DESIGN OPTIMIZATION OF A FIXED BED BIOMASS GASIFIER OF A TWO STAGE INCINERATOR

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A thesis submitted in fulfillment of the

requirements for the award of the degree of

Master of Engineering (Mechanical Engineering)

Faculty of Mechanical Engineering

Universiti Teknologi Malaysia

OCTOBER 2008

ABSTRACT

Waste wood, a renewable energy source is used as feedstock for Universiti Teknologi Malaysia's newly-developed two-stage incinerator system. The research goals are to optimize the operation of the thermal system, to improve its combustion efficiency and to minimize its pollutants formation. The work focuses on one of its components, i.e. the primary chamber which comprises of a large updraft fixed-bed chamber, measuring 187.5cm in height and 194.5 cm in diameter respectively. During experimental work, the primary chamber is fed in batches of the processed feedstock while the air for combustion is metered through an eight air nozzle supply system, incorporated at the lower side of the tapered chamber. The feedstock will undergo four different processes; drying, devolatilisation, gasification and combustion. The combustion process is evaluated with the variation of fuel's moisture content, i.e. set at 17%, 31%, and 40% respectively. The initial experimental work indicates that the temperature and oxide of nitrogen (NO) concentration are decreased with the increase of the moisture in the fuel. Furthermore, the concentration of carbon monoxide (CO) increases with the variation of this operating parameter. However the change for carbon dioxide (CO_2) and oxygen (O_2) concentrations are only around 1% with the variation of this operating parameter. For optimum operating condition, where the gasification efficiency is 95.53%, the moisture content of the fuel is best set at 17%; giving outlet operating temperature of 550^{o}C and exhaust gas concentrations with 1213 ppm of CO, 6% of CO_2, 66 ppm of NO and 14% of O_2 respectively. In parallel to the experimental work, a computational fluid dynamics software is used to simulate the performance of the primary chamber at optimum operating condition. This technique provides detail insights on the dynamics of flow and the combustion behavior that occur in the reference chamber. A steady state model is formulated for the updraft fixed bed reactor. Here the predicted optimum gasification efficiency stands at 95.49% with CO, CO_2, NO and O_2 concentrations as 1301 ppm, 6.5%, 53.7 ppm and 13.5% respectively. The major amendment to the chamber design is proposed on the aspects of air-exit-velocity, i.e. by using smaller diameter of the air nozzles. In doing so, it will create high air-jet penetration in the combustion zone. Higher combustion temperature above 850^{o}C is created for the gasification and combustion zones. This will also reduce NO formation from 54 ppm to 25 ppm at the exit point of the chamber.

ABSTRAK

Sisa kayu, merupakan sumber tenaga diperbaharui telah digunakan sebagai bahan bekalan untuk sistem penunuan dua peringkat yang baru dibangunkan untuk Universiti Teknologi Malaysia. Tujuan penyelidikan ini adalah untuk mengoptimakan operasi sistem terma, bagi meningkatkan kecekapan pembakaran dan meminimumkan pembentukan bahan tercemar. Kerja ini mengfokuskan pada satu dari komponen-komponennya, iaitu kebuk utama yang terdiri dari sebuah kebuk lapisan tetap yang besar berjenis api naik, dengan ketinggian berukuran 187.5 cm dan berdiameter 194.5 cm. Semasa kerja ujikaji, kebuk utama diisi bahan bekalan yang telah diproses secara berkelompok sementara udara pembakaran diukur melalui sistem pembekalan lapan muncung udara, yang digabungkan di bahagian bawah kebuk yang meruncing. Bahan bekalan akan mengalami empat proses berbeza; pengeringan, devolatilisasi, gasifikasi dan pembakaran. Proses pembakaran dinilai dengan perubahan kandungan kelembapan bahanapi, iaitu masing-masing ditetapkan pada 17%, 31%, dan 40%. Kerja ujikaji awal menunjukkan suhu dan penumpuan nitrogen oksida (NO) menurun dengan peningkatan kelembapan di dalam bahanapi. Di samping itu, penumpuan karbon monoksida (CO) juga dilaporkan meningkat dengan perubahan parameter operasi ini. Walaubagaimanapun, perubahan karbon dioksida (CO_2) dan penumpuan oksigen (O_2) hanya sekitar 1% dengan perubahan parameter operasi ini. Untuk keadaan operasi yang optima, dimana kecekapan gasifikasi adalah 95.53%, kandungan kelembapan bahanapi ditetapkan pada 17%; memberi suhu keluaran operasi sebanyak 550^{o}C dan penumpuan gas ekzos masing-masing adalah 1213 ppm bagi CO, 6% bagi CO_2, 66 ppm bagi NO dan 14% bagi O_2. Selari dengan kerja ujikaji, sebuah perisian pengiraan dinamik bendalir, digunakan untuk menyelaku prestasi kebuk utama pada keadaan operasi yang optima. Teknik ini menyediakan gambaran terperinci berkenaan aliran dinamik dan sifat pembakaran yang berlaku di dalam kebuk rujukan. Model berkeadaan mantap diformulasikan untuk reaktor lapisan tetap berjenis api naik. Disini, jangkaan kecekapan gasifikasi yang optima bertahan pada 95.49% dengan penumpuan CO, CO_2, NO dan O_2 masing-masing adalah seperti 1301 ppm, 6.5%, 53.7 ppm dan 13.5%. Pemindaan utama pada rekabentuk kebuk dicadangkan pada aspek kelajuan keluaran udara, iaitu dengan menggunakan diameter muncung udara yang lebih kecil. Dengan sedemikian, ia akan menghasilkan pancutan jet udara yang tinggi di zon pembakaran. Suhu pembakaran yang lebih tinggi melebihi 850^{o}C akan terhasil di zon gasifikasi dan pembakaran. Ini juga mengurangkan pembentukan NO pada titik keluaran kebuk dari 54 ppm ke 25 ppm.

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

The population in Malaysia grows rapidly and the response is expected to reach about 33,095 thousands of people in year 2025 with annual growth rate of 1.4% (U.S Cencus Bureau, 2005). The increasing society generates more waste and incinerator has been seen as one of the ways in reducing the original volume by 95%-96% (Ramboll Gruppen A/S, 2006) solid waste's volume. With an inadequate of available landfill, modern technologies has been applied in many countries as shown in Table 1.1. Incineration as an alternative method in waste reduction involves a thermal-treatment process that is used widely to demolish household waste, clinical waste, hazardous wastes, biomass wastes and others but not completely replace the landfilling method.

The incineration process which involves very high temperature treatment however causes creation of many polluted gases released from the stack to the environment that might harm to human's health. In this research, a numerical work is implemented to describe the combustion process in the incinerator so that the optimization can be done to achieve very low emission due to regulated value with high gasification efficiency.

Table 1.1: Incinerators in some countries (Aziz *et al*., 2002)

Country	Population (million)	Solid waste creation (million tones per year)	Number of incinerators
Switzerland	7	2.9	29
Japan	123	44.5	1893
Denmark	5	2.6	32
Sweden	9	2.7	21
France	56	18.5	170
Germany	61	40.5	48
Italy	58	15.6	51
Malaysia	23	9.0	7
USA	248	180.0	168

1.2 Solid Waste Management in Malaysia

Malaysia is one of the developing countries that faces the same problem pertaining to waste management. Public sector and private contractors are responsible for solid waste management services in Malaysia. Various collection and container systems are used which include both door-to-door collection and indirect collection, with containers or communal bins placed near markets, in apartment complexes, and in other appropriate locations for haulage to transfer stations and disposal sites by special waste vehicles (UNEP, 2002). The solid waste is then disposed according to three categories, i) solid waste disposal and incineration, ii) medical waste incineration and iii) hazardous waste incineration. Open dumping is used and takes place at about 50% of the total landfills (Consumers' Association of Penang, 2001).

Increasing population results in increasing of biomass or waste generation. The rapid growth of population demands for higher landfill. This leads to scarcity in landfill and incineration becomes important waste disposal nowadays. The solid waste generated in 1994 in Malaysia is shown in Figure 1.1. The emerging of this problem has brought out the incineration issue as an important subject to be studied on in this research.

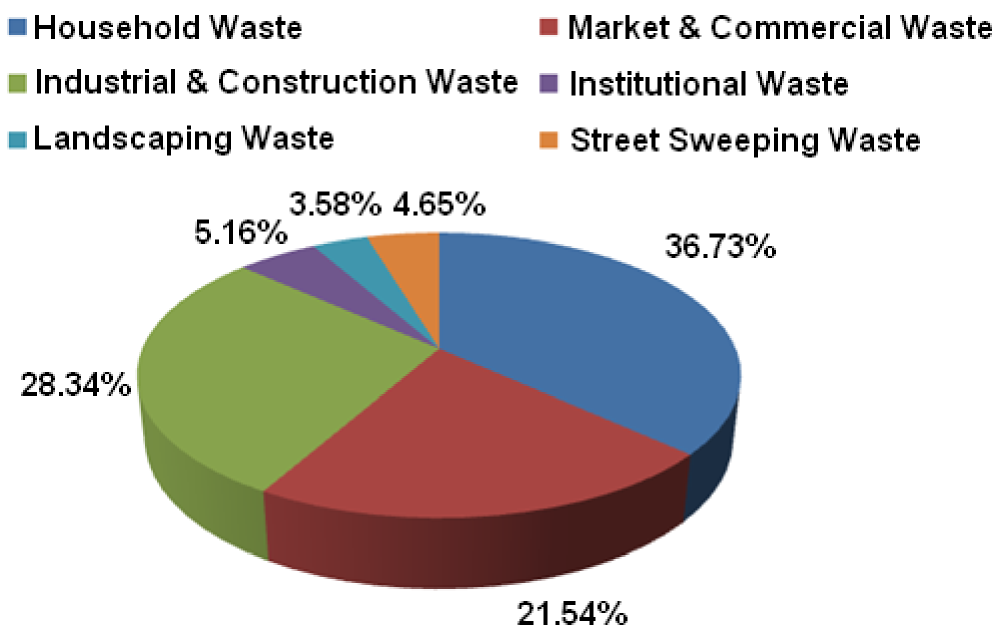

Figure 1.1: Solid waste generated (t/day) in 1994 (Begum *et al.,* 2006)

1.3 Biomass as Renewable Fuel in Malaysia

Malaysia has a tremendous biomass and wood waste resources which mostly comes from the agricultural sector. Biomass nowadays is used as a renewable fuel to run a power plant. As an example, a biomass power plant build up in Perlis is using rice husk as the fuel has a capacity up to 10 MW.

One type of biomass that has been studied here is wood fuel. Wood fuel contains minimal amounts of sulfur and heavy metals. A complex wood structure composed of cellulose, lignin, hemicelluloses, and minor amounts (5% to 10%) of extraneous materials contained in a cellular structure. The wood's proximate and ultimate analysis will be differed due to the geographical location, soil and weather condition.

1.4 Malaysia's Environmental Management

Bring in the incineration technology has rise to controversial issue regarding the by-products of the process to the environment and human's health. The incinerators emit a wide range of pollutants to the air, fly ash and bottom ash depending on the type of waste being burnt, the operating conditions and the pollution control equipment.

Due to the increase awareness of this problem, each country has different regulated level of emissions from incinerators. Malaysia government had established Malaysian Air Quality Guidelines, the Air Pollution Index, and the Haze Action Plan to monitor the air quality released from the incinerator's stack that would not cause significant harm. Figure 1.2 shows the emissions inventories of particulate matter, SO_2 and NO_x by sources in 2004. Meanwhile, the government had come out with the Malaysian Air Quality Standard compared to U.S.A and World Health Organization (WHO) as shown in Table 1.2. This air quality is set regarding on public health (Afroz *et al.*, 2003).

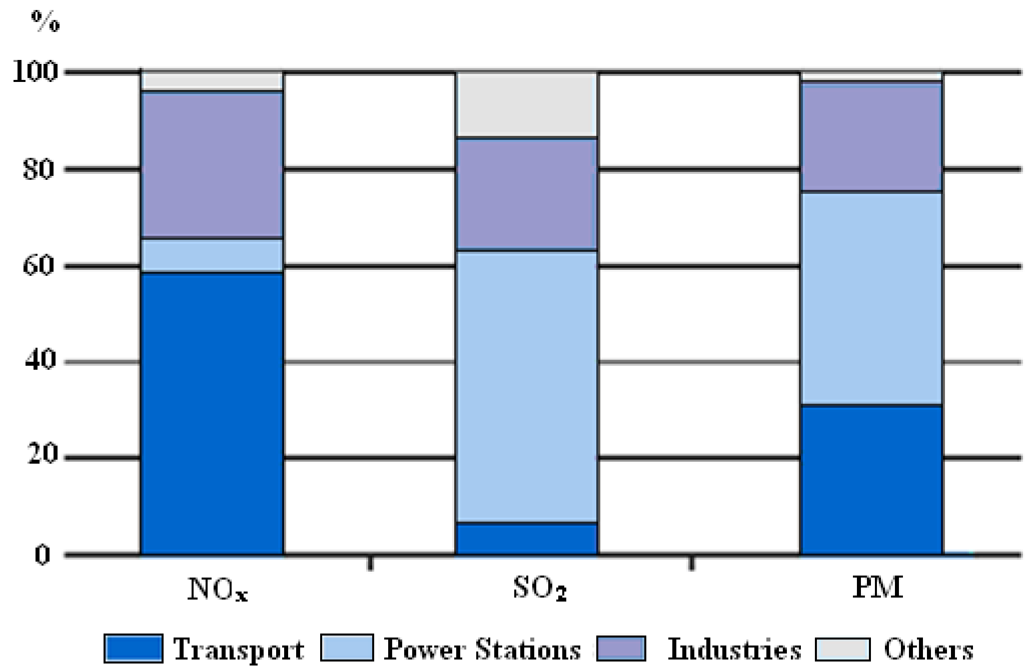

Figure 1.2: Emissions inventories of particulate matter (PM), SO_2 and NO_x by sources in 2004 (tons) (CAI-Asia, 2006)

Table 1.2: Malaysia and WHO 2005 Ambient Air Quality Guidelines (CAI-Asia, 2006)

Pollutant	**Averaging Time**	**Malaysian Air Quality Guidelines**		**WHO (2005)**
		ppm	$\mu g/m^3$	
Sulfur dioxide (SO_2)	1 hr 24 hrs	0.13 0.04	350 105	 20
PM_{10}	24 hrs 1 year		150 50	50 20
TSP	24 hrs		260	-
Nitrogen dioxide (NO_2)	1 hr 24 hrs 1 year	0.17 0.04	320 90	200 - 40
Carbon monoxide (CO)	1 hr 8 hrs	30.00 9.00	35 mg/m^3 10 mg/m^3	
Ozone (O_3)	1 hr 8 hrs	0.10 0.06	200 120	- 100
Lead (Pb)	3 months	1.5		1.5

1.5 Staging of the Universiti Teknologi Malaysia's Incinerator

A two stage incinerator was built in Universiti Teknologi Malaysia in 2000. A two stage method was applied to reduce the emission released through the stack. The air staging means the substoichiometric of air was introduced to the primary chamber while the excess air was introduced to the secondary chamber for complete combustion. However, the incinerator had not performed according to the expectations with good efficiency. Hence, the design of the incinerator had to be optimized to achieve the current regulation in air emission set up by government.

1.6 Sub-System for Optimization

The fixed bed updraft gasifier is the heart of the two stage UTM's incinerator where the main combustion process occurred. Hence, the primary chamber is chosen as the major equipment to study the effect on the overall performance of the system. Gasification process which is among the popular concept today is applied in the primary chamber. Lower emission is the main reason why the gasification method is set as the priority.

In optimizing the current gasifier, a cost-effective technique is chosen through numerical work. Using computational fluid dynamic approach, the whole combustion process is studied so that some data that cannot be measured due to the absence of measuring equipments can be analysed. This includes the temperature and gas concentration at any point inside the gasifier.

1.7 Problems Statement

The current primary chamber is designed without extensive working through numerical studies and experimental work. This study is important as incinerator is seen to be important technology for waste reduction yet will harm to human's health due to the product gases released from the stack. Analysis on the physical model is required to find out the optimum running condition of the incinerator. This research is carried out to provide the incinerator which suitable for performing experimental work. Hence, some analysis should be made so that significant data could be measured and collected to analyse important parameters that affect the incinerator's performance. Only four thermocouples are physically installed in axial position with the help of a stand to hold the thermocouples at predetermined position. However, the position is limited where no thermocouples are located near the grate because this may bring damage to the thermocouples during filling the chamber's with the fuel. The product gases released is experimentally measured at the chamber's outlet.

Hence, numerical analysis is applied to optimize the current gasifier's design using CFD software. The temperature at important zones; reduction and gasification zones which cannot be measured due to the absence of thermocouple could be predicted through numerical work. The distribution of gas concentrations can be analysed during drying, devolatilization, reduction and combustion process in the gasifier and any unmixed region can be identified. This is then used as a key indicator for optimization work.

1.8 Objectives of the Study

The objective of this research is to optimize the operation of the existing incinerator in order to improve its combustion efficiency as well as to minimize the pollutant generated during the combustion process. The optimization process will be done numerically using Computational Fluid Dynamic (CFD) software called FLUENT.

The scopes of the study are:

i) undertaking experimental work by varying the fuel moisture content.

ii) analyzing of toxic emissions released and the gasification efficiency through experimental work.

iii) analyzing the optimum working condition with the existing primary chamber.

iv) providing of a CFD model of the combustion process in the current primary chamber and validation with the experimental work done.

v) optimizing the design of the current gasifier through numerical work with varying air-exit velocity for improving efficiency and lower pollutant formation in terms of the carbon monoxide and nitric oxide released from the system at optimum working condition.