion of municipal solid waste is the energy recovered from its combustion. In order to evaluate the feasibility of energy recovery in the combustion plant, it is of a great importance to determine the energy content or calorific value of the solid waste. Calorific values and water content in municipal solid waste play an important role as higher calorific value significantly determines the quality of the combustion in terms of heat released. Water content influences the combustion behaviour in terms of its temperature profile and volume of gas produced. Because municipal solid waste is a heterogeneous material and production rate and physical composition vary from place to place as they are a function of socio-economic level climatic conditions, the energy content of municipal solid waste in one country will be different from that of another. Table 1.4 shows the heat content of municipal solid waste in Thailand and United Kingdom.

Table 1.4: Heat content of municipal solid waste

High Heating Value (HHV)	MJ/kg (as received)	MJ/kg (dry basis)
Thailand	6.49 MJ/kg*	15.59 MJ/kg*
United Kingdom	10.25 MJ/kg*	15.0 MJ/kg*

* Data from Patumsawad and Cliffe, (2002).

Knowledge of the physical characteristics and chemical composition of municipal solid waste are crucial as these parameters influence the overall behaviour of the combustion system. For example, differences in properties of coal and municipal result in differences in the combustion characteristics of these fuels and in turn affect the type of combustion equipment. In particular, the most important fuel properties are the size of the fuel particles and the fuel composition. The size of fuel particle affects the length of time required for its combustion. Municipal solid waste for example comprises of extremely variable sizes and shapes, thus longer residence times are required to completely burn the waste.

1.2.2 Selection of Thermal Treatment Methods

Various methods of waste decomposition have been employed due to several reasons depending on the end product requirement, such as pyrolysis, combustion or gasification techniques. Pyrolysis for instance, is the decomposition of waste with heat alone in the absence of air. It has been used to decompose biomass waste such as straw and stalk of rapeseed plants (Karaosmanoglu *et al.,* 1999) and wood, coconut shell and straw (Fagbemi *et al.,* 2001). Pyrolysis of the biomass has gained increasing attention since the process conditions can be optimised to produce high energy density liquid (tar) products in addition to the derived char (solid) and gas.

Normally pyrolysis reaction temperature is carefully controlled at around 500^0C. Much of the present interest in pyrolysis is focused on the liquid (tar) production. However, as pyrolysis liquid contains organic materials and water, many are reported to contain polycyclic aromatic hydrocarbon (PAH), some of which have shown to be carcinogenic. Horne and Williams (1996) reported that the pyrolysis liquid of mixed wood contains both monocyclic hydrocarbon such as benzene, toluene and dimethyl and ethylbenzene and polycyclic aromatic hydrocarbons. On the shorter note, by assessing the pros and cons of pyrolysis technique, the idea of using this method into the present research activities is unrealistic since pyrolysis technique is not intended for the mass reduction of solid waste. Hence, other techniques such as combustion or gasification will be the best bet for solving the problems of municipal solid waste disposal.

Combustion and gasification technology are two thermo-chemical treatments that have gained much interest in recent years. These processes offer a more realistic approach in dealing with the tremendous increase in the municipal solid waste in Malaysia. In a gasification process, waste is converted to a combustible gas mixture by partial oxidation (starved air condition) of waste at high temperature, typically in the range of 800 – 900^0C. The main gaseous components are carbon monoxide and hydrogen. Combustion process on the other hand requires excess air, thus producing carbon dioxide and water. These two processes carried out in a fluidized bed combustor offer upstream flexibility (biomass, coal and municipal solid waste) and downstream product flexibility (gaseous products) advantages.

1.2.3 Selection of Combustion Technology

The combustor is the heart of the combustion or gasification process. It is where the combustion of fuels (biomass, coal, municipal solid waste) takes place. Various combustion technologies have been employed and operated successfully. Combustors for biomass and municipal solid waste are predominantly either grate-fired system or fluidized bed. Biomass is generally fed into the fluidized bed. Past practices showed that municipal solid waste is normally incinerated in a grate-firing system, whereas refused derived fuel (RDF) is commonly burnt in a fluidized bed. Grate-firing systems are equipped with flat or sloping grates. The grates may either be moving or stationary in design. The moving grate system requires large operational area and not economical to be constructed just for the academic exercises. On the other hand, the stationary grate system is a fixed bed combustion system and even though requires less operational area and economical, the combustion behaviour of a fixed bed and fluidized bed is different. Both grates system do not have a fluidization medium, thus, not within the scope and objectives of the current research study. Grate-firing reactors were the most versatile units in the mid 1980s.

Fluidized beds have only gained tremendous acceptance in the recent years due to several reasons. One of them is the ability to burn various types of fuels because it provides long fuel residence times, good contacting of fuel and bed material with air with a relatively uniform temperature distribution inside the bed. In the fluidized bed system, the bed is first heated close to the operating temperature. The bed material, usually sand, absorbs and stores the heat, while the turbulence and mixing of the bed keeps the temperature uniform throughout the bed. When waste is introduced into the fluidized bed, the high heat and mass transfer characteristics of the bed permits the rapid energy conversion at practically isothermal condition. The high surface area available in fluidized beds on which reactions could occur, result in good conversion efficiency, higher throughput and lower operating temperature. Uniform temperatures and high heating capacities of sand permits a wide range of low-grade fuels of even non-uniform size and varying moisture content to be converted to desired products (Natarajan *et al.,* 1997).

Two types of fluidized beds are bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). In the bubbling fluidized bed (BFB) combustor, the majority of fuel particles which are fed onto the bed react in the bed with the oxygen in the upward airflow (primary air). Therefore, the lower combustion zone contains a high density of the fuel and during the combustion, the bed acts as a heat buffer enabling high heat transfer between the particles. Due to this, the BFB could tolerate larger fuel size (0 – 50 mm) than the CFB combustor and the BFB combustor is also less sensitive to variations in the fuel moisture content and it is suitable for waste with wide variation of moisture contents. The mass concentration of fine particles is less in the BFB compared to that of the CFB due to the lower application of the fluidization number in the BFB. The BFB combustor operates at lower fluidization velocity, typically 1-3 m/s whereas the CFB combustor operates at higher fluidization velocity ranges from 3 – 10 m/s (Koornneef *et al.,* 2007). As a result of the higher fluidization velocity in the CFB combustor, solids are entrained in the air flow more equally along the combustor height and the heat transfer and combustion temperature is more equally distributed with the combustor height compared to the BFB. With an increase in the mass load of the elutriated fine particles, the design of the cyclone separator would be larger in the CFB than in the BFB. Thus, increasing the investment cost of the CFB system (Anthony, 1995). In the CFB combustor, the major portions of the dust and unconverted carbon in the product gas are recycled to the reactor bottom through a cyclone, thus leading to high carbon conversion.

The BFB combustor offers the best solution as it gives good distribution of temperature inside the entire bed and freeboard. The heat exchange between the waste, sand and gases is very good due to their intimate mixing at high temperature. With larger fuel size acceptability and moisture content variations in the municipal solid waste, the BFB is considered the best choice despite the drawback in the temperature distribution along the bed height which is not as good as in the CFB. In the CFB combustor, the operation is carried out at higher velocity compared to the BFB combustor. Hence, it increases the pumping power of the fluidization air into the combustor which significantly increases the operating cost. Furthermore, additional costs of capital and operating costs have to be invested due to the construction of a ‘return leg’ at the bottom of the cyclone to enable the unconverted carbon from the cyclone to re-enter into the combustor. The difference in the operation and design of the BFB and CFB results in the variation of investment costs. The investment costs of the BFB and CFB systems less than 10 MW_e in several biomass-to-energy plants in Finland is presented in Table 1.5. The plants operate on the power-to-heat ratios of about 0.35 (Bain *et al.,* 1998).

Table 1.5: Investment cost of small cogeneration plants in Finland (Bain *et al.*, 1998)

Plant	Capacity power/heat (MW_e/MW_t)	Type of combustor	Investment cost (£ Million)
Pieks-m-ki	9/25	BFB	9.5
Kankaanp	6/16	BFB	8.0
Kuhmo	5/13	CFB	12.3
Ylivieska	5/15	BFB	8.7
Kuusamo	6/17	BFB	8.0
Lieksa	8/22	CFB	11.3

The schematic diagram of the bubbling and circulating fluidized bed combustors is shown in Figure 1.2.

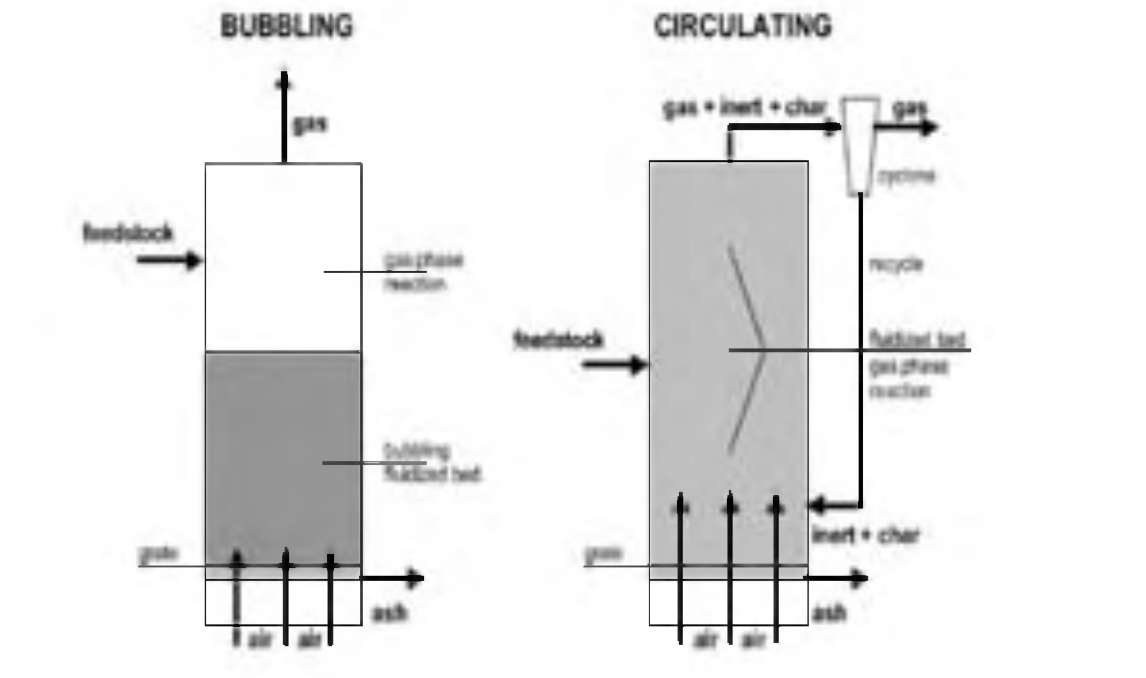

Figure 1.2: Schematic of Bubbling and Circulating Fluidized Bed Combustors (Belgiorno *et al.,* 2003)

Considering the existing laboratory facilities and from the evaluation of operation, design and costs of the BFB and CFB, the BFB combustor system is chosen for the current research work.

1.3 Justification of the Research

The title of the research is **'Design and Operating Parameters of a Fluidized Bed for the Combustion of the Municipal Solid Waste using Standpipes Air Distributor'**. As stated from the research title, the study focuses on the three major aspects, as listed below;

(i) operating parameters of fluidized bed
(ii) municipal solid waste
(iii) standpipes air distributor design

These three elements have been pointed out as the determining factors to the successful operation of the fluidized bed system and its importance in this research study. The study of the municipal solid waste combustion is difficult to be conducted in a laboratory scale fluidized bed due to reason associated to its heterogeneous and inconsistent compositions and varying in sizes from as bulky as the office furniture to as small as an organic human hair. Furthermore, the physical characteristics of municipal solid waste such as moisture content, volatile matter content, fixed carbon content and ash content also vary depending on the individual waste component. Chemical compositions of simulated municipal solid wastes such as carbon content, oxygen content, hydrogen content also varies according to the waste itself. Hence, the municipal solid wastes characteristic, physical and chemical compositions at any given time are not constant and pose problems during the experimental investigation in a small fluidized bed laboratory scale. However, the limitation can be overcome with the use of the simulated municipal solid waste, which is formulated from the typical average waste compositions in Malaysia. The simulated municipal solid wastes comprise of four major waste components in the actual municipal solid waste namely; paper, plastic, green (vegetable waste) and food waste. Other wastes components such as glass, rubber and metal are omitted from the formulation of simulated municipal solid wastes since their compositions are low in the actual municipal solid wastes. These four components of wastes are taken from the same source, thus, giving consistent waste characteristics in terms of its physical and chemical compositions and moisture content. Results from the combustion of the simulated municipal solid wastes are used as an input to the actual combustion of municipal solid wastes.

Physical and chemical characteristics of municipal solid waste are useful in the design of a fluidized bed combustion system. For example, information on the carbon, hydrogen and oxygen content of the municipal solid waste or simulated municipal solid waste enables the calculation of air requirement for the complete combustion, excess air combustion or even starved air combustion (gasification). Furthermore, enables of estimation of air compressor power and costing. Physical characteristic on the other hand provides information of the waste itself such as the density of the waste which gives an indication of the mixing of the waste in the fluidized bed, whether the waste float on the sand or penetrate inside the sand bed. The amount of water in the waste gives an indication of the burning profile in the sand bed. It shows the sustainability of the waste combustion inside the sand bed. Volatile matter for example gives information whether the combustion is on the freeboard (region above the surface of the sand bed) or bed combustion. Therefore, knowledge of the municipal solid waste characterization, physical and chemical compositions are crucial as data gathered are useful for the formulation of the simulated municipal solid waste, design and operation of the fluidized bed.

The design of the air distributor in which the fluidizing air flows through the bed is critical as it determines the quality of the fluidization inside the bed. Various designs have been used such as porous and perforated plates. However, the drawback of these designs is the clogging of un-burnt fuels and its inability to freely dispose off the remaining ash and other incombustibles, as one needs to dismantle the air distributor after each test. Furthermore, the mixing of low density waste with sand is poor due to the inability of the waste to penetrate inside the bed. These designs unable to cause good circulation of sand and therefore mixing of low density wastes are relatively poor. The new air distributor design has the ability to control the air into the fluidized bed, thus, permitting the mixing of low density waste into the sand bed. The new design also has the advantage over those two conventional designs as it permits the disposal of ash and other incombustibles without even dismantling the distributors. Focus on the new design includes the geometrical design such as orifice size, orifice distance and distance between each distributor pipe and their effect on the bed hydrodynamics.

The combustor shape and size are also looked into to study their effects on the fluidization. The shape of the fluidized bed chosen for the study is of rectangular and circular columns. The effect of combustor shapes and sizes on the bubble formation would be observed as bubble plays a significant part in the mixing behaviour of waste and sand. Other aspects such as the fluidizing numbers and bed height are also investigated. The sand size (fluidizing medium) also plays an important role as their properties would influence the bed hydrodynamics. The operating parameters such as air factor (ratio of air supplied to the combustor to the stoichiometric air) and feed rate into reactor are also part or the research activities as the purpose of the fluidized bed combustion is to maximize the feed rate of fuel.

In a much larger picture, the Malaysian government has encouraged the use of new source of energy such as renewable energy to supplement the conventional oil, gas, hydro and coal. In this regard, the fuel diversification policy is extended to include renewable energy as the fifth fuel, particularly biomass waste. These include waste from palm mills, sawmills and paddy straw and rice husk. The government's policy on the renewable energy through Small Renewable Energy Programme (SREP) is seen as a major milestone in determining the success of the 'waste to energy' projects. To date three small power producers (SPP) are under construction. The SPPs are Bumibiopower, TSH Resources and Jana Landfill. Bumibiopower's renewable energy plant uses palm waste as biomass fuel and is located at Pantai Remis, Perak. The plant will have the capacity to generate 5.2 MW of electricity with the use of stoker type boiler. TSH Resources also uses palm wastes as its fuel and generates 14 MW of electricity. The plant is located in Kunak, Sabah. Jana Landfill's energy plant in Puchong, Selangor will have a generating capacity of 2 MW and will use landfill gas as fuel. The thermal method of 'waste to energy' concept using fluidized bed system has many advantages over the conventional land-filling operation.

The fluidized bed system can be used for biomasses and municipal solid waste (in the form of refuse derived fuel), thus, with its broad feedstock flexibility, the fluidized bed operation is highly recommended for fast disposal of waste. According to Ma (1997) there are 2.4 million hectares under oil palm cultivation nationwide which produce a large amount of residual waste. The timber industries generate some 12 million tonnes of logging residues and 3 million tonnes of wood waste a year. Paddy straw and rice husk accounted to about 3 million tonnes and 434,000 tonnes per year respectively.

Various incentives have been offered by the government to promote the renewable energy power projects (Koh and Hoi, 2002). The government can endorse *Pioneer Status (PS)* with full exemption for 10 years or given a *Investment Tax Allowance (ITA)* which is beneficial for heavy up-front capital costs.

1.4 Objectives of the Research

The objectives of this research are as follows;

(i) To design and fabricate a new air distributor for the hydrodynamics and combustion studies

(ii) To study the bed hydrodynamics of fluidized bed under various experimental rig design

(iii) To determine the range of operating parameters for the combustion of the simulated municipal solid waste

(iv) To determine the operating parameters for the combustion of municipal solid waste

1.5 Scope of the Study

In order to achieve the objectives of this research, the programme of work have been divided into several sections as listed below;

i) The initial work consisted topics related to the fundamental concepts of fluidized bed hydrodynamics, combustion theory and waste combustion in a fluidized bed.

ii) The proximate and ultimate analyses were conducted to gives an insight into the waste physical characteristics. Methods on the formulation of the simulated waste were presented in great details. Geometrical design and the fabrication of air distributors were also presented.

iii) Bed hydrodynamic studies were conducted using circular and rectangular columns (small rigs) to give better understanding of the fluidization concept. The studies involved the manipulation of fluidizing numbers and bed height to determine the fluidization quality. Sand physical characteristics and its effect on fluidization were also examined.

iv) Up-scaling of the smaller rig were based on the findings from the hydrodynamics studies. The study focused on the Air Flow Strategy introduced into the fluidized bed reactor.

v) The combustion of the simulated municipal solid wastes were conducted according to the specified choice of fluidizing numbers, bed height, sand size and air flow strategy. The ranges of operating condition were obtained through the manipulation of fluidizing numbers, feed throughput and the air factor. Temperature monitoring in the bed and freeboard region were used to explain the combustion profile.

vi) Combustion of municipal solid waste was based on parameters obtained from the combustion of the simulated municipal solid waste

1.6 Thesis layout

The thesis covers the study of the combustion of the simulated waste based on the following chapters;

Chapter 2 reviews some information on the fundamental description of the general bed behaviour such as Geldart's classification of particles, minimum fluidization velocity, bubble formation, bed mixing, entrainment and elutriation of particles and transport disengaging height (TDH). The influences of air distributors on the mixing behaviour are reviewed and this chapter also deal with the combustion of a carbonaceous material, which includes drying, de-volatilization and char combustion. Finally, the combustion of wastes such as biomass, refused derived fuel (RDF), high water content wastes, coal in a fluidized bed are reviewed.

Chapter 3 concentrates on the experimental procedures in conducting the ultimate and proximate analysis. It also describes the experimental set-up and procedures during design of standpipes air distributors, bed hydrodynamics studies and combustion tests for both simulated municipal solid waste and actual municipal solid waste.

Chapter 4 discusses the results obtained from the studies of the optimum geometrical design of the standpipes air distributors, bed hydrodynamics and combustion studies.

Chapter 5 reports the concluding remarks derived from this study and proposes recommendations for future studies.

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