VARIABLES AFFECTING THE COMBUSTION EFFICIENCY OF A CLINICAL WASTE INCINERATION PROCESS

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Jurnal Teknologi, 42(F) Jun. 2005: 11–24

VARIABLES AFFECTING THE COMBUSTION EFFICIENCY OF A CLINICAL WASTE INCINERATION PROCESS

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Abstract. Incineration is known to be the best available option for treating clinical waste, particularly the pathological related waste. A proper operation of the incinerator is essential to ensure complete destruction of the waste. It is anticipated that variables such as feed rate (waste), both the combustion temperatures of the Primary Combustion Chamber (PCC) and Secondary Combustion Chamber (SCC), fuel and combustion air consumption play a major role in affecting the performance of the incineration process. Particularly, the combustion efficiency (one of the performance indicators) of the incinerator determined by the presence of carbon monoxide and carbon dioxide emission after the SCC must be continuously monitored. In this regard, a study to investigate the relationship between variables affecting the combustion efficiency, namely waste, temperatures and fuel, were performed using regression analysis and further verified by ANOVA. Results showed that waste, primary and secondary combustion temperatures contribute significantly to the combustion efficiency of the process. The correlation between these affecting variables were also investigated and discussed in the paper.

Keywords: Incineration process, combustion efficiency, regression analysis, ANOVA

Abstrak. Pembakaran merupakan satu kaedah pelupusan dianggap terbaik bagi pembuangan sisa klinikal terutamanya sisa buangan patologi. Operasi yang cekap bagi sesuatu pembakar itu penting bagi memastikan keberkesanan pemusnahan sisa buangan tersebut. Pembolehubah seperti kadar kemasukan sisa (sisa), kedua-dua suhu pembakaran bagi kebuk pembakaran primer (PCC) dan kebuk pembakaran sekunder (SCC), bahan api dan udara bagi pembakaran memainkan peranan penting dalam mempengaruhi prestasi proses pembakaran. Kecekapan pembakaran iaitu salah satu petunjuk prestasi proses pembakaran yang ditentukan oleh kewujudan emisi karbon monoksida dan karbon dioksida selepas SCC perlulah sentiasa diawasi. Justeru itu, satu kajian meninjau hubungan di antara pembolehubah yang mempengaruhi kecekapan pembakaran seperti sisa, suhu dan bahan api telah dijalankan menggunakan analisis regresi yang ditentusahkan menggunakan ANOVA. Keputusan kajian menunjukkan bahawa sisa, suhu pembakaran bagi kebuk pembakaran primer dan kebuk pembakaran sekunder menyumbang kepada kecekapan pembakaran bagi proses ini. Korelasi di antara pembolehubah ini juga dikaji dan dibincangkan.

Kata kunci: Proses pembakaran, kecekapan pembakaran, analisis regresi, ANOVA

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1.0 INTRODUCTION

In the past, clinical waste did not receive much attention. However, with the emergence of deadly diseases such as AIDS and hepatitis B, it has been the area of increasing concern. In fact, the World Heath Organization (WHO) has initiated a number of activities to improve hospital waste management, particularly in developing countries [1]. In Malaysia, such concern has resulted in clinical waste being classified as a scheduled waste to be controlled under Environmental Quality (Scheduled Waste) Regulations [2].

Clinical waste is defined as any waste which consists wholly or partly of human and animal tissue, blood or any other body fluids, excretions, drugs or pharmaceutical products, swabs or dressings, or syringes, needles, or sharp instruments, being waste which unless rendered safe may prove hazardous to any person coming into contact with it. It also includes such waste arising from medical, dental, veterinary, pharmaceutical or similar practice, investigation, treatment, care, teaching, or research, or collection of blood for transfusion, being waste which may cause infection to any person coming into contact with it.

Incineration is a process in which waste is burned under controlled condition to oxidize the carbon and hydrogen present in the waste. It is known to be the best available option for treating such wastes particularly the pathological related waste. It has the advantage of converting waste into inert or less infectious material and at the same time reduces its volume up to 95% of its original size. Although incineration is a preferred method of treatment, air impurities associated with the burning of the waste is a major concern to the public.

However, there is a rising sentiment that waste incineration has serious drawbacks. While waste burn, chemical transformation is taking place. Formation of organic compounds even at a very low concentration is found to be toxic [3]. Polychlorinated dibenzo-p-dioxin (referred to as dioxin) and polychlorinated dibenzofurans (or furan) are two such toxic combustion products and, according to the United States Congressional Office of Technology Assessment [4], concentrations of both dioxin and furans are considerably higher in hospital incinerator fly ash than in municipal incinerator fly ash.

Therefore, a strict operational condition in which the waste is burned inside the incinerator must be adhered. As such, the performance of an incinerator must be regulated through its combustion efficiency, namely carbon monoxide and carbon dioxide gaseous, to ensure complete burnout of the waste [5].

Rashid *et al.* [6] studied that the performance of the clinical waste incinerator meets its criteria of destruction and removal efficiency (DRE) of greater than 99.9999%. However, the underlying factors affecting the performance were not reported in their study. This paper discusses the use of statistical analysis to identify the variables affecting the destruction efficiency i.e. the combustion efficiency of the clinical waste incineration process. Regression analysis and Analysis of Variance (ANOVA) are chosen to study the relationships between the variables.

2.0 CLINICAL WASTE INCINERATOR

In this study, data obtained from a regional clinical waste incinerator facility in Melaka, owned by Pantai Medivest Sdn Bhd (formerly known as Tongkah Medivest Sdn Bhd) was investigated. The schematic diagram of the facility is shown in Figure 1. The clinical waste incineration plant consists of both the combustion unit and the air pollution control system. The former serves as the destruction unit whilst the latter serves to clean the air impurities originating from the combustion unit. The combustion unit comprises of Primary Combustion Chamber and Secondary Combustion Chamber.

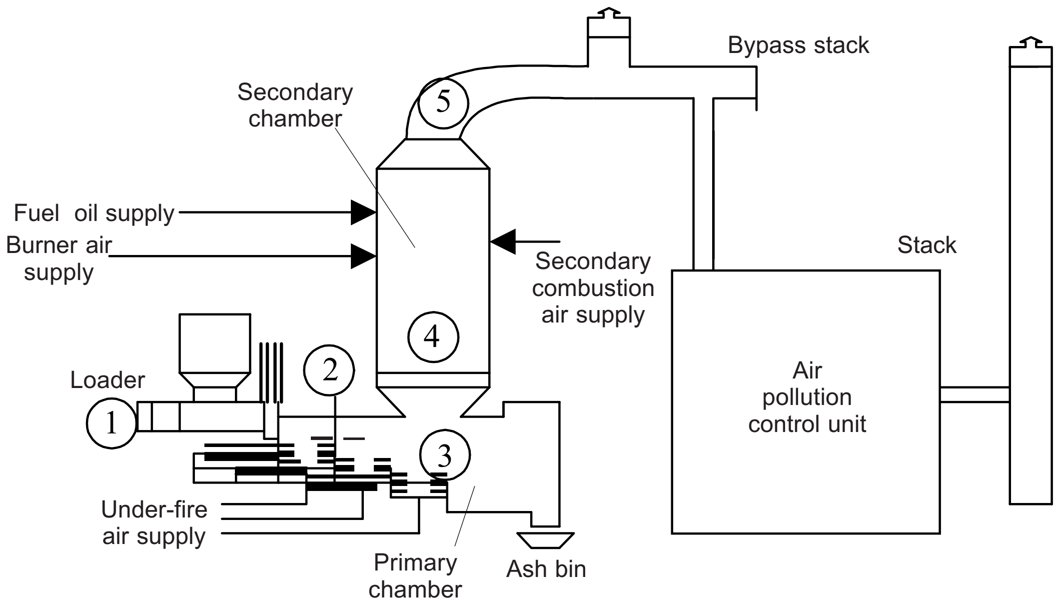

Figure 1 The schematic diagram of a clinical waste incinerator

Preliminary study by Sabariah *et al.* [7] to investigate the flow of the incinerator has initiated this work to resolve the following potential variables affecting the combustion efficiency. Clinical waste is a vital input for the incinerator. The waste was collected from various government or private hospitals and clinics throughout the southern region. It was a heterogeneous mixture of general refuse, laboratory and pharmaceutical chemicals, containers, pathological wastes and cytotoxic wastes. Even though the waste composition being fed into the incinerator was not the same throughout the process, it was anticipated that the amount of the waste did contribute

Table 1 Characteristics of waste burned

Material	Percent
P.V.C.	3
Pathological	5
Plastics other than P.V.C.	33
Paper including waxed paper	30
Hospital dressings, swabs,etc.	10
Miscellaneous (including flowers, rags etc.)	10
Non-combustible including glass, metal etc.	10

to the performance of the process. Table 1 presents a typical waste characteristic that is being incinerated by the facility [8].

The waste was weighted before they were fed into the combustion chamber using a hydraulic powered bin tippler at the rate of 250 kg/hr. The waste was tipped into the incinerator loading hopper into the incinerator every 10 to 12 minutes.

The primary chamber is a stepped hearth type which consists of three stationary hearths on which the waste burns. The stepped hearth utilizes a series of rams to slowly push the waste material through the incinerator onto the hearth for a complete ash-burnout. Each hearth is equipped with an ash pusher for the purpose of pushing the burning materials and clinker from the hearth. Each zone of the hearth is equipped with modulating combustion air supply. This allows total flexibility allowing the incinerator to operate efficiently as the properties of the waste may change in the future.

The final stage of the stepped hearth incinerator is the burnout hearth where carbonaceous matter generated in the controlled air environment is contacted with excess air to burn out the carbon to an acceptable level. As the waste is pushed through the incinerator, it progressively burns to ash. The incinerator combustion ashes are discharged from the primary chamber into water sealed trough for immediate quenching. These ashes are then removed from the trough by ash conveyor.

Temperature control within the primary chamber is critical to prevent the melting and subsequent fusion of glass. The use of the stepped hearth type primary combustion chamber allows such temperature control. The primary chamber is constructed from a mild steel casing internally lined with refractory firebrick capable of withstanding in excess of the operating temperatures of 800°–1000°C. Waste solids retention time in the primary chamber is in the range of 2–8 hours. Here, the temperature at the first and second hearths is denoted as T1 and the temperature at the third hearth is denoted as T2. These are temperatures acquired within the primary chamber.

Whilst the incinerator primary chamber can operate under reducing or oxidizing modes, it is generally recommended that reducing conditions be maintained. Clinical waste being volatile and of high energy content is well suited to reduce air operation commonly known as controlled air or starved air operation, involve using less than the required quantity of combustion air necessary for complete destruction in the primary chamber. By starving the process air, the volatile components of the waste are gasified. The combustible gases produced can be considered to be a fuel and are mixed with air and completely combusted in the secondary chamber after ignition by a diesel burner in the ignition chamber [9].

The exhaust gases known as the product of combustion from the primary combustion ignition chamber are drawn into the secondary combustion chamber. Temperature exiting the primary chamber into the secondary chamber is taken as T3. This zone is equipped with auxiliary diesel fuel burners. An auxiliary fuel burner is used to maintain the secondary combustion chamber temperature. The fuel is injected into the secondary chamber along with the burner air supply. Combustion efficiency is assured by operating the secondary combustion chamber at $\geq 1000°C$ whilst maintaining an oxygen rich environment. The burners will re-ignite the partial products of combustion emitted from the primary chamber and raise the temperature of the gases to in the excess of 1000°C. An efficient secondary chamber is essential to minimize emissions of dioxins and other products of incomplete combustion.

The secondary chamber is designed to provide a secondary chamber retention time of at least two seconds at a temperature of 1000°C, and is capable of achieving destruction efficiency of at least 99.99%. Combustion air is supplied by the secondary combustion air fan and is controlled to maintain an oxygen level of not less than 7%. The performance of the combustion process is continuously monitored through the flue gas analyzers and the temperature T4 measured at the exit of the secondary chamber.

The online gas analyzers are continuously measuring the emissions of oxygen (O_2), carbon monoxide (CO) and carbon dioxide (CO_2) concentrations immediately after the SCC. The concentrations of these gases play determine the performance of the incineration process. In particular, the combustion efficiency of the incineration process is determined by both the concentration of CO and CO_2 formed in the combustion unit. The combustion efficiency (CE) is calculated by the following equation [5]:

$$\mathrm{CE} + \frac{\mathrm{CO_2}}{\mathrm{CO_2} + \mathrm{CO}} \times 100\% \tag{1}$$

On the other hand, the O_2 level serves as an indicator of whether enough air is fed into the system for complete combustion. The concentrations of these gases are routinely recorded in the daily operation of the plant. The plant ensures that its combustion efficiency performance is maintained at least 99% at all time.

Carbon monoxide, CO, is produced when there is insufficient amount of O_2 in the combustion chamber. The greater the amount of air present and the higher degree of turbulence, the less CO will be formed. Unfortunately, turbulence as a combustion parameter cannot be easily quantified. Hence, only the amount of air present (indicated by the amount of O_2 emitted), and the combustion temperatures affecting the equilibrium constant and the relationship of CO and CO_2 produced is being considered [10].

3.0 METHODOLOGY

An hourly operational data for the whole year of 1999 was investigated in this study. A total of 100 sets of hourly observations were used in the analysis. The rationale made in the selection of variables for the study along with a simple note on the regression analysis and the analysis of variance [11] is briefly discussed in this section.

3.1 Selection of Variables

Based on the discussion given in Section 2.0 on the influential variables of the clinical waste incineration process, the variables that are thought to contribute to the performance of the process were determined (as shown in Table 2).

Table 2 Variables and its measured location

Parameters	Measurement location	Position as shown on Figure 1
Waste	Entrance of PCC	1
Temperature 1 (T1)	First and second hearth of PCC	2
Temperature 2 (T2)	Third hearth of PCC	3
Temperature 3 (T3)	Inlet of SCC	4
Temperature 4 (T4)	Outlet of SCC	5
Fuel	At SCC	4
Oxygen (O_2)	After SCC	5
Carbon monoxide (CO)	After SCC	5
Carbon dioxide (CO_2)	After SCC	5

Carbon monoxide, an indicative of burning or combustion efficiency, is produced where insufficient oxygen is provided to completely combust a fuel. This is also shown by Equation (1) whereby the value of CO that make a difference to the calculated value of CE, hence making it a determining variable of CE. Thus, variable CO was taken to be the dependent variable of our regression model. The variables

Table 3 Dependent and independent variables of the regression model

Dependent variable	Independent variables
	Waste
CO	T1
	T2
	T3
	T4
	Fuel

such as Waste, T1, T2, T3, T4, Fuel, and O_2 were taken as the independent variables of the model. However, O_2 contributes to the formation of CO_2 and CO. Therefore, by putting O_2 as an input variable would make the resulting model to be monopolized by this particular variable. Eventually, O_2 was disregarded from the independent variables list. Table 3 summarizes the selection of variables for the regression model as based on discussion in Section 2.0.

3.2 Statistical Method

3.2.1 Regression Analysis

A regression analysis may have two different goals: to predict the dependent variables by using a set of independent variables and to quantify the relationship of one or more independent variables to a dependent variable. This paper attempts to produce accurate estimates of one or more regression coefficients in the model.

The simplest form of general regression problem deals with one dependent variable Y and one independent variable X. The analysis begin by trying to find the curve (which can be of a straight line, parabola etc.) that best fits the data, which closely approximate the true but unknown relationship between X and Y. When there is more than one independent variable involved, the interactions between these independent variables have to be considered. Interaction is the condition where the relationship of interest is different at different levels of the extraneous variable(s). For example, if the interaction involving three variables X_1, X_2, and X_3 is of interest, one model to consider is:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_1 X_2 + \beta_5 X_1 X_3 + \beta_6 X_2 X_3 + \beta_7 X_1 X_2 X_3 + E \quad (2)$$

The 2-factor products of the form $X_i X_j$ are often referred to as first-order interactions, and the 3-factor products, like $X_1 X_2 X_3$ are second-order interactions and so on for higher products. The higher the order of interaction, the more difficult it becomes to interpret its meaning. Statistical testing can be used to evaluate interaction for a given regression model. One approach is to test for interaction beginning with the highest-order terms.

Several general strategies can be used to study the relationship between two variables by means of regression analysis. The most common is the forward method, which begins with a simple structured model, usually a straight line and adds more complexity to the model in successive steps. The other strategy is the backward method, which begins with a complicated model and then successively simplifies it usually by eliminating unnecessary terms.

3.2.2 Analysis of Variance (ANOVA)

Once a multiple regression model has been obtained together with the estimates of the various parameters of interest, the contributions of various independent variables to the prediction of Y have to be clarified. Such situations raise the need for three basic types of tests:

(i) Overall test.
This is to see whether the entire set of independent variables (or equivalently the fitted model) contribute significantly to the prediction of Y.

(ii) Test for addition of a single variable.
This is to affirm whether the addition of one particular independent variable of interest add significantly to the prediction of Y achieved by other independent variables already present in the model.

(iii) Test for addition of a group of variables.
This test is to see whether addition of some group of independent variables of interest add significantly to the prediction of Y obtained through other independent variables already present in the model.

Each of these tests can be expressed as an F test. All F test used in regression analysis involve a ratio of two independent estimates of variance. An overall summary of the results of any regression analysis, whether straight line or not, can be provided by a table called an ANOVA table. This name derives from the fact that the basic information in an ANOVA table consists of several estimates of variance.

R^2, known as the coefficient of determination, provides a quantitative measure of how well the fitted model containing the independent variables of interest predicts the dependent variable. The quantity R^2 lies between 0 and 1. If the value is 1, the fit of the model is said to be perfect. R^2 always increases as more variables are added to the model, but a very small increase is not practical nor it is statistically important.

4.0 RESULTS AND DISCUSSION

Two regression models as in Model 1 and Model 2 are considered for the clinical waste incineration process to identify the variables affecting the process. The models are investigated by omitting the intercept, which means that the intercepts are taken to be zero. This is with an assumption that there will be no value for the dependent variable when the values of the independent variables are zero. Thus, the performance or the combustion efficiency of the incineration process could not be determined if the process does not run. The two types of regression models considered are:

(a) When there are no interactions between the variables

Model 1

$$CO = \beta_1 Waste + \beta_2 T1 + \beta_3 T2 + \beta_4 T3 + \beta_5 T4 + \beta_6 Fuel + E$$

(b) When there are interactions (first order interactions) between all the variables

Model 2

$$\begin{aligned} CO = {} & \beta_1 Waste + \beta_2 T1 + \beta_3 T2 + \beta_4 T3 + \beta_5 T4 + \beta_6 Fuel + \beta_7 WasteT1 \\ & + \beta_8 WasteT1 + \beta_9 WasteT2 + \beta_{10} WasteT3 + \beta_{11} WasteT4 + \beta_{12} WasteFuel \\ & + \beta_{13} T1T2 + \beta_{14} T1T3 + \beta_{15} T1T4 + \beta_{16} T1Fuel + \beta_{17} T2T3 + \beta_{18} T2T4 \\ & + \beta_{19} T2Fuel + \beta_{20} T2T3 + \beta_{21} T2T4 + \beta_{22} T2Fuel + \beta_{23} T3T4 \\ & + \beta_{24} T3Fuel + \beta_{25} T4Fuel + E \end{aligned}$$

with E taken as the error term.

With these considerations and by using Statistical Package S-Plus 4.5, we obtained the following results, as illustrated in Table 4.

Table 4 Comparison between types of models considered

Model	**Consideration made**	**R^2**
Model 1	By using all data	0.9609
	By discarding 3 outliers	0.9641
Model 2	By using all data	0.9641
	By discarding 3 outliers	0.9680

Table 4 shows that the differences in the values of R^2 for the two types of models are very small (≈ 0.004). This indicates that the increment of the adequacy of the model is minimal. Therefore, for simplicity and by the law of parsimony, Model 1 by discarding 3 outliers is considered. A simpler regression model with no interactions between the independent variables is sufficient in representing the system as compared to its more complex relationships between the variables. This resulted in the following regression model to quantify the relationship of the independent variables to the prediction of the dependent variable of the clinical waste incineration process as specified in Table 3 and using Model 1.

$$CO = 0.675Waste + 0.5062T1 - 0.0042T2 + 0.2751T3 + 0.1236T4 + 0.0132Fuel \quad (3)$$

The residual plot shown in Figure 2 indicates that the residuals plotted against fitted values are within a horizontal bar against the graph. This suggests that the fitted model with the assumption of equality of variance is correct. In other words, this shows that the model is adequate for the system. The plot of the observed value CO against the fitted values of independent variables is shown in Figure 3. It can be seen that there is a band across the graph with roughly equal vertical width for all values of the independent variables. This again suggests that the assumption of equal variances of the dependent variable CO is correct. Again, this supports that the model is adequate for the system.

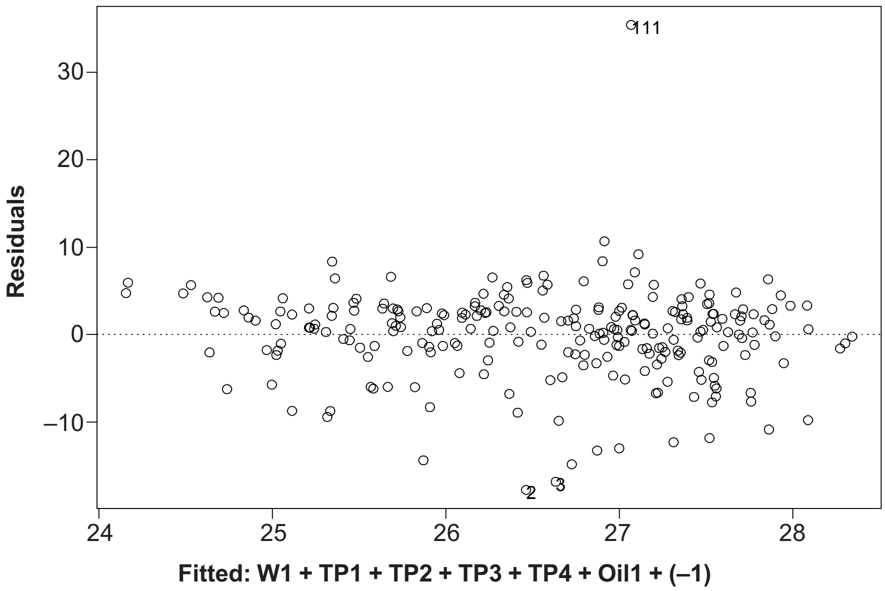

Figure 2 Residual plot

From Figures 2 and 3, there still exist few outliers which can be removed from the data. This removal of outliers is anticipated to improve the model further. Even though there was equality of variances in both figures, still the range was wide. This phenomenon was probably due to the forcing of the regression model through the

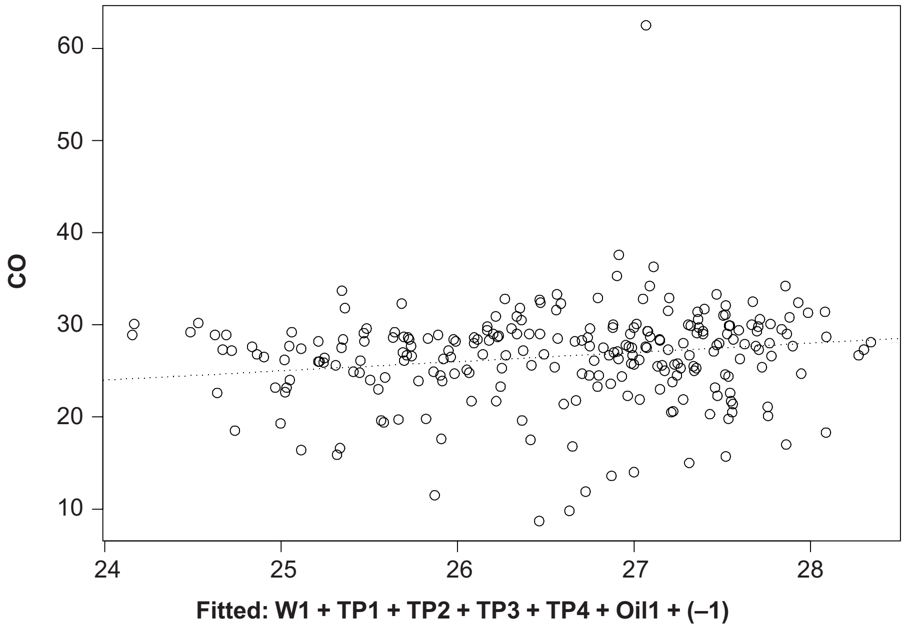

Figure 3 CO vs Fitted line

origin. Actually, a lot more tests could be done to attain a better model for the clinical waste incineration process, but the model obtained here is seen to be adequate for the system. This is especially when it is a complex system such as this one.

To verify the significant contribution of each of the independent variable to the prediction of CO, the ANOVA Table represented in Table 5 was analyzed. This table shows that the values of Pr (F) < 0.05 were attributed by the variables waste, T1 and T3. This means that these three values are significantly contributing to the value of CO emitted in the clinical waste incineration process [11]. This in turn implies that these three variables are also the contributing variables to the combustion efficiency of the process.

Table 5 ANOVA table

Variables	Degree of freedom	Sum of squares	Mean squares	F Value	Pr (F)
Waste	1	170871.6	170871.6	63333.553	0.0000000
T1	1	3622.7	3622.7	134.278	0.0000000
T2	1	1.7	1.7	0.063	0.8013165
T3	1	128.1	128.1	4.749	0.0302882
T4	1	7.9	7.9	0.294	0.5878706
Fuel	1	1.1	1.1	0.039	0.8432877

Table 6 Correlation of coefficient

	Waste	**T1**	**T3**
Waste	1.0000	0.1432	0.0535
T1	0.1432	1.0000	0.3690
T3	0.0535	0.3690	1.0000

Apart from knowing that the waste, T1 and T3 were affecting the combustion efficiency of the clinical waste incineration process, the relationships between these variables were also investigated. Their relationships were interpreted by the correlation of coefficient between the variables presented in Table 6. These variables were not significantly correlated except for T1 and T3, which illustrated the notion of multicollinearity between them. The finding suggests that other technique of analysis such as ridge regression approach would give a better representation of the combustion efficiency model [12].

Nevertheless, the correlation between these variables did provide explanation to the relationship between them. The correlation between the waste and T1 illustrates that as the weight of the waste increases, meaning that more waste are feed into the incinerator, the temperature in the first and second hearth of the primary chamber of the incinerator would also increase. The waste serves as the fuel to the process wherein its input would increase the amount of fuel to the chamber, which would eventually increase the temperature. A low correlation between the variables was probably due to the starved air mode of operation of the incinerator and also due to the heterogeneous nature of the waste input.

The fact that T3 was located further away from the point entry of waste into the incinerator as compared to T1, resulted in the correlation between the waste and T3 insignificant. However, the positive value of the correlation indicates that the increase in the amount of waste would also increase the temperature of T3. This is in accordance to the increase in the temperature T1 would also increase the temperature of T3 as shown by the positive value of the correlation between the variables. The correlation between T1 and T3 is slightly higher due to the reasons explained earlier.

5.0 CONCLUSION

A study to investigate factors affecting the combustion efficiency of a clinical waste incineration process revealed that waste, primary combustion temperature (T1) and secondary combustion temperature (T3) play an important role to this effect. A regression model explained the combustion efficiency related to the variables. However, the existence of multicollinearity between T1 and T3 indicates that improvement to enhance the representation of the relationship could further be investigated. Nevertheless, the study provides a better understanding of the variables affecting the combustion efficiency vis-à-vis the performance of the incinerator.

ACKNOWLEDGEMENTS

This study is part of a research funded by the Research Management Centre, Universiti Teknologi Malaysia, with vote number 71904.

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