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The design of a portable municipal waste incinerator with fuzzy logic based support for emission estimation

Jude C. Akpe[1]*, Olatunde Ajani Oyelaran[2], Ibrahim Onuwe. Abdulmalik[1]
[1]Hydraulic Equipment Development Institute, Kumbotso - Kano, Nigeria
[2]Department of Mechanical Engineering, Federal University, Oye –Ekiti, Nigeria
*Corresponding author email: akpe213@yahoo.com

Abstract - A fuzzy logic interface system to estimate oxygen requirement for complete combustion as well as the level of pollution from incinerator gas flue in order to manage solid waste from domestic, institutional, medical and industrial sources was designed. The designed incinerator is double chambered operating with a maximum temperature of 760 °C in the lower chamber and 1000°C in the upper chamber. The insulating wall is made up of a refractory brick of 55mm in thickness having a 2mm thickness low carbon steel as the outer wall. Hydrogen Chloride (HCl) and Nitrous oxides $(NO)_x$ are the gases was used to demonstrate the Fuzzy Inference System (FIS) model. The FIS was built with five input variables (Food, PVC, Polythene, Paper and Textile) and three input variables with two membership functions. The FIS was developed to estimation the degree of possibility distribution of pollution that should be expected when a certain composition of waste is incinerated. The plots of composition of waste high in food against oxygen require for combustion gives a possibility distribution of about 0.9 which is high according to the fuzzy set definition while the plot of waste composition high in PVC against HCL shows linearity.

Introduction

Design is generally regarded as a creative process by which new methods, devices, and techniques are developed to solve new or existing problems (Yogesh, 2008). During engineering design, the engineer based his/her decision on particular parameters and the decision variables and constraints. Most times, the decision about certain characters is based on manufacturer's catalogue. The basic approach to the design process, starting with the formulation and concept, the design calculation for a portable municipal waste incinerator have been presented, followed by fuzzy knowledge based support of the gas emission estimation. This research considered the design of a 60kg of waste incinerator with fuzzy knowledge base approach to emission estimation. This is a non-traditional design methodology based on experience, informal approaches, information on existing systems, current practice, and the use of linguistic variable to represent vague terms and imprecision. The main elements of this method and the overall scheme are outlined, followed by representations of parameters used in incinerator design to demonstrate the power and usefulness of this approach. Also considered are some additional important issues with respect to fuzzy logic inferring system, such as different type of membership functions, the minimum (AND) operation and minimum (OR) operations. An overview of the design of portable waste incinerator is also presented.

Waste combustion or incineration is a controlled burning process done essentially to prevent air pollution that results from open air burning (Kwawukume, 2008, Knox, 2005, Ontario Ministry of the Environment, 1986). The indiscriminate dumping of refuse poses severeenvironmental, health and aesthetic hazards including blocked drainage channels, spreading of epidemics, dumbing site providing breeding ground for rat and the likes (Kwawukume, 2008, Josiah *et al,* 2004). In developing countries like Nigeria, most undeveloped plot is turned into a refuse dump even among well plan residential estates.

(Kadafa *et al,* 2013). In developing countries, attempt such as the use of collecting agencies to dump waste in a dedicated site have not been so successful. The volume of solid waste being generated continues to increase at a faster rate than the ability of the agencies to improve on the financial and technical resources needed to parallel this growth (Ogwueleka, 2009). Incinerators are used to control open air burning basically to reduce air pollution and sometimes where its convenience, energy recovery is practice (Annunziato, 2006). In spite of the control burning that is supposed to take place with the use of incinerator, air pollution still takes place. To monitor and limit to formation of hazardous gases with the use of incinerator, various technique have been used. The incineration of municipal waste involves the limit generation of climate-relevant emissions (Johnke, 2014). These are mainly emissions of CO_2 (carbon dioxide) as well as NOx (oxides of nitrogen), NH (ammonia), HCl (Hydrogen Chloride), Sulphur Oxides and organic C, measured as total carbon. To control pollution emission from incinerator, the use of Air Pollution Control (APCs) and scrubbers are incorporated into the design cof incinerator. Though this has reduced emission of pollutants, it has not completely eliminated pollution. To estimate emission, calculations are done using standardized conditions: percentage of oxygen, dry gas, and temperature and atmospheric pressure (Johnke, 2014). Statistical forecasting models such as the geometry average method, saturation curve method, least-squares regression method, and the curve extension method can be used. These methods however, are designed based on the configuration of semi-empirical mathematical models (Chen, 2000). The structure of these models is simply an expression of cause–effect or an illustration of trend extension in order to verify the inherent systematic features that are recognized as related to the observed database. But the imprecise nature of waste composition and the level of approximation employ by the use these methods make these methods less desirable. Another drawback of these methods is the fact that these methods are in-effective under uncertainty environment and while dealing with non-homogenous data (Chen, 2000). Waste composition is not homogenous as it varies from day to day and from place to place. The composition cannot be stated at any given time with a clear certainty. Since fuzzy logic allow the use of vague terms and allow partial membership of set between regions within a set and region completely outside a set (Yen, 2010), waste composition with it inherent uncertainty can best be dealt with Fuzzy logic. For handling non-homogenous data, fuzzy seasonality forecasting technique was proposed (Chang, 1997). And for working with heterogonous data and under uncertain environment, Fuzzy Logic provides a better way.

The heat energy requirement for incinerator operation entirely depends on the combustion process. Combustion dictionary definition has it as chemical reaction of two or more substances with a characteristic liberation of heat and light; which is commonly called burning. The burning of a fuel (e.g., wood, coal, oil, or natural gas) in air is a familiar example of combustion. Not all combustion involves oxygen; e.g., hydrogen burns in chlorine to form hydrogen chloride with the liberation of heat and light characteristic of combustion. Combustion reactions involve oxidation and reduction. Before a substance will burn, it must be heated to its ignition point, or kindling temperature. The design of the incinerator has air inlet holes which freely allow flow of air into the burning chamber. Also accommodated in the design is the area of air hole channels. The air aperture size is more than enough to feed the material for effective combustion. Extra heat source (Fire) from a match stick is usually needed to start the burning

$$C_6H_{10}O_5 + 6O_2 \rightarrow 6CO_2 + 5H_2O + heat$$
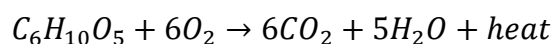
In normal operation, sufficient oxygen is served by natural induction through the air apertures where it meets with fuel and heat so that a complete combustion is experienced in the primary and secondary chambers. Oxygen starvation often leads to partial combustion of the carbon to CO rather than CO_2: Hydrogen will normally burn to H_2O. Secondary combustion will take place if the CO and other intermediate products meet with oxygen or non- depleted air at a sufficiently high temperature for gaseous combustion to CO_2 to take place. In an open fire, this secondary combustion can be observed as "flames" immediately above the burning material, as fresh air is drawn in to the zone by convection. Since combustion effectiveness is also a function of gas residence time (defined as the ratio of total combustion chamber volume to gas volume flow), it is important that the air volume flow is not too great, otherwise the incinerator dimensions would need to be increased with consequent cost penalties.

Municipal Solid Waste (MSW) is generated by households and other similar wastes in nature and composition, which in general is collected and managed by or on behalf of municipal authorities, and includes materials such as paper, plastics, and food, glass and household appliances. Fig. 1 shows typical

composition of MSW usually associated to these waste streams, based on Gentil *et al.* (2009). But in country like Nigeria, this table might be different. In places like school and administration office block, you may have more of paper waste than any other component of waste. Eatery and places like abattoir will be expected to have more organic waste that any other place. Waste composition is a major factor in incinerator design. It influences the heat release per kilogram of waste also the type of gas flue that should be expected from burning.

Incinerator are used to control open air burning basically to reduce air pollution and sometime where it convenience, energy recovery is practice. In spite of the control burning to that is supposed to take place with the use of incinerator, air pollution still take place. This had led to stringent emission control measure in places in the developed world where incinerators are in used. Uncontrolled burning leads to serious air pollution and if measures are put in place to check the effect of these gases coming from incinerator stack, air pollution will occur. Unfortunately in developing countries, uncontrolled burning happens all the time. Therefore there is need to take cognizance of the composition of waste being burn at a particular time in order to know what to expect as gas flue. The incineration of municipal solid waste generates a number of air pollutants including particulate matter, hydrogen chloride, oxides of nitrogen and sulphur, carbon monoxide, hydrocarbons and small to trace quantities of many other materials. All these substances are pollutant when release above certain amount cause serious pollution problem.

Fuzzy logic deals with uncertainty in engineering by attaching degree of certainty to answer of logical question. The term fuzzy has been used in two different senses (Yen, 1999). It is therefore important to clarify the distinction between these two different usages of them. In the narrow sense, fuzzy logic refers to a logical system that generalizes classical two-valued logic for reasoning under uncertainty. In a broad sense, fuzzy refers to all of the theories and technologies that employ fuzzy set, which are classes with unsharp boundaries. Fuzzy logic is much more general than traditional logical systems. The greater generality of fuzzy logic is needed to deal with complex problems in the realms of search, question-answering decision and control. Fuzzy logic provides a foundation for the development of new tools for dealing with natural languages and knowledge representation (Zadeh, 2004). Fuzzy logic allow vagueness to be better represented where otherwise would have been difficult to represent. Membership Functions are curves that define how one value (decision) belongs to a set of values previously determined or to an interval of possible answers. Membership functions can be Triangular, Trapezoidal, Gaussian, etc. Trapezoidal and Triangular membership functions are the most commonly used among the membership (Yen, 1999).Emissions from incinerator are not crisp. There are in ranges with no clear cut boundaries between. The emission also depends on the composition of waste. It is very difficult to know for certainty what to expect with regard to emission as the composition of waste cannot be known with sure certainty. So, with the fuzzy nature of waste and the emission produced when burnt, there is need to incorporate a component that can estimate expected emission in the design in portable waste incinerator. It is expected that certain composition of waste produces certain type of emission. The criterion for choosing or determining waste composition should be a flexible function capable of manage different criteria. The performance should of incinerator should be based on the how little the gas flue from the stack interact with the atmosphere. These values are defined out of the control context and it constitutes an immediate and powerful instrument to monitor the good operation of incinerator with an index in the range (0, 1). The definition of this index is obtained by means a problem specific multi-objective approach and it represents the global formalization of the goals we want to fulfil. In this way, in order to combine conflicting constraints and objectives into a unique performance index, we defined a proper combination of fuzzy sets on estimated amount and composition of waste to be expect in a particular place.

Material and Method

This study was carried out in two parts: (1) The design of incinerator and (2) development of fuzzy inference model for estimating pollution from incinerator stack. In achieving this, the following steps were taken. Determination of amount of waste and it composition by mass, Conceptual design, Characterization and sorting of expected wasted from different location and its expected composition of gas emission and Development of a fuzzy logic inference system for estimating the level of pollutant emitted from incinerator gas stack

The Incinerator Design

The incinerator was designed to be charged manually with a de-ash door and ashtray that allow for easy removal of ash. The waste is ignite with the aid of a burner at the primary chamber. The auxiliary burner in the secondary chamber is to re-burn products coming from the primary chamber.

Primary Chamber

The primary chamber is designed to have heat release of 900,000 kJh⁻¹ m⁻³ (kilojoules per hour per cubic meter) (Ministry of Environment, Ontario, 1986). The total expected heat release from waste is 1,101,471.85 kJ (see table 1). 1.3 cubic meters was gotten as the volume.
Using volume of cylinder, where *l is the length and r is the radius.*

$$v = \pi r^2 l$$

Length = 1meter (taken)
1.2 meters was gotten as the base diameter.

Secondary Chamber

The secondary chamber was designed to have a gas resident time of is 1.3 seconds. Assuming product have the property of dry air, ideal gas law was used to calculate the volume of the secondary chamber. The calculated volumetric flow rate of dry products was 1.168m³/s. The calculated flow rate for total moisture was 0.168m3/s. Therefore the total volumetric flow rate is $1.33 m^3/s$.

Thickness of insulator (inner wall)

To prevent heat lost and maintain outside temperature at 31°C (taken as ambient temperature), a refractory brick (fire clay) is used. From basic principle, the conduction heat flow through a homogeneous medium, the rate of heat transfer is $Q = -kA\frac{dt}{dx}$ (Kumar, 2013)
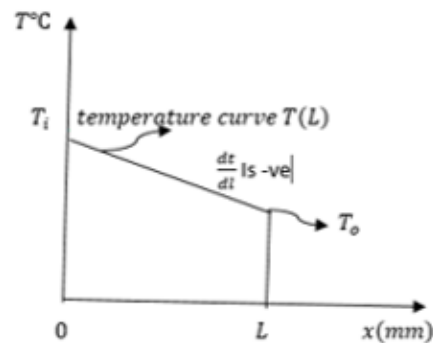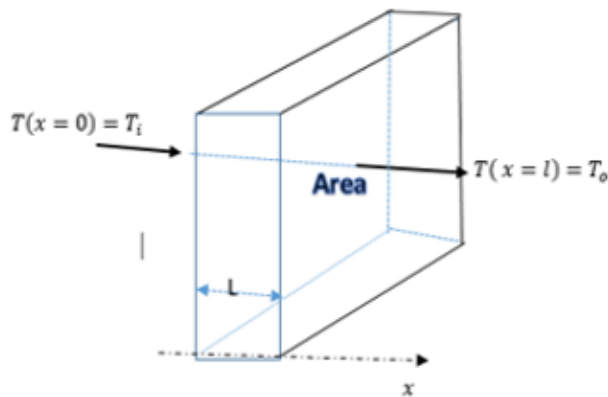
$$\frac{Q}{A} = \frac{t_1 - t_2}{L/k}$$

Fgure1 Heat conduction through a layer of brick   Figure2 Heat through distance L in x direction

T = T(x) steady flow in X direction
$$T(x = 0) = T_i \, and \, T(=\text{L}) = T_o$$

Boundary condition (assuming no convective boundary). The value of the thickness L was determined and 0.0494 meter was gotten. Therefore the thickness of the inner wall was taken as 50millimeter. The combustion air was supplied by a blower installed at the back of the incinerator and the air flowed through runner pipes to both chambers. The amount of air at 21 percentage oxygen was calculated. The flow rate was controlled with the aid of a butterfly valve to match the air control principle. A summary of the essential designed parameters are shown in Table 2.

Table 1. Waste constituent by % mass and high heating value

	Constituent	Percentage	Mass (Kg)	Higher Heating Value (KJ/kg)	Total heat (MQ) (KJ)
1	Food	53.39	32.03	19,228	615,876.84
2	PVC	7.45	4.47	22,630	101,156.1
3	Polythene	13.15	7.88	46,304	364,875.52
4	textile	3.03	1.8	9,270	16,686
5	Paper	22.89	13.73	18,119	24,877.39
	Total	**100**	**60**		**1,101,471.85**

Source: (Ministry of Environment, Ontario, 1986)

Table 2: Designed Parameters of Incinerator

|	
Capacity	60kilogramm
Charging rate(when necessary)	20kg/minute
Primary chamber	1.2m^3
Secondary chamber	1.3m^3
Insulator thickness	0.05m
Expected heat release from waste	1,101,471.85kJ
Amount of stoichiometry oxygen require	100.5kg.
Amount of air needed at 21 percentage O_2	478.571kg
Natural gas require for auxiliary heat supply	27.063m^3
Temperature of primary chamber	400-700^{0}c
Temperature of the secondary chamber	800-1000^{0}c
Outer wall temperature	31^{0}c
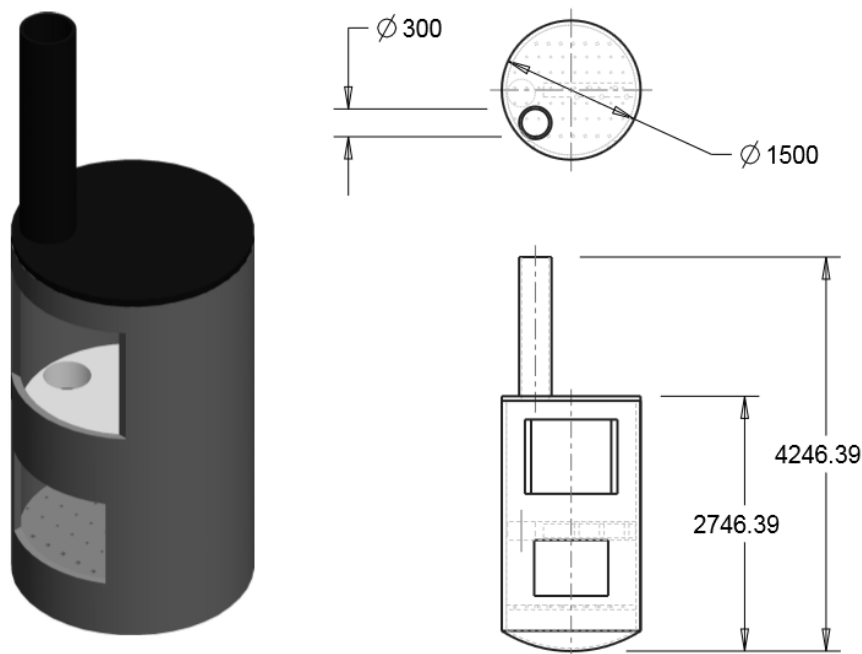
Figure 3. Waste Incinerator with schematic

Developing a fuzzy logic inference system for estimating the level of pollutant (air) from incinerator

For each variable influencing the amount of undesirable substance emitted from the stack, a fuzzy set and a membership function was calibrated over the various composition of waste expected from the different site as indicated in Table 3.

Table 3: Fuzzy Set and Membership Function.

Input index	Variables	Fuzzy set	Membership function
W_1	Food	"Amount of food"	Triangular
W_2	Paper	"Amount "	Triangular
W_3	Textile	"Amount"	Triangular
W_4	Polyethylene	"Amount "	Triangular
W_5	Polyvinyl chloride	"Amount"	Triangular
Output index			
X_1	Oxygen	"working range"	Triangular
X_2	Hydrogen chloride	"Level"	Triangular
X_3	Nitrous oxides	"Level"	Triangular

After this, the Fuzzy Inference System (FIS) for this emission estimation work on input- output bases. Using triangular membership functions, the waste constituents were classified into classes that are represented by membership functions.

i.   Food and organic matters had two classifications: high and low,
ii. Plastics were classified into two groups: high and low.
iii. Textile waste had two classification: high and low
iv. Paper waste had two classes: high and low.
v.   PVC had two classes: high and low

The output was a combination of amount and level of oxygen require for complete combustion of waste and gas flue expected from burning. These can either be high or low which in turn estimates the level of Hydrogen Chloride and Nitrogen Oxides gas produced. Tables 4 and 5 show the input variables and output variables with membership functions.

Table 4: Input variable for Fuzzy Inference System

Variables	Membership function	Range
Food	Triangular	0-1
PVC	Triangular	0-0.45
Polythene	Triangular	0-0.2
Textile	Triangular	0-0.6
Paper	Triangular	0-0.2

Table 5: Output Variables for FIS

Variables	Membership function	Range
Oxygen	Triangular	3-12
Hydrogen chloride	Triangular	0-.035
Nitrogen oxides	Triangular	0-1.2

After the grouping had been done, rules were written to connect the outputs and inputs. . Using Mandala FIS with centroid defuzzification method (Yen, 1999), plots of graph showing the relationship between waste composition and gas emission. Connections were also made using the Fuzzy Logic Mat lab rules editor. Each input variables had its own number of membership function.

Result and Discussion

When fuzzy sets are applied to real data, its behaviour on how it can be used to predict and monitor the emission from incinerator stack is very useful. In the rule viewer of the FIS emission

estimation, prediction can be made. In real-world problems, we are interested in finding the functional relationship between a set of observable parameters (waste composition) and parameters that are not known or whose values are not known (in this case the pollution level from incinerator stack). From the observable state variables, the graphs (figures 4 to 8) show the functional relationship with controllable parameters (emission and oxygen level) in form of colour mapping

Oxygen

The rule stating IF (Textile is high) AND (Paper is high) with matching conditions give us the possibility distribution level of oxygen needed for possible waste distributions high in paper and food composition. In figure 3, the consequent 0.94993 gives the degree of possibility distribution level of oxygen since the range of possibility is between 0 and 1, oxygen level is high. In contrast, figure 4 gives a different degree of possible distribution of oxygen level. The possibility distribution of waste composition high in PVC and polyethylene gives a possibility degree of less than 0.4 which is low according to fuzzy set definition. This might be due to the fact that polyethylene melts rather than burn.
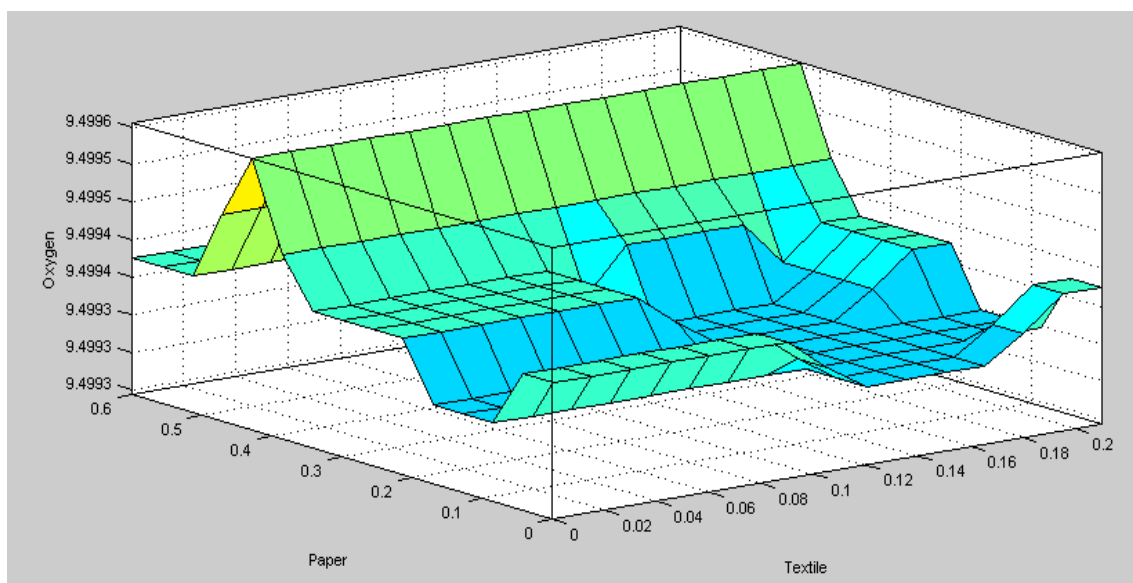

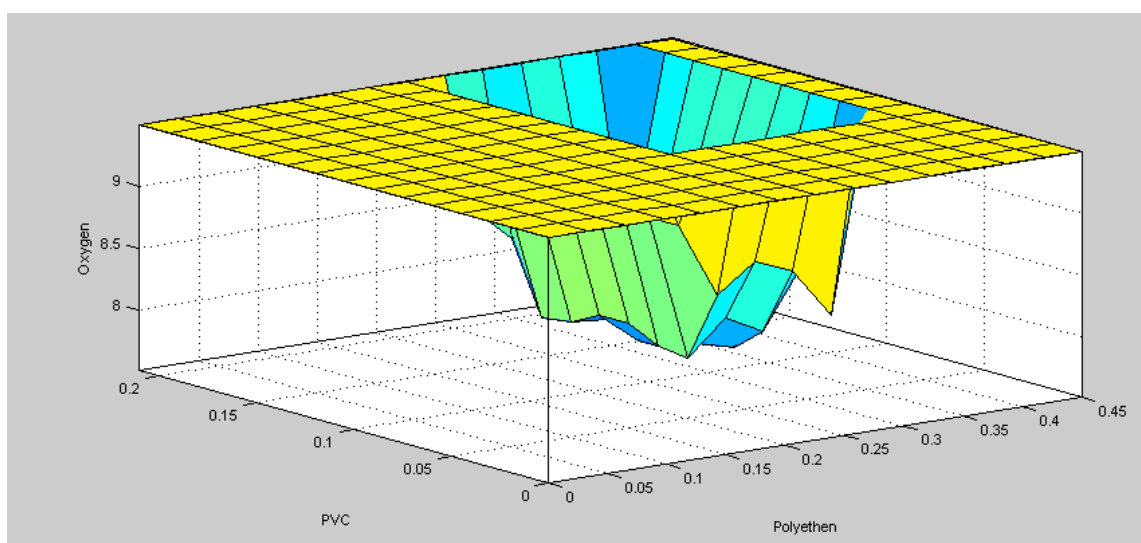Figure 4. Oxygen level for waste high in paper and textile

Figure 5. Oxygen level for PVC and Polyethylene.

Hydrogen chloride

Waste composition high in PVC produces high level of hydrogen chloride in it gas flue. Composition high in textile also produces fairly high hydrogen chloride. The possibility distribution degree of HCl for waste composition high in PVC Textile give a number that show clearly that HCl will be present in waste composition that contains PVC and Textile. Figure 6 show a linear relationship between waste composition high in PVC and HCl.
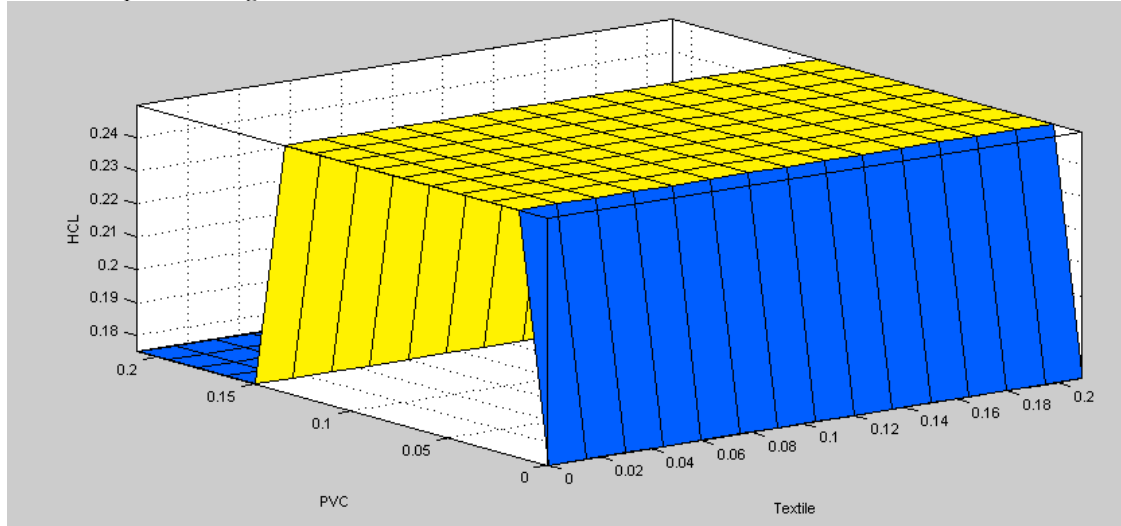

Figure 6. HCL level for waste high PVC and Textile

Nitrous Oxides

The relationship between nitrous oxides and waste composition high in food and textile shows linearity. Though nitrous oxides is produced majorly from air, the fact that waste composition high in food require high degree of oxygen level mean higher air. Figure 7 shows a possibility distribution emission level is 0.6 degree. The high heat production during burning of waste composition high PVC and polyethylene may be the reason for fairly high nitrous oxides production as nitrous oxides can be produced by high heat.
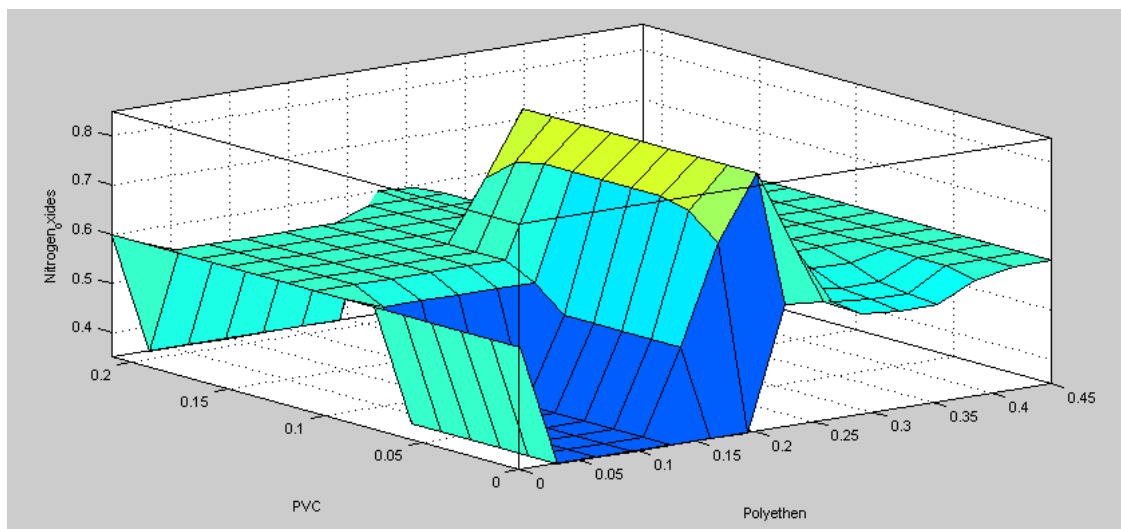

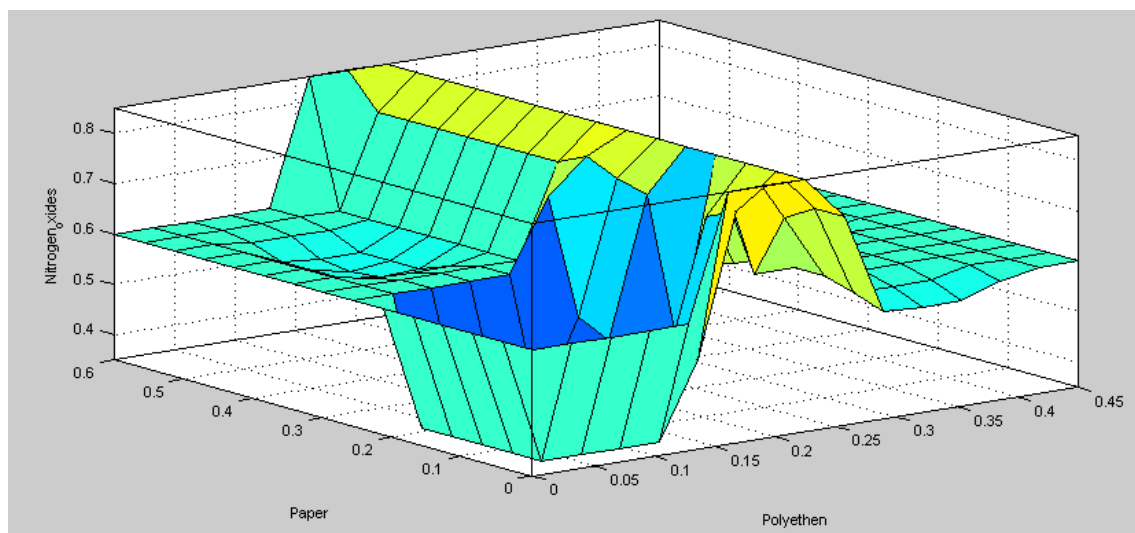Figure 7. Nitrous oxides possibility distribution level for waste high in PVC and polyethylene

Figure 8   Nitrous oxides possibility distribution degree for waste composition high in paper and polyethene

Conclusion

The aim of this work is to design a municipal waste incinerator and develop a fuzzy logic support base for emission estimation. The fuzzy logic inference system was used for the estimation because it measures the possibility distribution degree and the degree to which an outcome belongs to an event. This quality of fuzzy allows us to model for or rather establish a functional relationship between waste composition and emission as well as the oxygen requirement. This can be done under uncertainty and without being precise. The variation of waste composition from place to place and from day to day makes fuzzy logic vary suitable. The efficiency of incinerator should be based on how little pollutant are expel into the atmosphere. Hydrogen chloride and Nitrous Oxides are the gases used to demonstrate this FIS model. The amount of HCl or $(NO)_x$ depend on waste composition. The FIS model gives the degree to which a waste composition will produce what level of pollution. In countries like ours, it is a common sight to see waste being burn in the open or every empty plot of land in a residential area being turn to a dump site. Despite the pros and cons of incineration, a portable incinerator is one of the possible ways of managing municipal waste. Besides burning to ash all solid waste, the requirement for landfill is greatly reduced. It also gives an added advantage of possible expansion to energy production if energy recovery device is added.

The incinerator is designed to have an outer temperature of 31°C so as not to cause harm to persons that come in contact with it during operation. The high temperature (1000°C) and the 1.3 seconds retention time is to ensure that complete oxidation of gases that can interact with the atmosphere. This is to produce inert gases with little or no interaction with the atmosphere. However, experimental data had shown that gases that can interact with the atmosphere are still being produced hence; the need to develop the FIS model to tell what should be expected from a possible waste composition.

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