Incinerability Index of Municipal Solid Waste and Its Correlation with Carbon Monoxide and Nitrogen Oxides Emissions

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Abstract: The main objective of this study was to establish optimal incineration conditions through the analysis of pollutant formation mechanisms involved in the combustion process of a retort incinerator. Calorific values of several types of municipal solid wastes were determined and related to specific incinerability indexes. The incinerability testing concerning this study was conducted on residues with an incinerability index (II) of 123. The samples were tested under different conditions: with and without chamber preheating, varying the percentage of inlet air (25, 50 and 75% of the system capacity), measuring the temperatures of the primary and secondary chambers, and gauging the CO and NO stack emissions with an electrochemical cell. With comparative purposes in mind, samples with indexes of $I = 112$, $I = 123$, $I = 130$ and $I = 132$ were also tested to assess the influence of the II on pollutant emissions.

Key words: Incinerability index, municipal solid waste, optimal conditions of incineration, calorific value, index.

1. Introduction

The negative environmental impact of capitalist consumption patterns, inadequate solid waste management and Mexico City's increasing population have made it necessary to implement preventive measures to reduce and improve the collection, transport, reuse, recycling, recovering and final disposal of garbage.

Such an optimization, along with the valorization of the economic potential of solid wastes as energy sources in terms of their calorific value, imposes great challenges to modern society.

The Mexico City Council reported that in 2015, 12,843 tons of trash were generated daily. Of that total, 8,677 tons were sent to final disposals in sanitary landfills outside the city [1]. In the interest of minimizing the amount of garbage being sent to landfills, in 2016, the City Council implemented a Solid Waste Management Plan. This initiative had a "zero waste policy" which promoted a more efficient

use of litter [2].

Recognizing the economic potential of garbage means recovering the remnant value of wastes through the exploitation of their energy content. Engineering activities associated with the reincorporation of solid wastes in the productive process under environmental, technological and economic criteria may represent a big step towards the social development of the country.

In that sense, incineration is a great option. It destroys the solid, liquid and gaseous wastes through thermal applications in controlled combustion systems to reduce not only the volume of garbage, but also its hazardous properties [3].

Despite the fact that in 2005 approximately 30 million tons of municipal solid wastes were used globally at WtE (Waste-to-Energy) facilities to produce 45 million kilowatts-hour of electricity [4], garbage incineration also generates emissions that pollute the environment. The damage done to ecosystems and the consequent negative effects on human health require the application of preventive actions to ensure adequate operating conditions with acceptable emission values.

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Such emissions are closely related to the formation and control of the global combustion process and thermal oxidation mechanisms, both of which can be manipulated by parameter control technologies such as appropriate oxygen excess inside the combustion zone, turbulence and constant mixture of residues and oxygen, consistent combustion temperatures so that exothermic reactions are guaranteed and exposure time to certain temperatures to ensure that even the slowest combustion reaction is completed [5].

2. Material and Methods

2.1 Incinerator

The incinerator used for this experimentation is a double chamber Villareal retort type incinerator located in one of The Metropolitan Autonomous University-Azcapotzalco laboratories. The incinerator's primary chamber capacity is one cubic meter with a 800,000-1,000,000 BTU/hour burner. The solid waste incineration takes place in the primary chamber, while the 0.4 cubic meter secondary or post-combustion chamber, with a 1,200,000-1,500,000 BTU/hour burner, is used to oxidize gases from the primary chamber. The incinerator is made of high-quality refractory brick as shown in Fig. 1.

The primary air supply for combustion comes from a fan attached to the burner. The secondary air supply comes from two 62-square-inch metallic screens pierced with 40 holes half an inch wide, located alongside of the exterior wall of the incinerator. The secondary air supply that enters through the screens is directed to both the primary and the secondary chambers through a double wall.

For the experiment, the primary air was controlled by a butterfly valve in the burner (Fig. 2), whereas the secondary air was regulated by two sliding doors in front of the pierced screens. The sliding doors opened at 25%, 50% and 70% of the inlet area (Fig. 3).

2.2 Incinerability Index Determination

The calorific value is an important parameter in the

process of determining the incinerability index (II) of municipal solid wastes. The II was calculated according to the equation developed by Brunner, C. R. [6] in 1993, but it was modified to suit solid waste

Fig. 1 Incinerator feed door.

Fig. 2 Burner fan control valve.

Fig. 3 Inlet air control sliding doors.

components by considering the percentage of weight of the byproduct mixture instead of the percentage of concentration of hazardous wastes. So it is as Eq. (1).

$$I = S + \left(\frac{a}{H} \right) \quad (1)$$

Where:

I = incinerability index (without dimensions);

a = constant with a value of 100 (Kcal/gm);

H = calorific value (cal/gm);

And S = solid waste component, % of weight.

Heat value was obtained following the NOM-AA-33-1985 method [6] and using a 1341 Parr calorimetric pump.

2.3 Incinerability Tests

To obtain optimal combustion efficiency the following variables were considered:

I. Waste properties:

- a. Class and amount of waste
- b. Physicochemical properties
- c. Incinerability index

II. Incinerator characteristics:

- a. Air supply
- b. Temperature
- c. Chambers preheating

LPG (Liquefied Petroleum Gas) was used as fuel and a Testo 350 electrochemical cell was used to instantly analyze the combustion gases. The values obtained were adjusted to a 7% excess air as established by the NOM-098-SEMARNAT-2002 Mexican Official Regulation [7]. The emissions were measured in the sampling ports located in the stack (Fig. 4).

To observe the variability resulting from different incinerability indexes, three tests were conducted. For these tests, the secondary chamber was preheated to more than 700 °C and the inlet air supply was reduced by 50%.

3. Results and Discussion

3.1 Incinerability Index

The calorific value needed to determine the

incinerability index was obtained from testing a mixture of university wastes, rather than from specific byproducts. The calorific value was determined through five sets of six tests each. The incinerability index was determined using Eq. (1). The values gathered are shown in Table 1, where I = 123 is the most representative index of non-separated municipal solid wastes.

3.2 Burning Time Determination

For this test, three loads of 30 kg of residues with an incinerability index of 123 were burnt at 50% of the system's inlet air capacity. Burning time was determined by the lapse taken until: (1) wastes in the primary chamber were reduced to 10% of their original volume,

Fig. 4 Platform and sampling ports.

Table 1 Urban solid waste with different incinerator indexes.

Urban solid wastes	Nitrogen %	Heating value (Cal/gram)	Incineration index
Wastes from lumber workshop mixed with paper	0.25	3,084	132
Wastes from gardening mixed with paper	2.97	3,301	130
Urban solid wastes	0.72	4,416	123
Wastes from plastic workshop mixed with PET (Polyethylene Terephthalate)	0.06	8,401	112

and (2) until unburnt and amorphous materials were observed within the residue mixture. Burning time results showed a lapse of 35 minutes.

3.3 Optimal Incinerator Inlet Air Determination

In order to obtain the optimal amount of air needed by the incinerator, tests were performed on solid wastes with an incinerability index of 123 under two conditions: first, burning the residues without preheating the secondary chamber, and the second, preheating the chamber to a temperature superior to 700 °C. Both tests were undertaken with a 25%, 50% and 70% of the incinerator's air capacity. The results obtained are explained in Figs. 5 and 6, respectively.

In considering the information gotten when there is no oven preheating, temperature variation in the secondary chamber ranges from 500 to 700 °C. The maximum value was obtained with an inlet air of 25%, while the minimum value corresponds to an inlet air percentage of 75. Temperature increases in correlation to the time passed.

In contrast, when the oven is preheated, the temperature range is shorter and the opposite behavior is observed: less inlet air capacity means less temperature in accordance to time.

3.4 Emissions at Different Temperatures and Inlet Air Capacities

Fig. 7 shows the amounts of CO (Carbon Monoxide) obtained for different inlet air capacities and no chamber preheating. As it may be seen, there is a reduction in CO generation once the temperature exceeds 700 °C. The greatest amount of CO was observed when the air supply was at its minimum, and vice versa, CO generation decreases with more air in the chamber. The minimum amount of CO emissions was recorded when inlet air was at 50% of the incinerator's capacity.

During the first moments of incineration, this pollutant surpasses the maximum limit allowed by the norm (72 ppm). Nevertheless, as time goes by and temperature increases, emissions return to be under 72 ppm as officially established.

Fig. 5 Temperature variation without second chamber preheating.

Fig. 6 Temperature variation with second chamber preheating.

Fig. 7 Emissions at different temperatures and inlet air capacities.

In terms of NO_x (Nitrogen Oxides) generation, tests indicated that samples were mostly composed of NO (Nitrogen Oxide) which is more stable and prevails in combustion processes. These results agree with what

was reported by Gardinier, W. C. [8] in 1999.

More NO is produced when temperature rises. When there is no chamber preheating, the highest temperature can be achieved and, therefore, the highest records of

NO when inlet air is at 25%. If the chamber is preheated maximum temperature and, consequently, more NO is generated at an inlet air supply of 50% as shown in Fig. 8.

So, from the data gathered in Fig. 8, it can be concluded that the prevailing formation mechanism of NO is the thermal NO_x , since the NO production is higher when the temperature increases.

The maximum allowable concentration of NO according to the NOM-098-SEMARNAT-2002 Mexican Official Regulation [7] of 368 ppm was not exceeded in either case.

3.5 Temperature Variations with Different Incinerability Index Materials

Incinerability tests for this section were performed on residues of different incinerability indexes with an inlet air supply of 50% of the incinerator's capacity and with chamber preheating. The objective here was to compare the influence of different incinerability indexes on emissions. The temperature variation for diverse incinerability indexes is shown in Fig. 9.

It can be observed that the maximum temperature is reached with the lowest incinerability index ($I = 112$) because the calorific value of these residues is higher than 800 cal/g, meaning that these materials are highly flammable. The calorific value determines the temperature in the secondary chamber. The higher the incinerability indexes are, the lower the temperatures.

3.6 CO and NO Variations with Different Incinerability Indexes

Fig. 10 shows that CO production fluctuates according to different incinerability indexes in a preheated chamber with 50% of the air supply. Wastes with an index of 130 (garden residue) and 132 (wood residue) did not generate CO. This may be because this type of garbage occupies less space and because the amount of oxygen is enough to complete the combustion. Other kinds of garbage such as urban solid wastes and plastic are more voluminous, leaving empty spaces inside the incinerator where the air is not properly mixed, thus, leaving products of incomplete combustion.

Fig. 8 NO emission at different temperatures and inlet air capacities.

Fig. 9 Temperature variation with different incinerability index materials.

Fig. 10 CO variation with different incinerability index materials.

NO variations for different incinerability index materials in a preheated chamber with 50% of the air supply are shown in Fig. 11. The highest amount of NO generated is related to incinerability index 132,

followed by I = 130. This is a result of the composition of the residues: garden and wood residues contain more nitrogen, so that the mechanisms of nitrogen oxides formation are a mix of fuel and thermal NO_x s.

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Fig. 11 NO variation with different incinerability index materials.

4. Conclusions

Emissions can be reduced and controlled if optimal incineration conditions are established. Process optimization can be achieved through the evaluation of the incinerability index (calorific value capable of generating heat and maintaining combustion temperature) of the type of wastes being burnt, as well as the air-fuel relation, incinerator chambers' temperature, retention time and the ability to generate an efficient mix through turbulence.

The tests showed that temperatures reached without incinerator preheating ranged from 500 to 700 °C. This range was found to be optimal to incinerate municipal solid wastes, since chamber preheating increases temperatures up to a range of 600 to 700 °C [9], a slight growth that does not justify fuel consumption and its consequent expenses rise.

In terms of carbon monoxide emissions, an increment was observed when the volume, shape and the superficial area of the wastes represented a mixing (turbulence) difficulty. Any restrictions to the free circulation of air through the burning wastes result in

zones where the combustion is incomplete due to the lack of oxygen.

The dominant mechanism in the formation of nitrogen oxide is thermal. The condition that favored this production was an inlet air supply of 25% of the incinerator capacity. Here, the highest temperature was achieved chamber preheating does not influence the nitrogen oxide formation because temperatures recorded in the secondary chamber are similar to those recorded when the incinerator was preheated.

It is important to take into consideration the composition of the residues in terms of nitrogen contents. If wastes are rich in nitrogen, the mechanism that causes greater production of nitrogen oxide is that of fuel.

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