DESIGN AND CONSTRUCTION OF A LIQUID INCINERATOR; A NOVEL METHOD FOR FAST CHEMICAL MEASURMENTS AND FEEDBACK CONTROL

BY

Pasl Abdel Jalil

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UMI
300 North Zeeb Road
Ann Arbor, MI 48103

KING FAHD UNIVERSITY OF PETROLUEM AND MINERALS
DHAHRAN 31261, SAUDI ARABIA

COLLEGE OF GRADUATE STUDIES

This dissertation, written by Pasi Abdel-Hamid Abdel-Jalil under the direction of his dissertation advisor and approved by his Dissertation Committee, has been presented to and accepted by the dean of the College of Graduate Studies, in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY IN CHEMISTRY.

Dissertation Committee

Prof. Abdul-Aziz Al-Suwaiyan
Dissertation Advisor

Assoc. Prof. Abdulrahman A. Al-Arfaj
Dissertation Co-Advisor

Assoc. Prof. Herman Perzanowski
Member

Assoc. Prof. Esam Z. Hamad
Member

Assoc. Prof. Habib I. Abualhamayel
Member

Assist. Prof. Esmail M. A. Mokheimar
Member

Assoc. Prof. Abdulrahman A. Al-Arfaj
Department Chairman

Dean, College of Graduate Studies

18/5/98
date

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DISSERTATION ABSTRACT

FULL NAME OF STUDENT Pasl Abdel-Hamid Abdel-Jalil

TITLE OF STUDY Design and Construction of a Liquid Incinerator; A Novel Method for Fast Chemical Measurements and Feedback Control

MAJOR FIELD Physical Chemistry

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A small scale hazardous chemical liquid waste incinerator is designed, constructed and operated. The design was based on the thermodynamics parameters e.g. temperature and volume. The chamber, the insulation, the feed system and the cooling system were designed and constructed at King Fahd University of Petroleum and Minerals. Making use of the heat generated by the incinerator, the liquid waste is converted to vapor before entering the burner. An on-line monitoring system was assembled and operated. Automation was implemented using the microprocessor of the gas chromatograph (GC) used in the monitoring system.

Simulated waste consisting of a mixture of benzene and heptane has been studied. A better than 99.99% destruction and removal efficiency (DRE) has been achieved.

A unique method is proposed for the control of the incinerator. Previous methods depend on the analysis of the exhaust gas. The new technique is based on the correlation of the voltage developed in the flame with the DRE. Under steady state conditions, a correlation between the measured voltage and the concentrations of some species in the exhaust gas has been observed. The voltage probe acts as an active sensor that gives very fast information about the incineration process. This information allows for fast corrective actions without waiting for the analysis of the exhaust gas.

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خلاصة الرسالة

اسم الطالب الكامل : باسل عبد الحميد عبد الجليل

عنوان الدراسة : تصميم و بناء معالج حراري كيماوي للنفايات الكيماوية السامة، طريقة جديدة وسريعة للتحكم ولقياس تركيز بعض المواد الكيماوية

التخصص : الكيمياء الفيزيائية

التاريخ : مايو، ١٩٩٨

تم تصميم وبناء معالج حراري كيماوي للنفايات الكيماوية السامة، حيث صمم الجهاز على أسس ديناميكا الحرارة. وقد تمت عملية التصميم والبناء كاملة في الجامعة. تدخل المواد الكيماوية السائلة السامة إلى حجرة التفاعل بعد تحويلها إلى غازات بواسطة المعالج نفسه. ويتم التحكم في المعالج الحراري ومراقبة مستمرة لجودة الغازات الخارجة منه بواسطة أنظمة تم بناؤها وتجهيزها لهذا الغرض .

أظهرت النتائج التي أجريت على خليط محدد من الهبتان والبترين، أنه تم التخلص بنسبة تزيد عن ٩٩,٩٩% لهذه المواد.

تم إيجاد طريقة جديدة وسريعة لقياس بعض المواد الكيماوية ويمكن استخدام هذه الطريقة للتحكم السريع بالمعالج. تعتمد هذه الطريقة على مقدار فرق الجهد اللحظي في اللهب، حيث وجد أن هناك علاقة واضحة بين هذا الجهد وبين تركيز بعض المواد الخارجة من المعالج. وهكذا يمكن التحكم في الجهاز بطريقة أسرع.

درجة الدكتوراة في الفلسفة

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

مايو، ١٩٩٨

CHAPTER I

INTRODUCTION

1.1 GENERAL BACKGROUND

Hazardous waste is legally defined as that waste that may cause adverse effects on human health or the environment when not properly controlled [1-5]. Due to the complexity of the waste nature, no single method is sufficient for the treatment of all types of waste or even most of them. The selection of a particular method for the treatment of waste depends solely on the type of waste to be treated. Therefore, a proper classification of waste is an important step towards its treatment.

It is difficult to classify waste materials into a neat package that follows all the rules. However, there are three basic classification methods used in the literature [1,2]:

(1) Physical classification which is based on the identification of the physical state of the waste. Typical waste materials are classified as: gas, liquid, slurry, sludge, solid and containerized waste. This classification is needed for the selection and design of waste handling systems and the choice of processing equipment.

(2) Chemical classification which is based on the identification of the elements that constitute a certain waste. Accordingly, the waste material can be classified as given in Table1.1. Chemical classification is the key to selection of proper process design parameters, selection of construction materials and equipment, design of incinerator hardware, the possibility of by-product recovery, and the requirement of flue gas and discharge water treatment systems.

(3) Thermal classification which is based on the thermal properties of the waste. Typical waste materials are classified as :

a) Combustible wastes: This group covers wastes which will sustain oxidation reactions without additional energy requirements.

b) Noncombustible waste: This group represents waste with low energy content value which will not sustain oxidation reaction without additional energy requirement.

Thermal classification is used to determine energy requirements for processing and the selection of a particular system configuration.

Another method of classification can be found in title 40 of the Code of Federal Regulations, USA, part 261 (40CFR261) [3-5]. This classification contains the following classes of waste: ignitable, corrosive, reactive, extract procedure (EP) toxic waste, acute and toxic waste. As can be seen, this classification is of low importance in an incinerator design. An interesting classification of chemical compounds based only on their tendency toward incineration, is given by Taylor et. al. [6].

Table 1.1. Chemical classification of waste material

waste	element constituents
clean waste	C, H, O
waste generating gaseous contaminants	C, H, O, N, S, F, Cl, Br
waste containing heavy metals	C, H, O, N, S, F, Cl, Br, Si, heavy metals
waste containing alkali metals	C, H, O, N, S, F, Cl, Br, Si, heavy metals, alkali metals, P, B.

1.1.1 Methods of Waste Treatment

As mentioned earlier, selection of a particular method for the waste treatment depends on the waste classification. Accordingly, many methods have been developed to meet certain needs. These methods range from reducing the size or changing it to another useful form to complete destruction of the waste. A fast review of some methods is given below [1, 7].

I- Physical Treatment

Adsorption by activated carbon or resin.

Centrifugation

Dialysis (membrane separation)

Electrodialysis

Electrolysis (for removal of some concentrated metals)

Filtration

Precipitation

Flotation (specially for microorganisms and paper)

Freeze-Crystallization

High-Gradient Magnetic Separation (for separation of paramagnetic materials).

Reverse Osmosis.

II- Chemical Treatment

Chemical oxidation (e.g. oxidizing of cyanide effluents or sulfur, nitrogen oxides).

Chemical reduction (e.g. Cl_2 to Cl^- or Cr(VI)(carcinogenic) to Cr(III)).

Neutralization

Ozonation (specially antibacterial).

Photolysis.

III- Biological Treatment

IV- Landfill

V- Thermal Processes.

a) Pyrolysis (defined as heating at 500-800 °C in the absence of oxygen with residence time range 12-15 min).

b) Catalytic incineration (defined as heating the waste using a catalyst at 300-600 °C) with a residence time of 1 sec.

c) Incineration, is defined as a process which is employing thermal decomposition through thermal oxidation at high temperatures (usually 900 °C or more) to destroy

the organic fraction of the waste and reduce its volume [5, 8, 9]. Residence time ranges form 0.1 sec. to 1.5 hr.

1.2 INCINERATION

Features of the incineration method include the following:

- The hazardous component of the waste is destroyed.
- Waste can be incinerated on-site, without being transported to a distant area.
- Air discharges can be effectively controlled for minimal impact on the environment.
- The ash residue may not be classified as a hazardous waste. In this case, incineration becomes, essentially, a final disposal method as well as a treatment method for hazardous waste.
- Incineration is easily terminated. The cessation of incineration activity will remove any liability for the generator or the operator. With landfill, the liabilities are indefinite and uncertain.
- Through heat recovery techniques, the cost of operation can be reduced or offset by the use or sale of the produced heat energy.

Although incineration is becoming increasingly attractive as a waste disposal option, it is not universally acceptable as a waste disposal method, Because of the following considerations:

- Some materials, such as highly aqueous wastes or noncombustible soils, are not incinerable.
- The control of metals from the incineration process may be difficult for inorganic wastes with a heavy-metals content(e.g. lead, chromium, cadmium, mercury, nickel, arsenic, etc.).
- Incineration represents a high capital cost.
- Skilled operators are required.
- Supplement fuel is required to bring up an incinerator to the required operating temperature and, with some materials, to maintain combustion temperatures.

Moreover, commercially available incinerators are not always feasible and suitable for all types of waste. Therefore, modifications must be introduced to meet certain requirements [1, 5, 8, 9]. On one hand, incineration is an efficient way of waste disposal; on the other hand, it may be a dangerous way. For example, chlorine-containing compounds may produce chlorodioxines, and butanol may produce butylaldehyde and butyric acid if improper conditions are applied.

Optimum conditions (parameters) could be achieved to ensure 99.99% destruction and removal efficiency (DRE) defined as:

$$DRE = ((\text{Weight in} - \text{Weight out}) / \text{weight in}) \times 100$$

Temperature (T), Residence time (t) and excess air [10] are the most important parameters to be specified for any incineration of any waste type [1-10].

From the definition of incineration, one concludes that combustible waste with a significant organic content is considered as the most appropriate type for incineration. Technically, however, any waste with a hazardous organic fraction, no matter how small, is at least a functional candidate for incineration. For instance, significant amounts of contaminated water were incinerated in the United States during the early 1980s. Contaminated soils are also being incinerated with increasing frequency. American Environmental Protection Agency (EPA) for example, has employed a mobile incinerator to decontaminate 40 tons of Missouri soil which had been contaminated with four pounds of chlorinated dioxin compounds [9].

In the Kingdom of Saudi Arabia (KSA) hazardous waste is produced as a by-product of various chemical industries, hospitals and educational institutions. The produced waste in KSA could range from less hazardous to very poisonous chemicals. For example, at King

Fahd University of Petroleum and Minerals (KFUPM) cyanide waste is stored in the University Chemical Store and cannot be disposed of any where in the Kingdom [11].

The only industrial scale incinerator in the Kingdom is in Al-Jubail for Beea'h company with a capital cost around 40 million Saudi Riyals.

1.2.1 Incinerators

Generally any incinerator consists of four major subsystems [1-9]:

1. Waste preparation and feeding

   Liquids are blended, then pumped into the combustion chamber through nozzles or specially designed atomizing burners. Solids may require shredding for control of particle size. Chlorinated compounds could be blended with other nonchlorinated compounds so that the percentage of HCl in the exhaust is less than the international standard (see Table1.2, section 1.2.3).

2. Combustion chambers

   The physical form of the waste and its ash content determine the type of combustion chamber selected. A more detailed description is given in section 1.2.2 "Types of Incinerators".

3. Air pollution control

Flue gases need further treatment for the removal or reduction of particulates, removal of acid and any other hazardous gases. The temperature of the flue gas has to be reduced. One of the most commonly employed air pollution control systems is quenching (gas cooling and conditioning) followed by high-energy venturi scrubber (particulate removal), a packed tower absorber (acid gas removal) and a demister (visible vapor plume reduction).

4. Residue and ash handling

The inorganic components are not destroyed by incineration. Ash is commonly either air-cooled or quenched with water after discharge from the combustion chamber, and then accumulated for disposal in a permitted waste disposal place.

1.2.2 Types of Incinerators

The types of incinerators are derived from the combustion chamber configuration used which, in turn, is determined according to the physical form of the waste and its ash content. There are five known types of combustion chambers (or incinerators) [1-5,7, 8]:

1) Liquid injection incinerators

In liquid waste incinerators, the waste is introduced as a spray in the burner. Waste material is considered as a liquid if it can be pumped to a burner and atomized. In general, a material can be pumped if its viscosity is less than 10,000 Saybolt-seconds universal (SSU), (2.23 kg/ms). For conventional nozzles the stream viscosity should not be greater than 750 SSU (0.167 kg/ms) for proper atomization to occur [5].

Almost any liquid stream nozzle will include a means of atomization. Mechanical nozzles utilize a plate or another surface as a target for liquid stream. The liquid stream is pumped at a relatively high pressure. The high velocity of the flow, created by this high pressure, will strike the target and form small atomized droplets.

Air atomization utilizes an external air stream to break up the waste stream. Approximately 100 standard cubic feet (scf) of air is required per gallon of waste for atomization. The atomizing air stream normally ranges from 50 psig (3 atm) to 75 psig (5 atm) above the pressure of the liquid stream.

2) Rotary kiln incinerators

A rotary kiln incinerator includes provisions for waste feed, air injection system, the kiln itself, an afterburner, an ash collection system, and an air pollution control system [5]. They can handle solid, liquid, gaseous, and sludge wastes. Throughout the world, more rotary kiln incinerators are being used for the destruction of non-liquid hazardous waste compared to other types of incinerator.

3) Fixed Hearth

This is also called starved air or pyrolytic incinerator. Waste is incinerated in two stages. First waste is pumped into a first stage primary chamber and burned at starved air conditions. At this stage the volatile fraction of the waste is introduced to a second chamber where additional air is added for complete combustion.

4) Fluidized Bed

This is a type of incinerator which is primary used for materials including soil, sludge or liquids. Generally fluidized bed incinerators consist of a refractory-line combustion vessel partially filled with particles of sand, alumina, calcium carbonate or other similar materials. Combustion air is supplied through a distributor plate at the base of the combustor. High gas-to-solid ratios offer high heat transfer efficiencies and good mixing which provides the potential for in-situ acid gas neutralization by lime or carbonate addition.

5) Infrared Furnaces

In this type of incinerators, infrared radiation generated by electrical heaters is used for heating purposes.

The last three types of incinerators are of much less importance in industrial applications compared to the first two [1-10].

1.2.3 Criteria for Stack Emission From Incinerators

Gases released from incinerators to the atmosphere should be monitored. Concentration of certain gases must not exceed certain limits. To check the performance of a certain incinerator, test burns are used for quantitative evaluation. [12, 13]. Table 1.2 shows some stack emission criteria specified by the American Environmental Protection Agency (EPA). The failure of an incinerator to meet one of these criteria may indicate some problems in the incineration conditions [14-18].

Table 1.2 Some Stack emission criteria specified by EPA

Parameter	Criteria
HCl	< 100 mg/m^3 or 99 % removal efficiency (the lower one)
SO_2	< 500 mg/m^3
PCBs*	< 1 mg/kg PCB Fed (i.e. > 99.9999 % DRE)
Chloro dioxins/furans	< 30 ng/m^3 and > 99.9999 % DRE
Other organic constituents	> 99.99 % DRE
Visible emissions	Not to exceed 10 % OPACITY (For more than 6 minutes out of any hour)
CE*	> 99 %
PIC*	< 0.01 % of POHCs*
Total Particulate Emissions	< 34 mg/dscm* (0.015 g/dscf*)

*dscm : dry standard cubic meter, *dscf : dry standard cubic feet

*PCBs: Polychlorinated Biphenyls

* CE: Combustion Efficiency, CE = $CO_2/\{CO_2 + CO\}$

*PIC: Products of Incomplete Combustion

*POHCs: Principal Organic Hazardous Constituents

1.3 LITERATURE REVIEW

1.3.1 General Aspects

Incineration is the most effective way of hazardous chemical waste disposal [5, 8, 9]. It has attracted the attention of many scientists. A direct indication of the increasing interest can be seen from the number of Ph.D. dissertations on incineration during the last 18 years. Searching through "dissertation abstracts" CD ROM database under the word 'incineration', the following number of dissertations are obtained

From 1982 to 1987	13 dissertations, i.e. 2 per year
1988 to1992	46 dissertations, i.e. 9 per year
1993 to 1996	83 dissertations, i.e. 21 per year

As can be seen, incineration is becoming more attractive as an alternative disposal method. The main challenge in incineration is to maintain incinerator conditions to give the required DRE and other stack emission criteria.

1.3.2 Research Directions

Research in the incineration field aims to improve the DRE of the incineration. A lot of work is dedicated to studies of the incineration process focusing on the incineration parameters such as temperature, residence time, excess air and mixing.

Cooper used time-temperature design parameters to study the destruction in a hydrocarbon vapor incinerator [19]. Several research groups studied the effect of some additives on DRE. In these studies relatively expensive, toxic and difficult to handle chemicals have been used (methanol, CO, H_2O_2, O_3) [10, 16, 19-21]. Other groups studied the correlation of the DRE of specific principal organic hazardous constituents (POHCs) DRE with the incineration parameters [10, 16-17]. In these studies, one POHC is studied at a time, and assumed to behave the same in the waste, i.e. mixture of POHCs.

One way of increasing DRE without changing the incineration parameters is through using catalysts, e.g. catalytic incineration of volatile POHCs [1-2, 5, 9].

Thomson *et.al.* studied the effect of blending on reducing hazardous waste incinerator emissions [22]. They studied the effect of addition of heptane and dodecane on 1,1,1-trichloroethane destruction. They found an increase in ethylene, acetylene and carbon monoxide levels for injection temperatures between 950 K to 1040 K, and a decrease in 1,1-dichloroethylene, phosgene, acetylene, and carbon monoxide levels for injection temperatures greater than 1050 K.

1.3.3 Relevant Studies

As mentioned above, most of the research is directed toward the conditions that affect the incineration either in the post flame region or in the pre-flame region, e.g. blending of the waste. The correlation between the conditions of incineration and the composition of the incinerator exhaust gas has been of speciai importance.

Stack emission is a function of the waste feed. In order to understand the thermal processes in the incinerators, many researchers have tried to find a correlation between the feed composition and the stack emissions. For example, the correlation of dioxins emission with the feed characteristics or incinerator conditions has been studied [16-18]. An important class of emitted compounds is the products of incomplete combustion (PIC) e.g. dioxins and carbon monoxide [9, 23-26]. As the name suggests, PIC indicates that an incinerator is suffering from insufficient conditions for destruction. The PIC could be used as an indicator of DRE of the feed. Other transient species could have certain relation with DRE as well [27].

The main aim of these correlation studies is to adjust the incineration parameters to give better DRE and less PIC. However there are two problems associated with these methods:

a- The time lag between the entrance of the waste in the incinerator and the analysis of the exhaust which prevents fast corrective actions in the incineration parameters.

b- The nature of PIC could change dramatically according to the feed. Correlation of certain PIC to the condition of the incineration is not possible because the composition of the waste may be continuously changing. Hence, it is very difficult to correlate the PIC with the incinerator conditions.

Is there a "universal parameter" that could give an idea about the DRE without analysis the stack emissions? In other words : Is there a parameter that will give an idea about the incineration process irrespective of the feed?

1.3.4 Ions in the Flame

It is well known that ions exist in the flame [28-31]. It is also believed that ionic species play a role in some flame reaction mechanisms. For example, the mechanism of soot nucleation is mostly believed to be through ionic chain reactions [28-31]. In a critical review of mechanisms of soot nucleation in flames, Calcote [31] concluded that neutral free radical mechanisms are not consistent with the chemical sequence leading to soot formation. Soot formation has been explained by mechanism utilizing both the neutral free radical mechanisms with the ionic mechanisms. In such mechanisms, the ions are assumed to be the precursor on which some free radicals repeatedly add in fast ion-molecule reactions. It is believed that "ionic nucleation played the dominant role in soot formation

and, further, that soot nuclei acquired this charge at a very early stage in their development"[30].

Recently Saito *et. al.* Showed that, there is a variation of flame shape and soot suppression by applying electric field on the flame [32]. The soot suppression is due to the flame temperature increase upon application of electric field.

1.3.5 The "Infinity Loop(s)" Challenge

"A current deficiency in incinerator technology is a rapid process monitor to detect periods in which combustion is less than ideal. If such a process monitor existed, it could be coupled into a feedback control system which would modify combustion conditions(e.g. decrease fuel flow rate) to bring the emissions back into design limits"[27]. The current practice of incineration monitoring is by extracting, conditioning and analyzing the exhaust flue gas of the incinerator. These methods are accepted by EPA and can be used to measure incinerator compliance with the Resource Conversion and Recovery Act (RCRA) incinerator standards [1-5,9]. According to EPA, the current permitting approach is reasonable and protective of human health and the environment. "But many argue that the availability of additional real time monitoring techniques to detect process upsets and alert operators to automatically take corrective action would significantly increase public acceptance of thermal destruction."[9].

However, all methods used suffer from a time delay between the upsetting conditions and the analysis time. One of the critical functions of the incinerator monitoring devices is monitoring the exhaust continuously or nearly continuously with very short lag time between the introduction of waste and the analysis of the exhaust. It is agreed that stack monitoring system "provides the operator with current data on the performance of the incineration" [5]. However this current data does not reflect the changes in the feeding system.

Take, for example, a liquid incinerator working at its optimum conditions and is at a certain steady state of a particular temperature. Suppose that for one reason or another the flame conditions are changed, (e.g. excess air is introduced) such that a new but less efficient steady state could be reached and this situation continues for some time. The monitoring system can not detect this new situation immediately because of the time delay of the incinerator chamber, i.e., the incinerator chamber is still at the original temperature, so the destruction will take place in the chamber to give as good results as before the new conditions. However, with time the situation is changing to less efficient conditions because of the new conditions of the flame. After sometime (it could be one hour or more) the effect of the new flame conditions will be detected by the analysis system. Thus the conditions in the incinerator chamber may become worse, but the detection system suffers from long lag time of the incinerator chamber.

Now suppose a corrective action on the flame conditions is made to bring the incinerator back to its original 'good' steady state. Since the chamber conditions are still 'bad', the

destruction will not be satisfactory, and the monitoring system will reflect this situation. According to the data given by the monitoring system, another corrective action has to be made. But this is not true because it will disturb the 'best' conditions which has already been set. If the operator follows the instructions of the 'current' data given by the monitoring system, a worse conditions will be imposed and again unacceptable data will be recorded by the monitoring system. The operator must not follow the 'current' data for corrective action. Otherwise, he will be involved in an "Infinity Loop(s)" measurements and corrective actions. Instead, he has to wait (one hour or more) to achieve the former steady state.

Is there a way to solve this "infinity loop(s)" by an electronic feedback loop? If one knows what given conditions in the incinerator lead to a better steady state without having to wait for the achievement of the steady state for analysis of the exhaust at that time, can he make the corrective action accordingly? Or, can one know ahead of time how the destruction will look? Can he 'measure' (not only predict) certain concentration of some species ahead of time?

If one has the "magic" to measure the steady state concentration one hour ahead of time, it will be a major step towards the solution of the "infinity loop(s)" challenge. Since soot is a very good 'indicator' of incomplete destruction, and that the charged particles are the main components in the mechanism of soot formation, the electrical properties of the flame could be used as an indicator of the destruction in incineration process. And this could be the key of solution the infinity loop challenge.

1.4 OBJECTIVES

There are two objectives for the proposed work :

1. To design and build a small scale incinerator consisting of a burner, chamber , cooler and monitoring system. In order to reduce the manpower needed for the operation, an automated feeding system as well as an on-line monitoring system will be installed.

2. Propose and test a new method for fast chemical measurements and fast feedback control as a step towards the solution of the infinity loop challenge.

CHAPTER II

DESIGN AND INSTALLATION

2.1 INTRODUCTION

As mentioned in chapter I, an incinerator consists of four major subsystems; The burner, the chamber, the cooler and the monitoring and analysis system. These subsystems are shown in a block diagram form in Fig. 2.1. A schematic flow diagram of the incinerator is shown in Fig.2.2. Automation of some equipment is accomplished using the microprocessor of the gas chromatograph (GC) used in the analysis system. One should be very careful in doing the interfacing between the electrical heavy equipment e.g. the pumps, and the boards of the GC. An important fact is that the integrated circuits (the chips) in the GC can handle a maximum current of 300 mA , while most of the equipment to be automated require current more than 1 A. For example, a current of 5 A is required for the vacuum pump and about 10 A is needed for the heating lines. However, by using suitable relays and adjusting the operating voltages of the relays so that they operate at less than 300mA, the GC could be used for automation. It is advisable to put a 300 mA fuse between each relay and the flip-flop chip that operates that relay. Using a good fuse system will protect the electronics in the GC from any damage that could occur as a result of automation of the incinerator

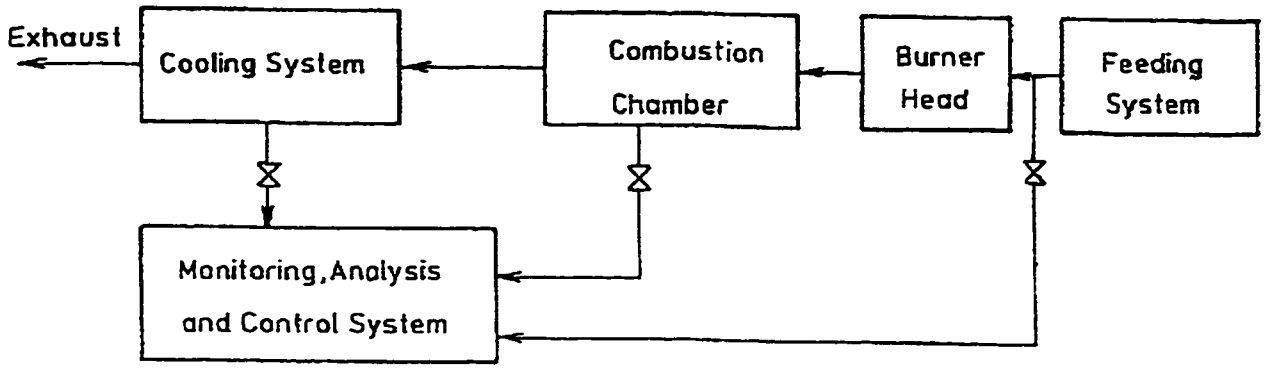
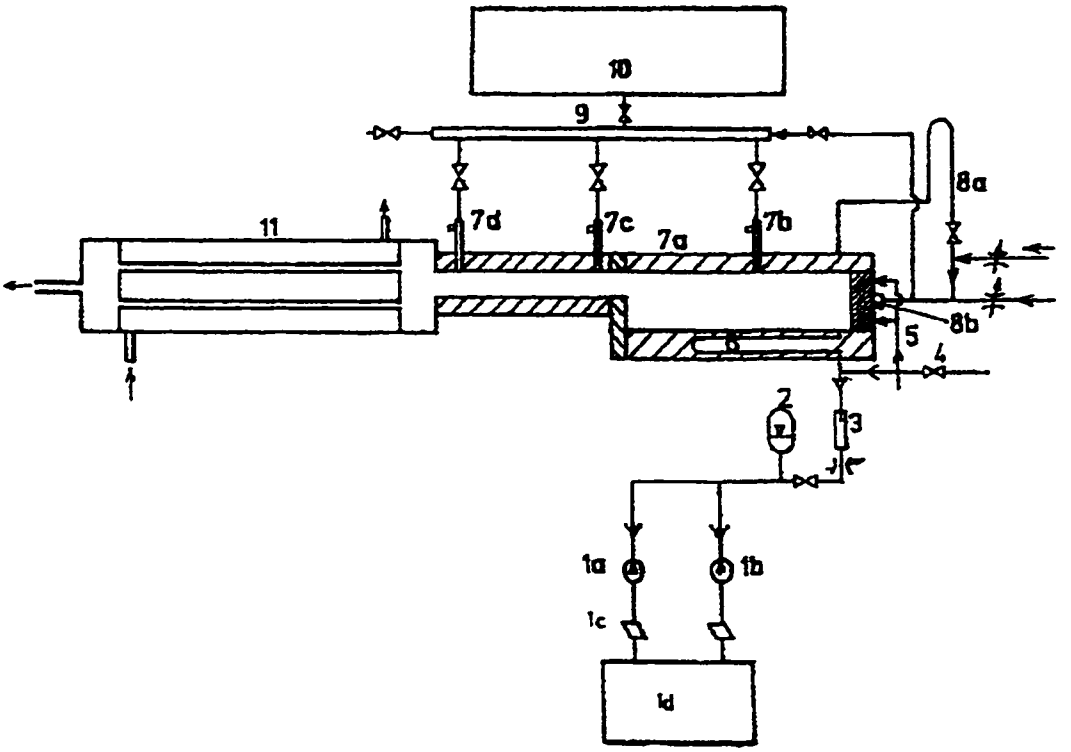


Figure 2.1 Block diagram form of the incinerator



1a, 1b : pulsating flow metering pumps
1c : filter
1d : liquid waste container
2 : accumulator
3 : rotameter with flow control valve
4 : cleaning-air
5 : cooling air lines
6 : waste heater inside the chamber insulation
7a : the chamber
7b-d : sampling ports and thermocouple locations inside the chamber.
8a : secondary electrically heated zone as "damper"
8b : burner head
9 : heated sampling lines
10 : monitoring, control and analysis system
11 : shell and tube heat exchanger.

Figure 2.2 Schematic diagram of the incinerator

The incinerator is designed in such a way that liquid chemicals enter the burner in the gas phase. Therefore essentially the burner is of gas type. It is made of steel. Fig 2.3 shows the burner head which is taken from an oven and used without modifications.

This design of the burner head (Fig. 2.3) is important in preventing flash back of the flame, especially with the associated feeding part just prior the burner head. For example if the opening in the burner is too large, a flash back of the flame may occur after some time, especially if the incinerator chamber gets very hot and the suction fan stops. If the opening is too small, the vapor-air mixture will be heated upon arrival at the burner outlet and a flow back of the fluid system may occur. This will disturb the flame after some time of operation causing fire extinguishing. Such simple burner head with the associated feeding system has been found to be effective in obtaining a stable flame. The design of the burner can handle wide range of different conditions of the feed components. Irrespective of the relative values of pressures of the natural gas and the combustion air, there will be no flow from one pipe to another. The air will not flow in the natural gas pipe and vise versa. Air pressures ranging from 3 psi to 40 psi and natural gas pressure at 6 psi have been used in this work without any problems.

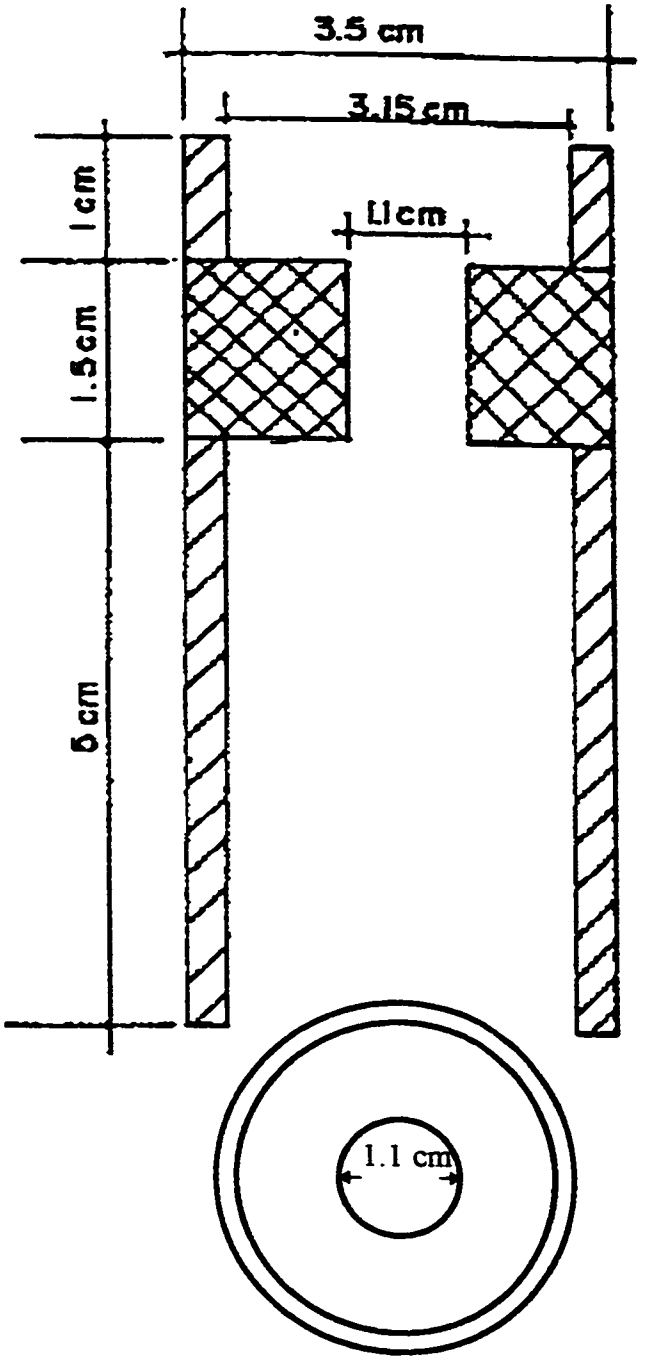


Figure 2.3. The burner head

As we explained, the burner design is of critical importance. If it is not designed properly many problems may occur. In addition it will not work properly especially upon introduction of the waste.

For safety purposes, a pilot flame is put underneath the burner to ignite it if the flame is extinguished during operation. It is advisable to keep the pilot flame on, especially in continuous operation. In addition, a pilot flame sensor is developed, such that, if the pilot flame is extinguished, the waste feeding pumps will automatically stop and an alarm will start ringing. The design of flame sensor with the associated electronic circuit is given in Appendix A.

2.3 THE CHAMBER

The design of the chamber is shown in Fig.2.4. It consists of two welded stainless steel (grade 304, schedule no.40) cylinders. The first cylinder is 60 cm (23.6 in) long and 15.2 cm (6.0 in) inside diameter (id). The second cylinder is 100 cm (39.4 in) long and 5.2 cm (2.0 in) id. An important point in fabricating the chamber and the heat exchanger is the homogenity of the parts to be welded. Hence all of the stainless steel as well as welding bars are made of grade 304.

The design equation obtained in this work is:

$$V = 11.5\tau F \qquad (1)$$

where:

V: the volume of the chamber in liters.

τ: the residence time in seconds.

F: the flow rate of the liquid waste in liters/hour.

In the present system, the volume of the chamber (V) is 13 L.

For good mixing purposes, the diameter (D) of the chamber was found as

$$D = 90\ F/Re \quad \text{(meters)} \tag{2}$$

Re: Reynolds number.

The complete design derivation is shown in Appendix B.

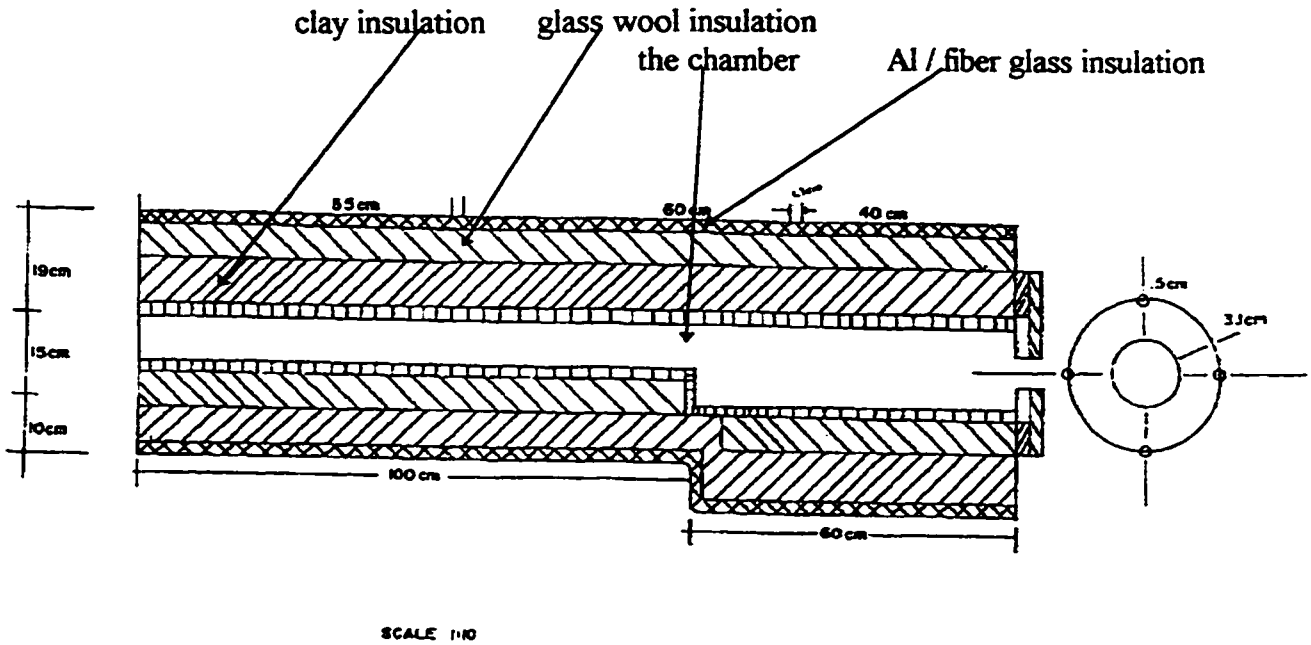


Figure 2.4. The chamber

The second part of the chamber is very useful to ensure complete mixing, because of the small D, for analysis purposes. However it can not be very small, otherwise, the flow of the gases from the bigger part will be retarded and this will cause disturbances in the chamber, which in turn may cause an explosion inside the chamber, because the system may approach the limit of the closed system characteristics.

The chamber is insulated on the exterior with a clay, used for making fire bricks, followed by two layers of fiber glass insulation. Thermal properties of the insulator used are characterized and accordingly, the design of the insulation is made. The details of the design and characterization of the insulator are given in Appendix B.

Thermocouples were located at three different positions of the chamber (Fig. 2.2 and Fig. 2.4). The same positions serve as sampling ports for analysis purposes. Thermolyne pyrometers with chromel-alumel (type K) thermocouple were used to measure the temperature inside the chamber. LEYBOLD digital thermometers 666452, a microprocessor-controlled temperature measurement, is used to monitor the temperature on the surface of the chamber as well as many locations in the incinerator by means of NiCr-Ni (type K) thermocouples. It should be remembered that type K thermocouples are rapidly contaminated in sulfurous atmospheres but are recommended for oxidizing and neutral conditions.

In the entrance of the chamber, four cooling-air inlets are made to adjust the temperature of the chamber to the required value (Fig.2.2 and Fig.2.4). These cooling-air inlets must be very near to the inner surface of the first part, so that cooling of the surface will be fast if any cooling is needed.

The air that enters around the flame from the entrance of the chamber could be considered as cooling air too. This cooling air can be adjusted to some extant by decreasing or increasing the distance between the burner head and the entrance of the chamber. However the main cooling-air system could be adjusted using a flow control valve of the air to control the temperature of the chamber.

2.4 COOLING SYSTEM

The cooling system consists of a shell and tube heat exchanger to cool the exhaust gases to the desired temperature (150 - 200 °C). Before released to the atmosphere, exhaust gases (Fig.2.2) are further cooled by mixing with fresh air.

For space limitations the length of the designed heat exchanger is taken to be 180 cm instead of 260 cm as calculated from the design equaions. However, this change has no serious effect on the operation. Any further cooling, if needed, can be done using air. The heat exchanger is made of stainless steel grade 304 sch. No 10. However the other parameters of the heat exchanger are the same as per design. Complete derivation of the heat exchanger design is given in Appendix C.

2.5 ANALYSIS SYSTEM

At the beginning of the work, we tried to purchase a gas monitoring system for analysis of the exhaust gas from the incinerator. These monitoring systems were found to be very expensive (at least 250,000 $) and will not be satisfactory for research purposes. For

example individual hydrocarbon components cannot be specified using these kinds of monitoring systems. Five components are mainly analyzed by such systems; namely oxygen, carbon monoxide, carbon dioxide, total hydrocarbons and HCl.

The analysis system consists of an infrared Miran 80 gas analyzer, with a variable length gas cell, and HP 5880A gas chromatograph (GC) equipped with thermal conductivity detector (TCD) and flame ionization detector (FID).

Miran 80 gas analyzer, which is a single beam variable wavelength IR spectrometer, has the potential of going to low detection limits making use of the variable-length gas cell. Path length could reach 23.5 m. Background subtraction is possible with certain limits. Even the interference of some compounds could be eliminated by using the associated FORTRAN program. Miran 80 gives a large dynamic range of absorbance vs. concentration for hydrocarbons in general.

For calibration purposes, the cell could be flushed with air (or any other gas) for about five minutes using the pump associated with the spectrometer. A vacuum pump is used to obtain about 10 mmHg pressure inside the cell. A known amount of the analyte is introduced (using a gas tight syringe) into the cell to give the maximum desired concentration. Then the valve of the cell is opened to obtain a total pressure of one atmosphere. The absorbance value at a certain wavelength and a path length is measured. The lower concentration could be obtained by pumping out some of the gas mixture in the cell and then diluting again to one atmosphere. With the help of a pressure gauge, which is connected to the cell, the dilution factor could be calculated and the new concentration will be known. In this manner, a plot of absorbance values versus analyte concentration is generated for a particular wavelength and a fixed path length.

Fig. 2.5 shows the concentration vs. absorbance of methane (standard high purity gas > 99.9 % from Fisher company). The curve has been found to be linear (correlation coefficient r = 0.999). In this case, the path length of the cell has been 21.75 m and the wavelength has been 3085 cm^{-1}.

Calibration curves for CO gas have also been obtained. Using high purity standard CO gas (>99.9 % from Fisher company), absorbance values at 2004 cm^{-1} were measured for different CO concentrations.

For CO the absorbance versus concentration has been found to be nonlinear. However nonlinear curves can still be used as long as the curve represents a one to one function.

The nonlinear behavior of CO is studied in a little bit more detail. The effect of vibrational coupling was thought to be one of the reasons for the nonlinearity. Hence absorbance vs. concentration was measured in helium gas as the environment. It has been found that the absorbance of CO is less in a helium gas environment than that if other diatomic gases are present. For more comprehensive explanation the reader is referred to references [33, 34]. Fig.2.6 compares the absorbance of CO under helium and nitrogen environments (path length = 21.75 m and wavelength = 2004 cm^{-1}). And Fig. 2.7 compares again the absorbance of CO in He compared with oxygen and air (path length = 9.75 m and wavelength = 2004 cm^{-1}). The trend is the same in all of the experiments done. The results are reproducible under the same conditions.

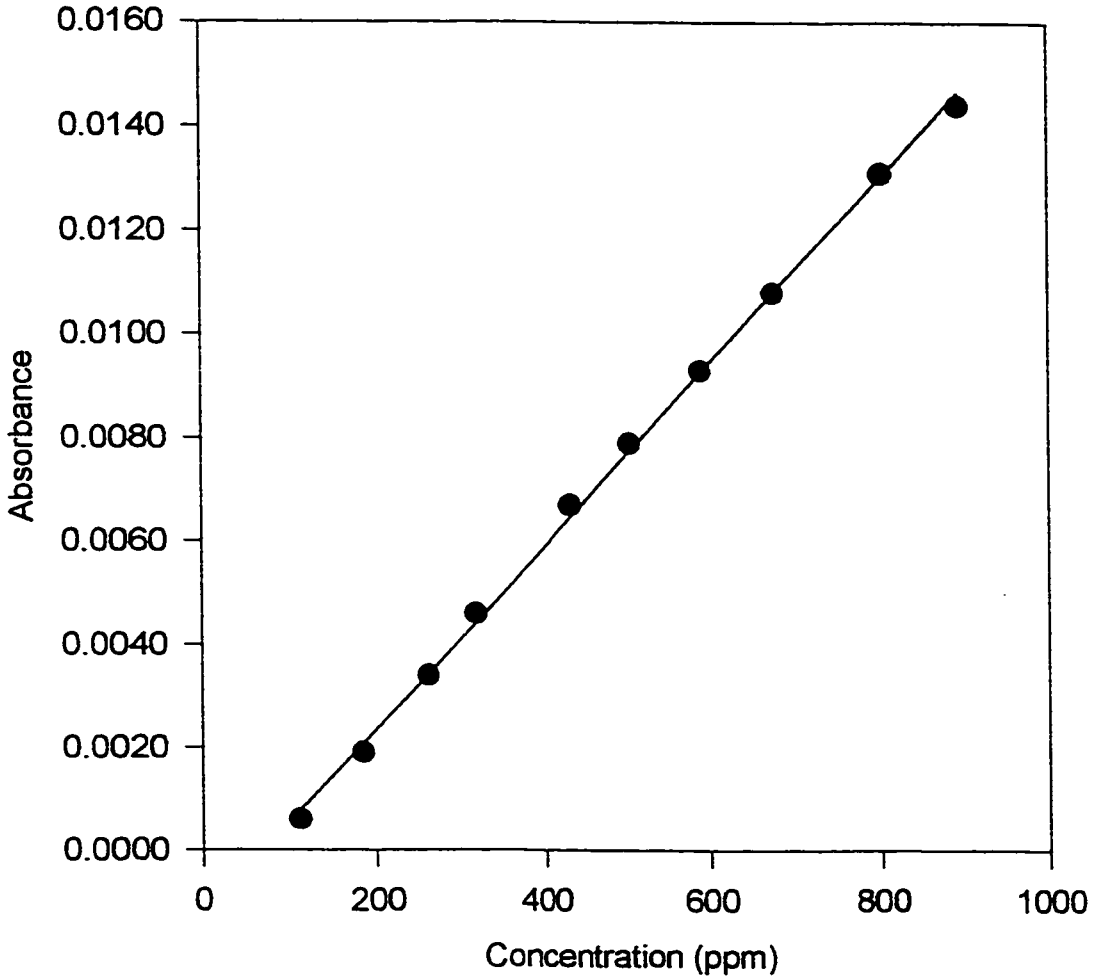


Figure 2.5 Methane calibration curve for Miran80 infrared gas analyzer.

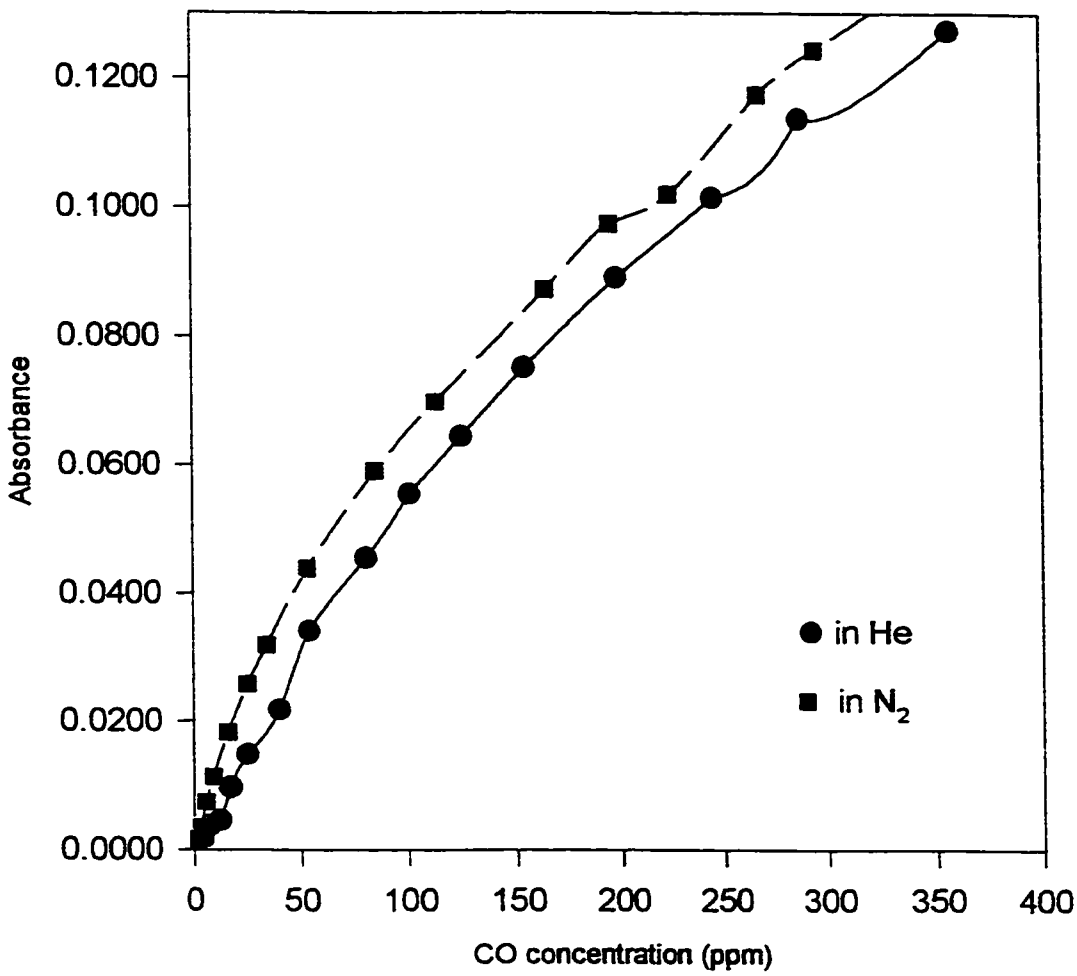


Figure 2.6 CO Absorbance vs. Concentration in helium and nitrogen

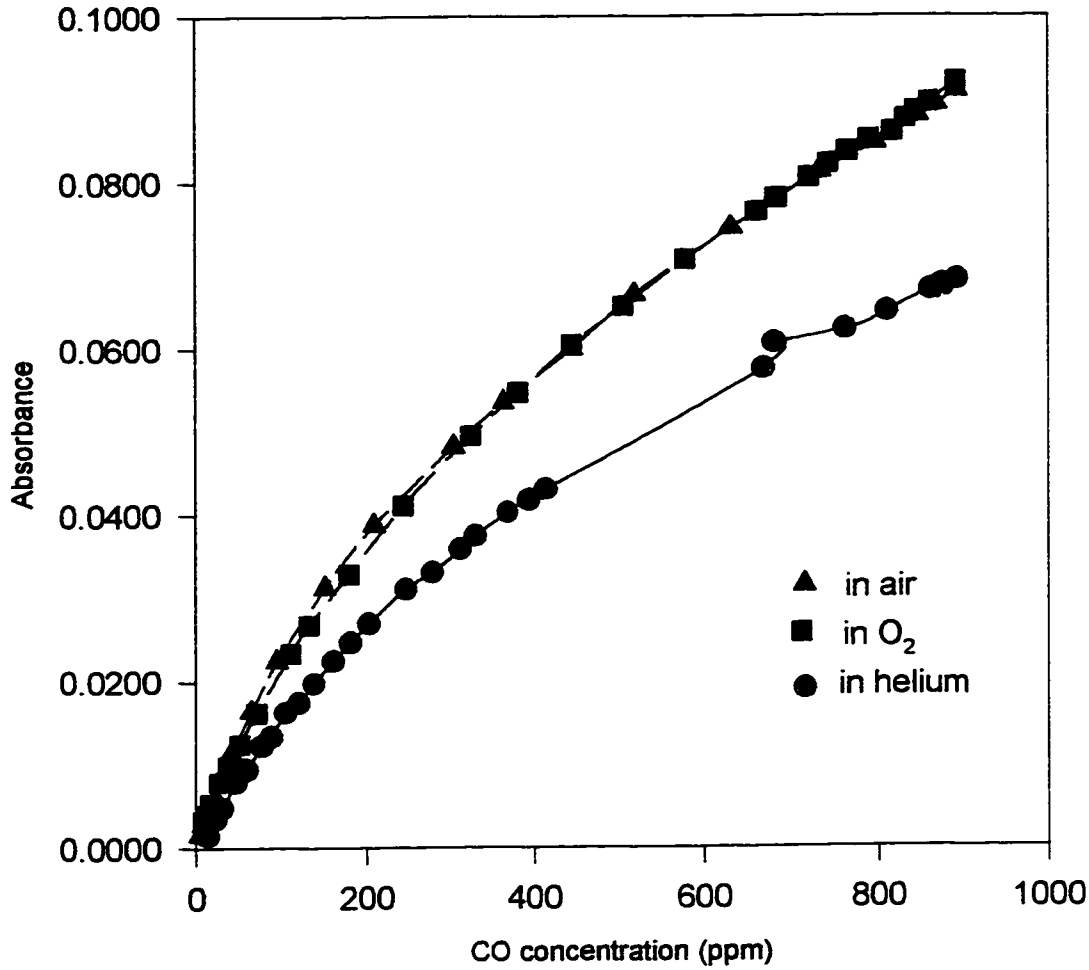


Figure 2.7 CO Absorbance vs. concentration in helium, oxygen and air.

For analysis using the GC, the sample is extracted from a sampling port by vacuum pump via ¼" outside diameter (od.) stainless steel heated lines and then through the 1/16" od. sampling loops of the GC. The pump as well as the heated lines are interfaced with the GC for complete automation which greatly enhances the reproducibility of the results.

A bypass ¼" heated line is connected from the burner to the analysis system, so that a quantitative comparison between the inlet and the outlet can be done.

The plumbing system in the GC allows the analysis of O_2, N_2 using TCD and CO and individual hydrocarbons using FID. Sampling loops are installed in the GC and operated by solenoid valves for automatic injection of the sample.

Columns used are of special importance. The types of columns could vary according to the need . More details will be given in the operation and procedure chapter; CHAPTER III.

During the course of work, the GC has been found satisfactory in giving the required data. Therefore, Miran 80 gas analyzer has not been used in this work.

2.6 FEEDING SYSTEM

Four important feeds are considered in the design :

- Chemical waste feeding

  Chemical waste feeding system consists of two pulsating flow metering pumps connected to a pressurized (25 psi) accumulator to convert the pulse flow to a continuous one (Fig. 2.2 and Fig. 2.8). The pumps are interfaced with the GC for automated operation. Complete description of the electrical circuit used is given in

Appendix D. The accumulator is connected to a rotameter to adjust and monitor the flow rate for each steady state. The rotameter is connected to a preheating 0.65 cm (1/4") od. stainless steel pipe inside the insulation of the chamber. Another electrically heated "damper" is used to absorb any disturbances in the flow of the steady state feeding(Fig. 2.2 and Fig. 2.8).

This type of feeding seems to play an important role for obtaining reproducible results. The outlet of the damper is connected to the burner as shown in Fig. 2.8

- Combustion Air Feed

  Air for combustion is connected from a compressor and/or a pressurized air (form the University main lines) through pressure regulators to the burner. The configuration (Fig. 2.2 and Fig. 2.8) allows premixing of air with waste feed before it enters the burner.

- Cooling-air Feed

  To control the temperature of the chamber at any desired value, it is necessary to be able to cool the chamber. The same source as the combustion air is used to cool the chamber as shown in Fig. 2.8 and Fig. 2.4.

- Additives Feed

  Any additive can be mixed with the air and chemical waste before entering the burner and/or after entering the chamber (Fig. 2.2).

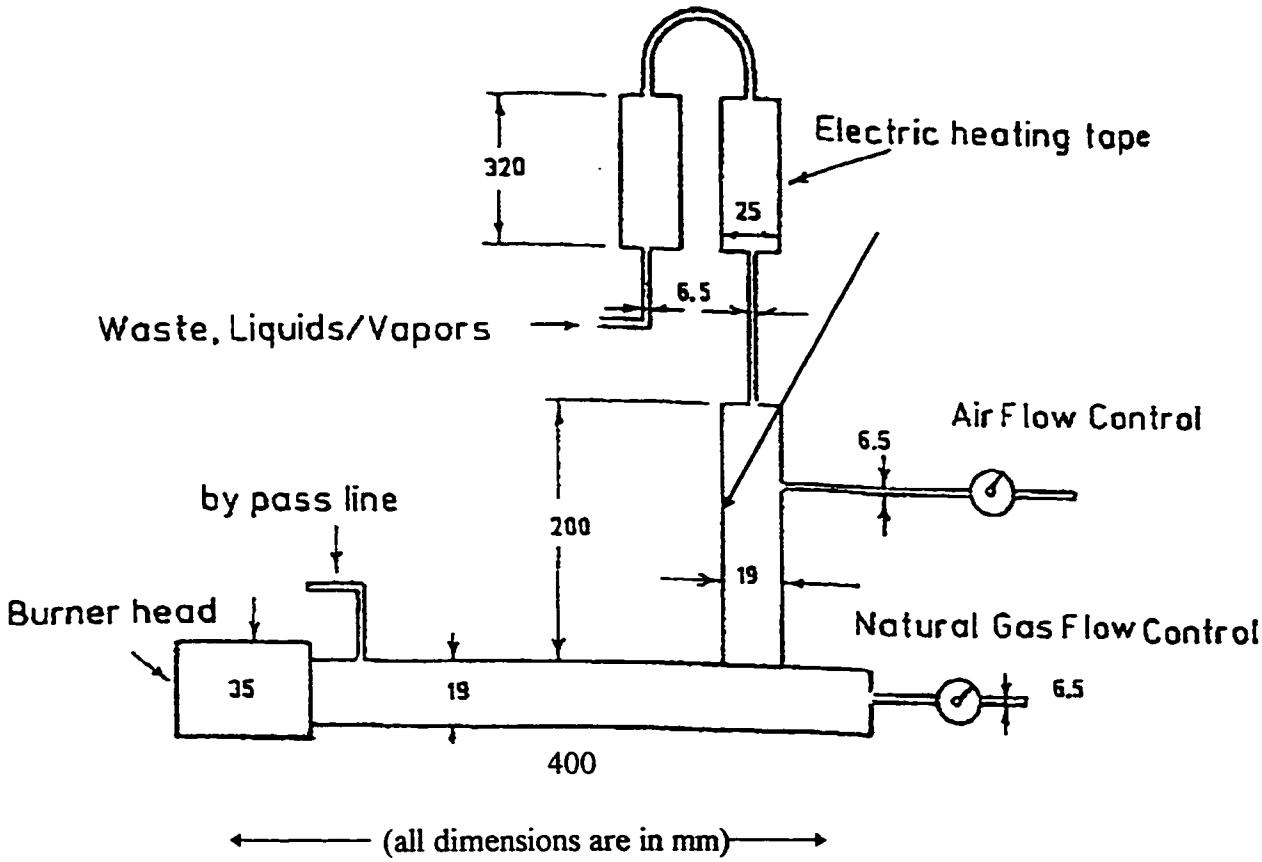


Figure 2.8. The feeding system

CHAPTER III

OPERATION AND PROCEDURE

3.1 OPERATIONAL PROCEDURE

The general operational procedure can be summarized in the following steps :

1- Heating up the incinerator by natural gas only to the desired temperature.

2- Starting heating of the sampling lines (automatically controlled).

3- Starting up the metering pumps to fill the accumulator with the liquid waste (automatically controlled).

4- Opening the pressure regulator of the accumulator to maintain a constant pressure in the accumulator (using air usually at 25 psi).

5- Opening slowly the liquid waste control valve while decreasing slowly the flow of the natural gas.

6- Waiting until the flow of the liquid waste becomes in a steady state.

7- Switching on the temperature monitoring system.

8- Starting sampling and analyzing (automatically operated) the exhaust gas every five or ten minutes.

9- Comparing the results of the successive analyses as well as the temperature monitoring (by chart recorder) to see whether a steady state is achieved or not.

10- If a steady state is verified, the system is ready for continuos operation. It is not safe to leave the system unattended in the first hour after the first introduction of the chemicals.

3.2 GENERAL CONSIDERATIONS

3.2.1 The First Operation

After the installation of all of the subsystems as shown in Fig.2.1, the incinerator was continuously heated at 800-900 °C for 10 days to remove any particulates or dirt that may be present inside the incinerator. After this period there was no smell from the incinerator. From the start-up operation to the end of this work, the system was running continuously either on chemicals or natural gas especially during the night.

Many problems appeared in the first days of operation. Upon introduction of the chemicals, the flame used to extinguish quite frequently. The reason found was mainly in the feeding system design. If the sample is immediately introduced from the primary heating zone (#6 of Fig. 2.2) to the burner, any disturbances in the flow of the waste will be reflected immediately on the flame. These disturbances were sufficient to extinguish the flame several times during the day. Using a secondary heater, as shown in Fig. 2.8 was found to be useful in adsorbing these disturbances. This design seems to ensure the introduction of a homogenous mixture to the burner. In addition to solving the problems with extinguishing flame, this design contributed a lot in solving the reproducibility of the analysis.

3.2.2 Waste Introduction

Waste must be introduced gradually up to the desired flow rate. This can be done using the flow control valve in the rotameter (#3 of Fig. 2.2). Fast introduction of the waste results in flame extinguishing. Depending on the heating value of the waste type, the quantity of natural gas may be decreased or increased upon waste introduction. In the work done, the natural gas is reduced to the minimum because of the high heating value of the simulated waste used.

Chemicals are introduced using the metering pumps as shown in Fig. 2.2, through the heated pipe (#6 of Fig. 2.2) and the secondary heater (#8a of Fig. 2.2, and Fig. 2.8). Thus, liquid chemicals are converted to vapor. This vapor is then mixed with air in a pipe (70 cm long and 19mm id.) before entering the burner head as shown Fig. 2.8.

It has been noticed that at least one hour is needed to establish a new steady state if the difference from the previous steady state is small. For example, a new steady state may be created by changing the fuel/air ratio. If this change is small and , therefore, the temperature difference between the initial and final states is small e.g. 5 -10 °C, about one hour is needed for the new steady state to be established. But if the difference between the two steady states is large (100°C), two or three hours are needed. If the difference is around 300 °C, 7 to 8 hours are needed to establish the new steady state of operation.

Since the incinerator is kept operating continuously, there is no need for heating the incinerator each morning.

By using the timer of the GC, the pumps and the heated sampling lines can be started. The timer could be programmed according to the procedure needed. To prevent the pumps from heating up, the two pumps work alternatively at about ½ hour intervals. A control valve in the rotameter can be adjusted to the desired flow rate of waste.

Upon introduction of each liquid waste, many disturbances in the flame occur. After half-hour to one hour, the flame becomes stable. The natural gas flow rate can be decreased slowly while adjusting the air flow rate to keep the flame stable. A good practice is to keep a little natural gas with the chemical feed which serves as "fine tuning" of the flame.

By the time a steady state is reached, the heated sampling lines also reach a steady state as could be shown from the readings on the temperature monitoring system. It is a good practice to flush the sampling lines for 5 to 10 minutes by the exhaust gases to be analyzed before any analysis is made. This practice ensures that the analysis represent the actual product and that adsorption-desorption process has reached the steady state. After this flushing, the sample is extracted through the GC loops by the vacuum pump interfaced with the GC. The GC can be programmed according to the specification of the analysis needed.

3.2.3 Safe Ignition

If the flame is extinguished for any reason, the pilot flame underneath the burner is supposed to ignite the flame again. However some times self ignition may not succeed. In this case the operator must interfere to ignite the flame. Immediate ignition of the flame may cause a small explosion inside the chamber, because of the accumulation of the

undestructed vapor waste inside the chamber. The operator should first close the valve of the waste after the secondary heater (#8a of Fig. 2.2) and allow air only to go through the system by using the air flow control valve (Fig. 2.8) for about 5 minutes. After flushing by air, the ignition is restarted using natural gas only. When the flame is stabilized using natural gas only, the valve after the secondary heater is then opened gradually while adjusting the flow of the natural gas to the desired rate. This procedure ensures a safe ignition of the incinerator if it is extinguished during the operation.

Flame extinguishing is one of the serious upsetting conditions that occur in incinerators. Because of this problem, an alarm is introduced in association with the pilot flame feed back control system. This alarm will warn the operator. The pumps will also stop automatically. However, the dead volume of the waste in the feeding system is still large and is sufficient to deliver a considerable amount of waste into the chamber. The operator should be very fast in reigniting of the flame. Coke formation inside the heating system is very probable; particularly if waste is kept for long time inside the heaters of the feeding system. In the present work, it has been found that about 7-8 minutes was sufficient to return the incinerator back to the original state.

3.2.4 Stopping of the Incineration of Waste

To stop the incinerator, the waste pumps must be stopped first. Then the flow rate is decreased gradually using the flow control valve before the rotameter (#3 of Fig. 2.2). Meanwhile the flow rate of natural gas is increased or decreased according to the previous situation prior to the introduction of the waste. After stopping the flow of the waste

completely, air is introduced (#4 of Fig. 2.2) through the feeding system for cleaning of the tubes to prevent coke formation inside the tubes which may plug the heating tubes in the incinerator. It is a good practice to keep combustion air going through the feed system overnight (when the incinerator is just operating using natural gas only) to ensure the cleaning of the pipes. Indeed before doing this procedure some of the pipes were plugged after the stopping of the waste flow. Using this cleaning air solved the problem completely. However, introduction of the cleaning air must be very slow, otherwise the remaining waste in the feeding system will be pushed in large quantities out of the burner which may cause a fire accident or leakage of the waste vapors inside the room where the incinerator is located.

After stopping the waste flow and after completely flushing the feeding system with cleaning air the temperature must be gradually decreased to the non-operating temperature (500 - 700 °C). One should remember that a sharp decrease in the chamber temperature, e.g. from 900 to 500 °C , may cause cracking of the chamber. Two hours could be needed for the safe decrease of the temperature from the operating temperature to the non-operating temperature.

3.3 CHEMICALS

In this work, a mixture of heptane and benzene(general purpose reagents,>99.5%pure) (4:1 v/v) is used. Heptane has been chosen as a representative of alkanes which are present in most of the waste of the University. Benzene has been chosen as a representative of aromatic compounds. It is known to be carcinogenic. It is one of the most frequently

detected organic compounds emitted from devices burning hazardous waste [9]. Benzene is ranked as the third most thermally stable hazardous organic compound among 320 compounds tested by Taylor *et al* [6].

3.4 ANALYSIS SYSTEM

3.4.1 Gas Chromatograph Conditions

As mentioned in section 2.5, GC has been found to be satisfactory for the present work. Using a suitable plumbing system in the GC many compounds could be analyzed for each sample. Nitrogen, oxygen, and carbon monoxide can be analyzed using *13X molecular sieve* 4'* 1/8" or *carboxen-1004* (from *SUPELCO*) columns. Benzene, toluene, heptane, hexane and methane can be analyzed using *GP5%SP-1200/1.75%Benton34* 6'*1/8" (from *SUPELCO*) column. A suitable configuration of the plumbing system with optimum conditions in the GC allows fast, five minutes between each two successive samples, analysis of the exhaust gas.

The following conditions have been used in the GC :

- Carrier gas was helium.
- 13X molecular sieve 4'* 1/8" column has been used for N_2 , O_2 and CO separation with He flow rate of 25ml/min
- GP5%SP-1200/1.75% Benton34 6'*1/8"column, from SUPELCO, has been used for benzene and heptane separation with He flow rate of 20 ml/min.

- Oven temperature is 65 °C
- FID and TCD are at 180 °C
- The volume of the sampling loops :

  for molecular sieve column, the volume is 0.511(±0.004) ml

  for Benton34 column, the volume is 0.258 (±0.003) ml
- The pressure for the solenoid valves is 80 psi
- The pressure of H_2 for FID is 70 psi
- The pressure of air for FID is 40 psi.

CO can be detected by FID after converting it quantitatively to CH_4 by using a Ni catalyst heated at 350°C under the hydrogen gas.

It has been noticed, when TCD is used, that the base line of the chromatogram moves steadily upscale during the run after 30 days of continuous running . This happens most probably because of saturation of the column (13X molecular sieve) with water and carbon dioxide, which in turn change the properties of the stationary phase of the column. This problem was reduced by keeping the column overnight at 115 °C, under helium carrier gas for desorption of some water or carbon dioxide. However, it was found that for complete correction of the base line, it has to be heated up to 300 °C overnight under helium gas. But it should be remembered that this temperature will damage the stationary phase, *GP5%SP-1200/1.75%Benton34*, of the other column which is a part of the analysis system. The maximum working temperature of the *GP5%SP-1200/1.75%Benton34* stationary phase is 125 °C . So for complete reactivation of the 13X molecular sieve column, the other column must be removed from the oven of the GC. It has been noticed

that Complete reactivation of the 13X molecular sieve column is needed every 40 - 50 days of operation, while partial reactivation (at 115 °C) was done daily.

At the beginning of the work *carboxen-1004* column from *SUPELCO* is used for separation of CO and CO_2 from other gases. Since the concentration of CO_2 to CO is very large and the retention time of CO_2 is much longer than CO, the optimization of the GC conditions was very difficult in two aspects. First, much longer time was needed for elution of the CO_2 which in turn increases the analysis time to at least 15 minutes if CO_2 to be analyzed. This makes the analysis system impractical for monitoring purposes of the incineration process, because the maximum allowed time between two measurements is 15 minutes according to EPA [9]. Second, the nickel catalyst could be poisoned because of the large concentration of CO_2 which is always the case in the incineration exhaust gas. Coke formation is expected on the catalyst upon methanation of CO and CO_2.

However, using 13X silica gel column is very practical in the analysis because it absorbs water and carbon dioxide. N_2, O_2, and CO are easily eluted without interference by water and CO_2. Another advantage, as mentioned above, of the adsorption of CO_2 is to increase the lifetime of the nickel catalyst.

At the end of each working day, the catalyst is kept overnight at 350 °C under H_2 gas for reactivation.

The volume of the loops were measured using liquid mercury . The loops were filled many times with mercury and the weight is measured using a four decimal analytical balance. The density of the mercury at room temperature (24 °C) is taken to be 13.536 g/ml [35]. The average of five measurements is calculated.

3.4.2 Reproducibility of the Analysis Results from the Monitoring System

In such big systems the reproducibility of the result could not be easily obtained in many cases, especially where high precision (less than 1% difference) is needed. If any disturbance occurs in the feeding system, it will be reflected in the outlet gas composition. Hence the reproducibility of the analysis of the outlet gases will be disturbed. So one should be careful in monitoring the feed before starting the analysis of the exhaust. This can be achieved by the analysis of the inlet by using the bypass line, Fig. 2.8, or simply by monitoring the rotameter of the waste and the associated pipes, since in our system they are made from transparent Teflon.

If one of the heating tapes of the sampling line is damaged while the analysis is going on, no reproducible results will be obtained; irrespective of the length of time spent for achieving a new steady state of the analysis system. This is because of the condensation of the water and other volatile organic compounds inside the part of the pipe where the heating tapes are damaged. In the present work, digital thermometers equipped with thermocouples systems are used to monitor each part in the analysis as well as other subsystems in the incinerator. It has been found that the rate of damage of the heating tapes is around one tape per month.

Flushing the sampling lines by the exhaust gas to be analyzed is a very important step to obtain reproducible results. Fast flushing can be done using the vacuum lines from the University main lines. It is connected to the end of the sampling lines (#9 of Fig.2.2). However, it was found that using the vacuum pump to draw the sample from the sampling

lines through the GC sampling loops, while leaving the University main vacuum line opened, results obtained are not reproducible (more than 10 % difference), irrespective of the time waited to achieve a steady state in the analysis system. However, if the vacuum valve of the University main line is closed during the sampling for analysis, the reproducibility of the results will be much better. So after flushing of the sampling lines using the University main vacuum lines, the vacuum pump only must be used for extraction of the sample from the incinerator as well as from the sampling line.

Forced draft using the University suction fan has been used to get red of the exhaust from the incinerator. If the flow rate of the suction is changed it will be reflected on the reproducibility of the results. This parameter must be constant or nearly constant if good reproducible results are needed. One can check the change in the flow rate because of suction disturbances by analysis of the nitrogen of the exhaust gas. The nitrogen has been analyzed from time to time to check the disturbances of the flow rate as a result of the exhaust fan. It was found that there is a little change from the day to night time and between the working days and the weekend. Sometimes, it was found that there is an unexpected change of nitrogen gas concentration in the exhaust gas of the incinerator at the end of the working day (around 4 o'clock). Therefore, enough time has to be given for a new steady state to be established after this time.

The flow rate of the water in the heat exchanger of the cooling system is found to affect the reproducibility of the analysis results. The main reason for this effect could be the analysis sampling port mainly used in this work (#7d of Fig. 2.2). It is to be noticed that the sampling port is near the heat exchanger. If the rate of water is changed, the rate of cooling of the gas will change as well; which in turn increase or decrease the volume (the

flow rate of the gases as well) of the exhaust gas. So it is necessary not to change any condition after the desired steady state is established.

Since the incinerator is inside a room (2.5m*4m*3m), the air conditioning system has been found to affect the steady state as well as the reproducibility of the analysis. Also it has been found that one hour is needed to reestablish a new steady state if the door of the room is closed or opened; depending on the previous situation.

Using the metering pumps, the accumulator and the non-returning valves has been found very important for obtaining reproducible results of the analysis of the exhaust gas of the incinerator. This feeding system, as one unit, guarantees that the flow goes through one direction towards the burner. One should notice that if the feeding system design was improper, a flow back of the waste may occur upon entering the heating zone of the feeding system. Even if there is no good design in the feeding system, any disturbances will affect the feed as well as the reproducibility of the results.

Coming to the analysis system itself, the GC has its own conditions to give a good reproducible result. Fortunately the literature is good enough in covering all of the information needed for operation and optimization of GC parameters. One point to be mentioned here, is the effect of injection method on the reproducibility. According to literature [31, 39], If a syringe injection is used the results of the analysis will be reproducible within 2% and if sampling injection loops are used the results will be reproducible within 0.5%. However, one has to be careful in reporting the reproducibility of the GC results as the conditions of the injection have to be clearly indicated. It has been observed that sometimes, a certain value of the reproducibility is indicated without indicating the exact conditions of analysis [31, 39]. This may give incomplete or misleading

information about the process. The reported reproducibility is not true if volatile organic compounds need to be analyzed especially at higher concentrations. In trying to reproduce the concentration of benzene or hexane above the surface of the liquid using the syringe injection method, an error of 800 or 1000 % was observed. However, by doing the same experiment using the permanent gases; nitrogen, oxygen, carbon monoxide and carbon dioxide, the results of the analysis were exactly within the reported literature value. Hence heating the sampling lines is very important for analysis of volatile organic compounds. According to the literature the highest reproducibility could be achieved, using GC by sampling loop injection method, is within 0.5%. Indeed in the present work most of the results were reproducible within 1% difference and several times the reproducibility was within 0.5%. This gave us confidence in controlling nearly every parameter that could affect the analysis; which in turn has a direct correlation with the incinerator parameters.

Another parameter, which is related to the effect of the injection on the reproducibility of the results, is the storage time of the sample in the sampling loops. After extracting the sample through the sampling loops from the sampling line using the vacuum pump, the sample must be stored in the loops for certain time to attain an equilibrium after the vacuum pump automatically stops. This storage time, between the stopping of the pump and the injection of the sample, is very critical in obtaining reproducible results for a given steady state. For example changing this storage time by one minute could change the result by an amount up to 30% difference. During this work, four to five samples are analyzed for each datum recorded. Each point is resulted from certain steady state. The first sample was always discarded because it was found always different from the other successive

measurements. However, the rest of measurements for the same steady state was found pretty reproducible.

Around 30 days of continuous work have been spent just to increase the reproducibility of the analysis so that the difference between two successive reading is reduced from 10% to within 1%.

As shown above, to obtain reproducible results one should be very careful in investigating all the conditions and the parameters of operation.

3.4.3 Unknown Peaks in the Background of the GC.

Some times the background of the analysis is desired to be seen. Many times some small peaks where found using TCD or FID in the GC if the air is taken from inside the room. It has been found that these unknown peaks disappear if fresh air is taken from the exhaust of the air condition in the room. This suggests that some chemicals may exist inside the room because of the working conditions.

3.5 SUDDEN CHANGE IN THE INCINERATOR CONDITIONS (UPSETTING CONDITIONS)

During operation, some troubles could occur, which requires fast corrective actions; otherwise meaningless data will be reported about the incinerator performance. The monitoring system is the indicator used to check whether any troubles or upsetting conditions occur in the incinerator.

More dangerous situation occurs if the troubles occur in the monitoring system rather than in the chamber, feeding system, cooling system and exhaust system. Some times the monitoring system could give 'excellent results' simply because it is not working properly or not doing real analysis for one reason or another. Here the problem is more serious. Checking the monitoring system can be done by analyzing a known samples.

3.5.1 Extinguishing of the Flame

Some times after fifteen hours of continuos operation using the simulated waste the flame suddenly extinguishes. It is very difficult to know the exact reasons behind it. A possible reason could be the formation of some coke due to over heating of the waste inside the heating pipes in the incinerator. With time the coke accumulates in the heating pipes, and after some time, could be few hours, it is pushed through the pipes of the feeding system. When coke goes through the feeding system pipes, especially the ¼" pipes, it may retard the flow of the waste to the extent of extinguishing of the flame. This problem can be overcome by introducing the cleaning-air (#4 of Fig.2.2) after each stopping of the incinerator and/or by increasing the quantity of the natural gas that is mixed with the waste feed. If the flame conditions are disturbed because of the retardation of the waste flow, the flame will be disturbed; but most probably will not be extinguished because the natural gas continues burning and thus maintaining the flame.

If the exhaust fan is stopped for one reason or another the flame will extinguish, especially if a lot of gases are to be exhausted. These gases can not be exhausted by natural draft alone. In this case the burner flame as well as the pilot flame may be extinguished because

of the flash back of the flame out side the chamber and out side the burner itself. This flash back is sufficient to disturb the flame conditions to the extent of extinguishing the flame. If this happened, it could be easily known because of the smell of the chemicals around the incinerator and a lot of soot will form at the entrance of the chamber and the burner itself. Flame extinguishing after a long run (15 hours) happened one time during the present work, when the incinerator is left overnight to achieve a certain steady state. Fortunately the feeding back electronic flame sensor was on and, therefore, the pumps were stopped automatically. The exhaust fan was found not operating in the morning. So this was the reason of extinguishing of the flame.

3.5.2 Lower or Higher Temperatures of the Chamber

Sometimes the temperature of the chamber increases or decreases from the operating temperature. If the flow rate of exhaust suction is changed, the air that enters from the opening of the entrance around the flame (Fig.2.4) will change as well. This air can be considered as 'cooling-air'. The temperature of the chamber will decrease if the amount of this cooling air is increased. On the other hand the temperature of the chamber will increase if the amount of this cooling air is decreased. The temperature of the chamber may change even when the air flow rate is constant. A possible reason in this case could be in the surroundings temperature during the day/night times. The 'cooling-air' associated with the flame will change the temperature of the chamber according to its temperature.

Using extra fuel will solve the problem of decreasing the temperature of the chamber. Decreasing the temperature of the chamber while keeping the flame conditions not changed

could be done by introducing the cooling-air through the four halls at the entrance of the chamber as shown in Fig.2.2 and Fig.2.4.

3.5.3 Sudden change in the reproducibility of the results of the analysis system.

Some times, while analysis is going on for certain steady state, an unexpected value could be recorded for the same datum under investigation. However after this sudden change the recorded values return back to the expected range. This kind of irreproducibility seems not avoidable from time to time. Most probably the analysis system itself is the reason behind this sudden change rather than the incinerator itself. Most probably some dirt, e.g. coke, may enter the analysis sampling lines before going to the sampling loops. These lines are 1/16" od. Also some dirt may enter the sampling loops themselves, 1/16" od., and, therefore, occupy some fraction of the volume which in turn will affect the results of analysis. This dirt could be removed by auto-flushing the sampling lines and the sampling loops for the preparation of the next sample. After removal of that dirt, every thing returns back to the former steady state conditions, which in turn gives the expected results.

However, if the results continued changing (more than expected), other things must be checked, as was explained in section 3.4.2.

Sometimes the analysis give 'excellent results' but they are wrong. In the case where the base line in the chromatogram is very flat, i.e. no peaks are indicated, the results are most probably not true, especially if carbon monoxide is analyzed. One could reach zero peaks for the hydrocarbons outlet from the incinerator. However to obtain nothing of CO seems more difficult. Even methane is found usually in the outlet of the incinerator.

Complete flat line in the GC could happen if soot is formed in the incinerator. This soot may plug the analysis lines which in turn will prevent the sample to go through the sampling loops. Hence nothing will be shown as the results of the analysis. This problem could be solved by back flushing of the sampling loops and sampling lines by water pushed at high pressure (up to 10 atm) then flushing by air for half an hour to clean the rest of the dirt and to remove the water from inside the pipes. This must be done while the valve of the vacuum line is opened to accelerate the removal of the dirt. The heating tapes are turned on and the valve of the main vacuum line must also be kept open. At least one hour of heating is needed to start sampling again for analysis. This procedure has been found to be effective to remove any plugging of the analysis system, especially that soot is not soluble in any solvent.

If one wants to be sure about the flat base line, the easiest way is to analyze the feed using the bypass line. Because the bypass line of the feed passes through all of the lines for the analysis of the exhaust gas. If the results of the analysis of the feed is as expected, then there is no problem in the analysis system.

Using filters in the sampling ports reduces a lot the plugging of the sampling lines. They could be changed or cleaned after one month of operation. In the present work, a stainless steal mesh is used as filter in the sampling ports. It seems to be effective in prevention of plugging of the sampling lines.

CHAPTER IV

ELECTRIC POTENTIAL ON FLAME SURFACES

4.1 INTRODUCTION

The destruction of the waste occurs in the flame as well as in the chamber of the incinerator. As stated in section 1.3.5, the current incineration technology lacks rapid process monitoring and control. This has led to the ' infinity loop(s) challenge' discussed in section 1.3.5. To overcome this problem, we propose to study the flame itself and investigate if any correlation can be observed between flame properties and the incineration products.

It is well known that any flame has ionic species [28-32]. Flame ionization detector in gas chromatography and ionization probes are the most direct applications of this phenomena. "The presence of ions in a flame may be demonstrated by the distortion which occurs when an electric field is applied across it. Ions are detected in flames by introducing a pair of electrodes and measuring the current flowing when a potential difference is applied across them. The measured current depends on the mobilities of the ions and on space charge and boundary layer effects. Ionization has also been detected by measurements of microwave attenuation and by direct detection in a mass spectrometer" [28].

As mentioned in section 1.3.4, ionic species play a role in soot formation. However, there is no well understood mechanism that leads to soot formation. For instance it is not clear which ions (positive, negative, or both) that play role in soot formation. In addition, the role of these charged particles on the destruction of the hydrocarbons in the flame is unknown. The distribution of the charged particles in the flame is not understood. If it is uniform, what will be its effect on soot formation, or the destruction? If no, what is the

driving force of redistribution of the charges and how this will affect the destruction? All of these questions come to mind when one wants to consider the charged species in the flame. As stated earlier, the ions exist in the flame. For charge conservation, each positive ion must have a negative counterpart, not necessarily an anion. Under usual conditions in the flame "the majority of negative species consists of free electrons" [39]. The electrons are produced by direct ionization or through different ion-molecule reactions in the flame.

Studies on laminar flame modeling do not consider the dynamics of charged species in the flame [40-47]. Based on fluid mechanics, thermodynamics and chemical kinetics, complex flame models have been developed to predict concentration, shape of the flame and temperature profiles [40-47]. Without several approximations it is extremely difficult to solve such reacting flow mixture; namely, the flame [45-47]. Laminar flame theory does not explain some characteristics of laminar flames related to electrical properties of the flame[40-41]. For example, it does not predict whether there is a potential on the surface of the flame or not. Furthermore, It does not explain whether there is an electrical potential gradient across the flame and whether the potential inside the flame is the same as that on the surface.

So far, there is no qualitative model describing the dynamics of charged particles in a flame. The electrodynamics of charged particles must be introduced in any model that attempts to explain the charge distribution of flames. Theories of fluid mechanics, electrodynamics, chemical kinetics, and thermodynamics have to be combined in order to have a comprehensive view of the flame. This combination of different fields will increase the complexity of the problem. A step-wise solution may simplify the problem. For example, one can study the electrodynamics of the flame without considering in detail the

other fields, and then consider the other fields. In this present work, only a qualitative model of the charge distribution, based on electrodynamics, in the flame will be given. This will be clearer in the next section.

4.2 A PROPOSED QUALITATIVE MODEL FOR THE CHARGE DISTRIBUTION IN PREMIXED (LAMINAR) - FLAMES.

Fig. 4.1 shows different shapes of premixed flames. The flame may be considered to be laminar if its shape is within the indicated region[28].

Before describing the qualitative model of the flame, a few physical quantities have to be mentioned, these are the following (in order of magnitude):

- The classical diameter of the electron [48]: 10^{-15} m
- The diameter of a molecular particle (ionic or neutral molecules): 10^{-10} m
- The mass of electron : 10^{-30} kg
- The mass of the ions or neutral molecules : 10^{-26} kg
- The mean free path between the molecular species (T = 2000 K) = 6 μm.
- The ratio of the mean free path to the diameter of a molecular species = 6×10^{4}
- The ratio of a mass of a molecular species to the mass of an electron = 10^{4}
- The flame speed near stoichiometric conditions [28, 43] = 0.4 m/s

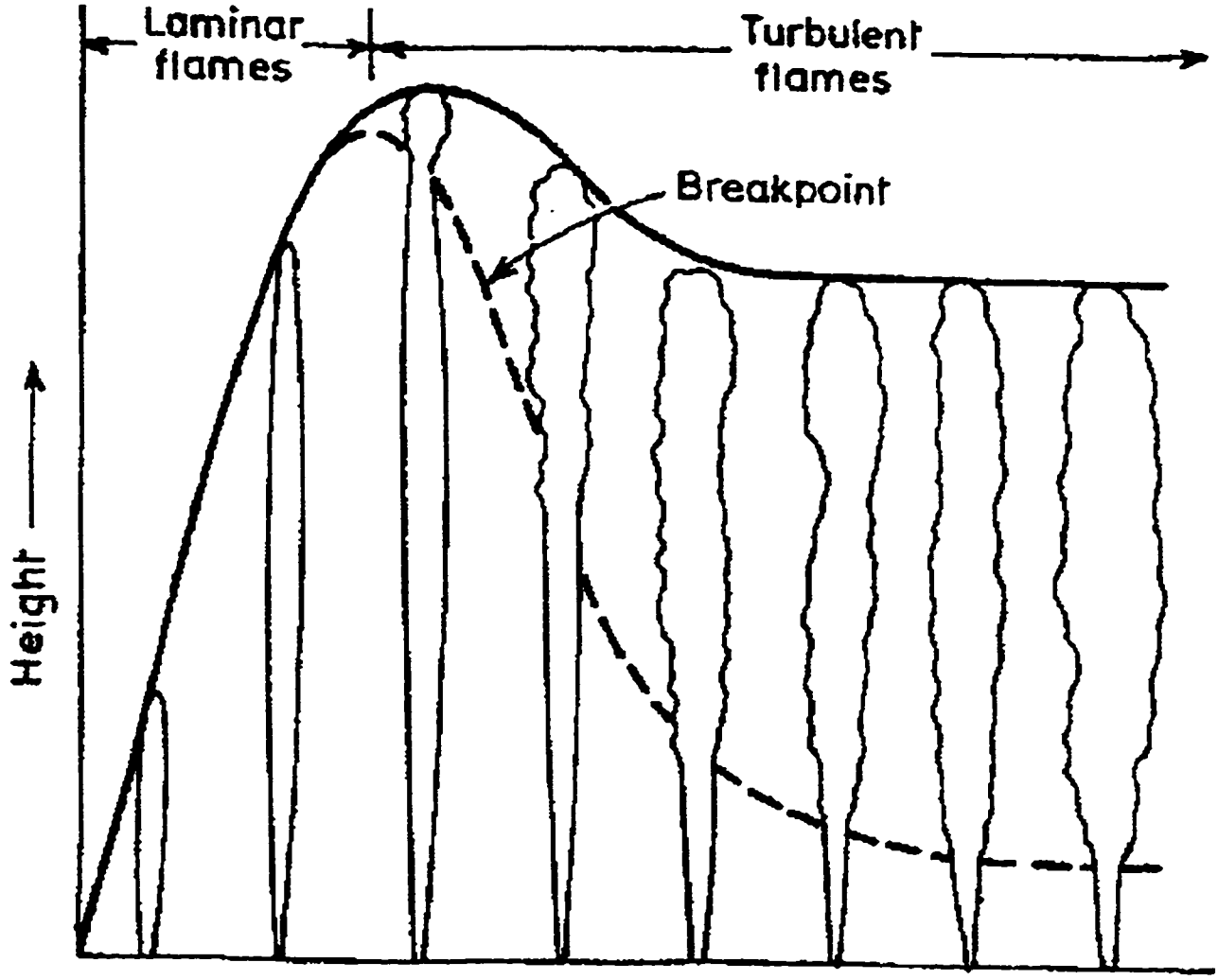


Figure 4.1 Breakpoints in laminar flame shapes [28].

To have a feeling of how these values are related, let's imagine the following:

- If the electron has 0.1 mm diameter, then
- the molecule diameter will be 10 meters, and
- the mean free path of the molecular species will be 600 km.

In this manner, the flame can be viewed as consisting of large entities (molecular species 10 m diameter). These entities are separated by about 600 km. Electrons (0.1mm diameter) will be somewhere in between these entities. This is a magnified 'picture' of the flame. This picture gives a feeling that the movement of the electrons is approximately free in all directions depending on the direction of the forces act on them. However, due to there masses, the motion of the molecular species, mainly, is in the direction of the flow of the flame. In addition, Laminar flames have distinct stream lines, which keeps the picture undisturbed in a given cross section of the flame.

The movement of the charged species produces an electric current. This current produces a circular magnetic field lines which is perpendicular to the direction of motion of the charged particles as shown in Fig. 4.2 [49]. If there is a charged particle (an electron in this case) which is relatively not affected by the flow of the flame, this charged particle will be trapped by the magnetic field lines produced by the moving ions.

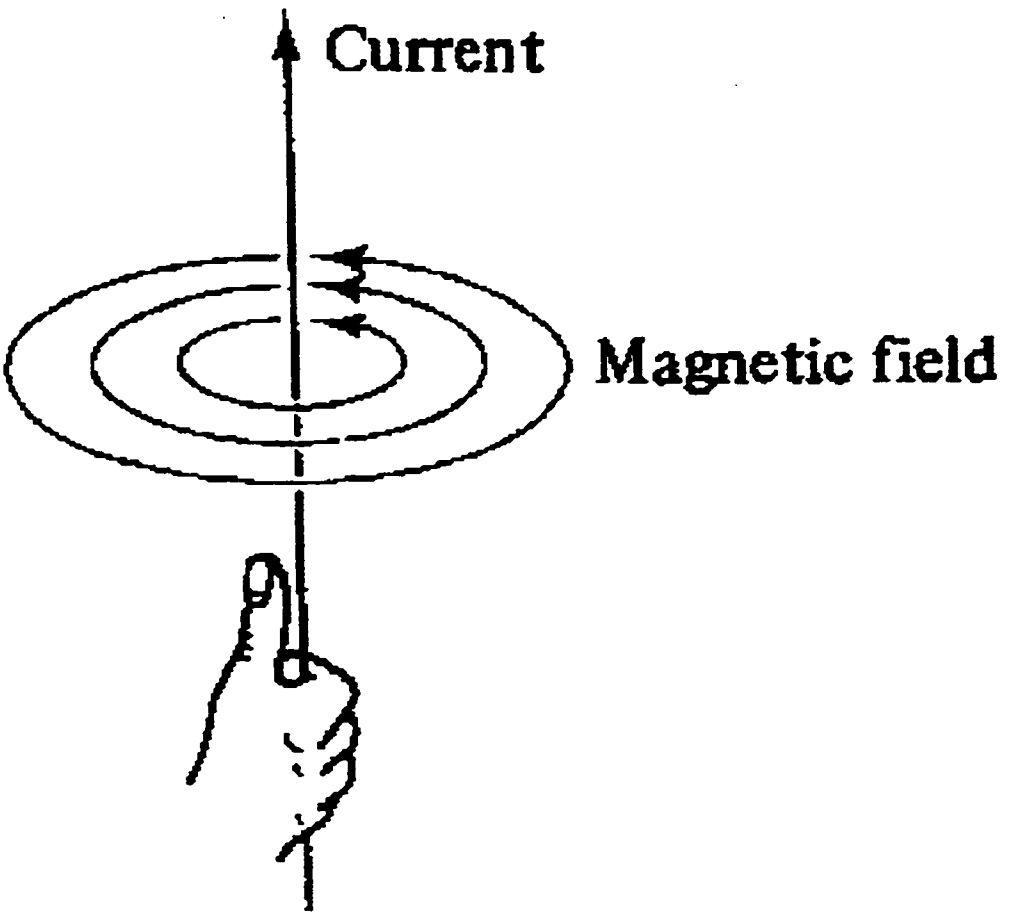
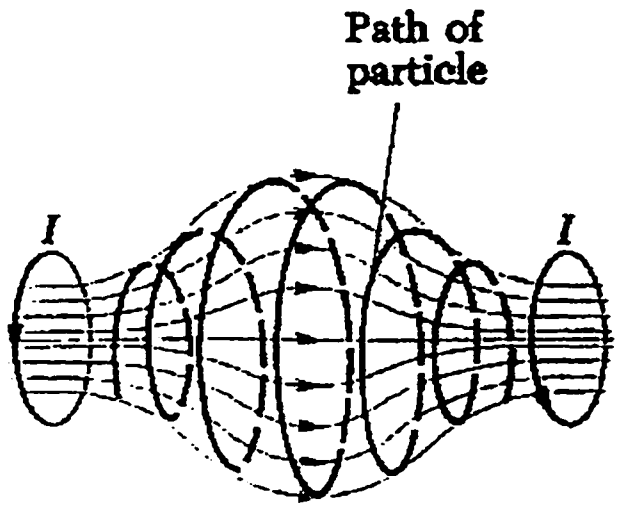


Figure 4.2 Magnetic field lines produced due to movement of charged particles (current).

From electromagnetic theory, the confinement of a charge to magnetic field lines takes the shape as shown in Fig. 4.3 [50]. The magnetic field creates a pressure (p_m) on these gyrating charges [50].The radius of gyration of the charged particles is known as Larmor radius. In our case, the magnetic field lines are circular. It can be shown that Larmor radius is directly proportional to the radius of the circular magnetic field lines. Fig. 4.4 summarizes the results of considering the electrodynamics of charged particles in the flame. Notice that, Fig. 4.4, Larmor radius is bigger in the outer circles of the magnetic field lines. Based on this qualitative model, it can be predicted that:

- The charge distribution in the flame is not uniform.
- The electrons will be concentrated more on a given hypothetical cylindrical surface in the flame compared to the inner parts of the cylinder. This will produce a net surface electron density (σ).
- There is a more positive electrical or current potential on a given cylindrical surface compared to the inner parts of the cylinder.
- Due to this electron density (σ), the surface of the flame has a positive potential. For a given radial distribution, the minimum value of the voltage is at the center. If the concentration of the positive ions, at the center of the flame, is more than that of the negative species, a negative voltage with respect to the ground will be developed.
- Electrons gyrate around the magnetic field lines contributing to the production of a net current.



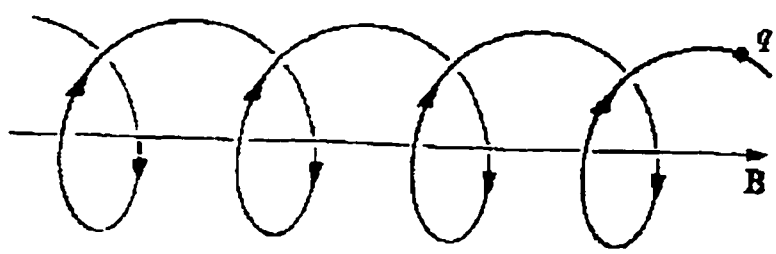


Figure 4.3 A confinement of a charged particle around a magnetic field lines.

up: inhomogeneous magnetic field, down: homogeneous magnetic field B.

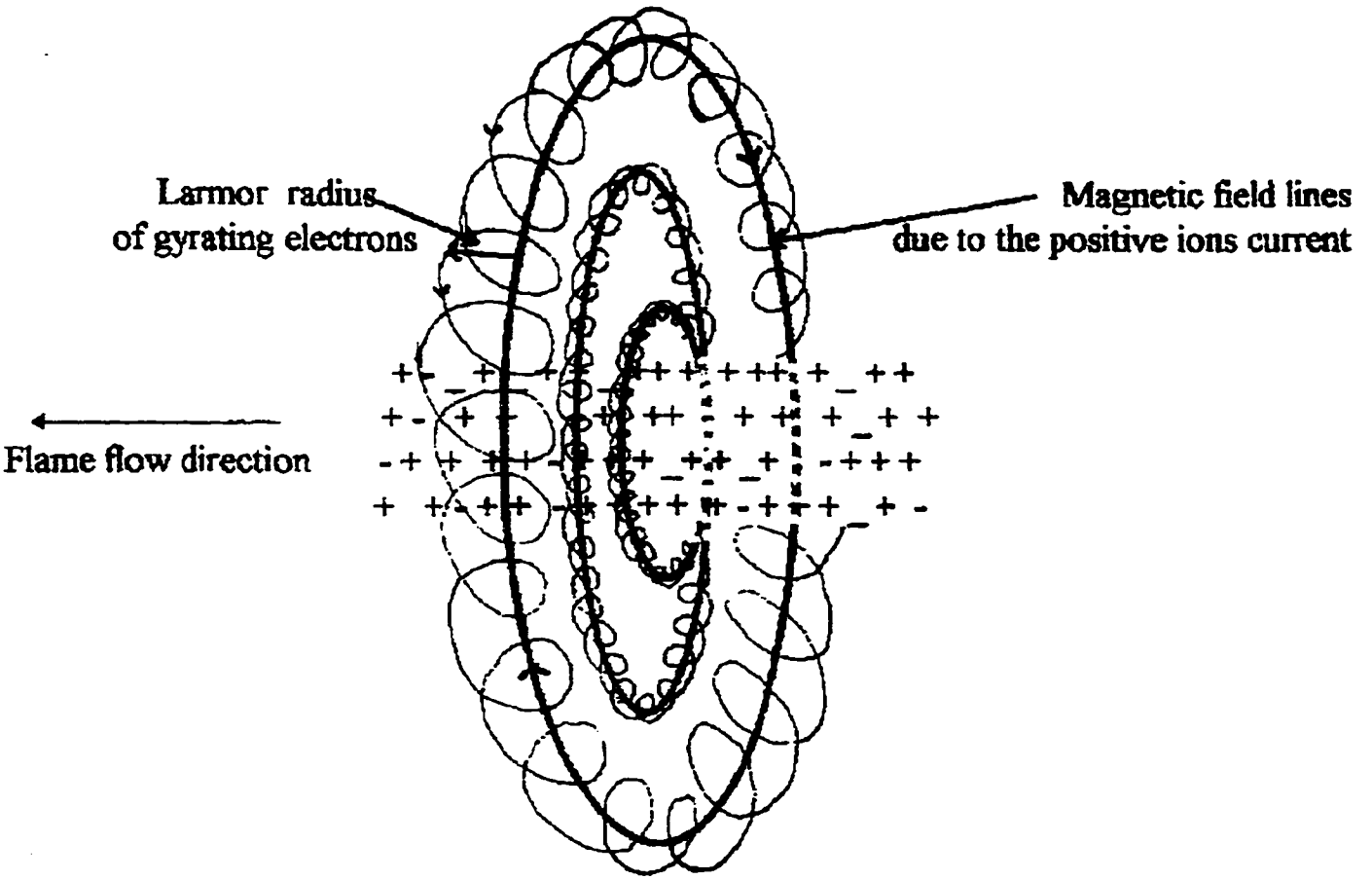


Figure 4.4 An electrodynamic 'picture' of the flame.
(the plus, +, and minus, -, signs represent the positive and negative ions respectively)
For simplicity, the magnetic field lines of the gyrating electrons are not shown

- The magnetic field of the gyrating electrons (magnetic moment) interacts with the magnetic field lines on a hypothetical cylinder. This interaction maintains a higher electron density on a given outer surface of the cylinder compared to the inner surface.

4.2.1 Experimental Evidence of the Proposed Model

How can some of these predictions be cheked? The developed voltage can be measured with respect to the ground, by simply inserting a conductor inside the flame and measuring the potential with respect to the ground using a voltmeter. In order to have a conventional configuration, the positive electrode of the voltmeter is attached to the burner head (grounded), while the negative electrode is inserted in the flame as shown in Fig. 4.5. The electrode used is a platinum cylinder. The electrode is insulated by a clay tube except its tip which is 1 mm diameter and 1mm long. For the stability of platinum electrode see sections 4.3.1 and 4.3.2.

A premixed flame with known composition as in Table 4.1 is used. The flame shape developed using this mixture is shown in Fig. 4.6. The outermost boundaries (air diffusion zone) are not fixed, and therefore, the tip of the electrode is inserted inside (about 3 mm) the outer cone. In this manner, the measured potential using this platinum probe has always been found to be positive.

Table 4.2 shows some axial surface potentials of the flame. The fact that a voltage is measured and that this voltage is positive is consistent with the prediction of the proposed

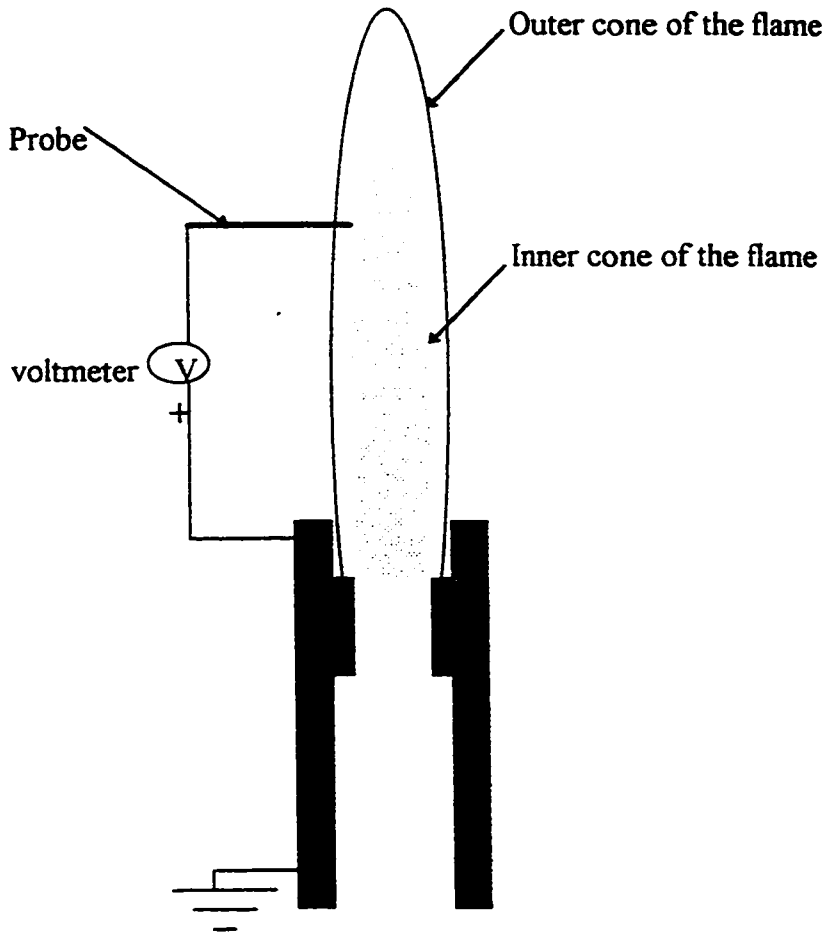


Figure 4.5 A setup for measuring the voltage of the flame.

Table 4.1 The feed composition of the flame for checking some of the predictions of the qualitative model of the flame.

Feed	Flow rate
Air	46.2 liter/min
Liquid hydrocarbons*	1.83 ml/min
Natural gas	4.40 liter/min

* Benzene & heptane, 1:4 (v/v).

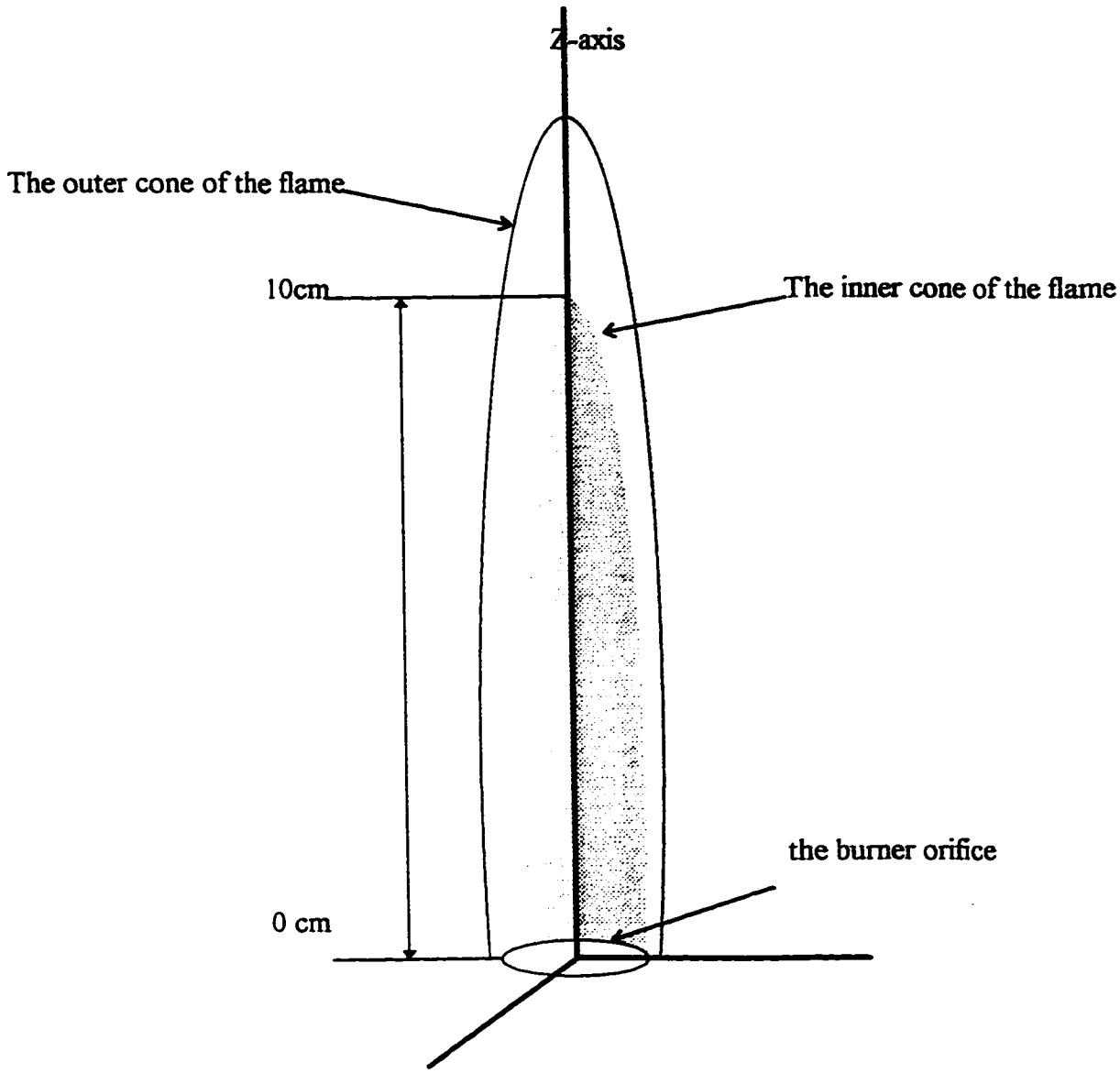


Figure 4.6 The flame shape developed using the feed as specified in table 4.1

Table 4.2 Axial potential and current of the surface of the flame (Fig. 4.6).

Z*(cm)	Voltage (volt)	Current (micro ampere)
2	+ 1.1	+ 0.09
3	+ 1.1	+ 0.09
4	+ 1.1	+ 0.1
6	+ 1.6	+ 0.13
8	+ 1.9	+ 0.14

* Distance form the burner orifice as shown in Fig. 4.6.

model. This means that the burner head can be considered as the 'cathode' and the flame as the 'anode'; i.e. the electrons flow from the flame to the burner head, which is an indication of the presence of electrons on the surface of the flame.

The voltage can be measured at any local point inside the flame, by allowing the tip of the electrode to touch the part of interest. Table 4.3 shows some axial potentials at the center of the flame. Again, The fact that a voltage is measured and that this voltage is sometimes negative is consistent with the prediction of the proposed model. At a distance of 8 cm from the burner head, the center of the flame has positive potential, this means that the negative species concentration is more than that of the positive species. However, the voltage is much less compared to the corresponding voltage on the surface as shown in Table 4.2. This is in agreement with the proposed model in the sense that the voltage of the flame in the center is less than that on the surface.

In addition to the voltage, the current in the flame can also be measured. As stated earlier, the current in the flame is the basic principle of the flame ionization detector and the ionization probes [28]. However, in these sensors a potential difference is applied to create a current across the flame, where the negative ions in the flame go toward the positive pole of the electrodes and the positive ions go toward the negative pole. The measured current depends on the applied voltage and on the concentration of the ions in the flame. In this case the current in the flame is measured with respect to the burner head. No external potential is applied. The driving force of the current flow, is the higher potential of the electrons in the flame compared to the ground (the burner head). The measured current on the surface shows that the electrons flow from the flame to the ground as shown

in Table 4.2. As in the case of the voltage, the current is also expected to be less positive (or negative) inside the flame, as shown in table 4.3.

Since the net current at the center of the flame closer to the burner head is negative, the total positive ions concentration is more than the total negative ions concentration. This is in agreement with results obtained using mass spectroscopy (Fig. 4.7) which has been used to study the ion concentration profiles in the flame [51].

Our interest in this work is related to the surface potential of the flame where it is expected to be positive. Therefore, whenever there is a reference to voltage in what follows in this theses, it always means the potential of the surface of the flame. In the following sections more concentration will be given to study the effect of the flame on some probes to be used in this work.

Table 4.3 Axial potential and current at the center of the flame (Fig. 4.6).

Z* (cm)	Voltage (volt)	Current (micro ampere)
2	- 0.3	- 0.04
3	- 0.3	- 0.04
4	- 0.2	- 0.03
6	- 0.05	- 0.03
8	+ 0.3	+ 0.05

* Distance form the burner orifice as shown in Fig. 4.6.

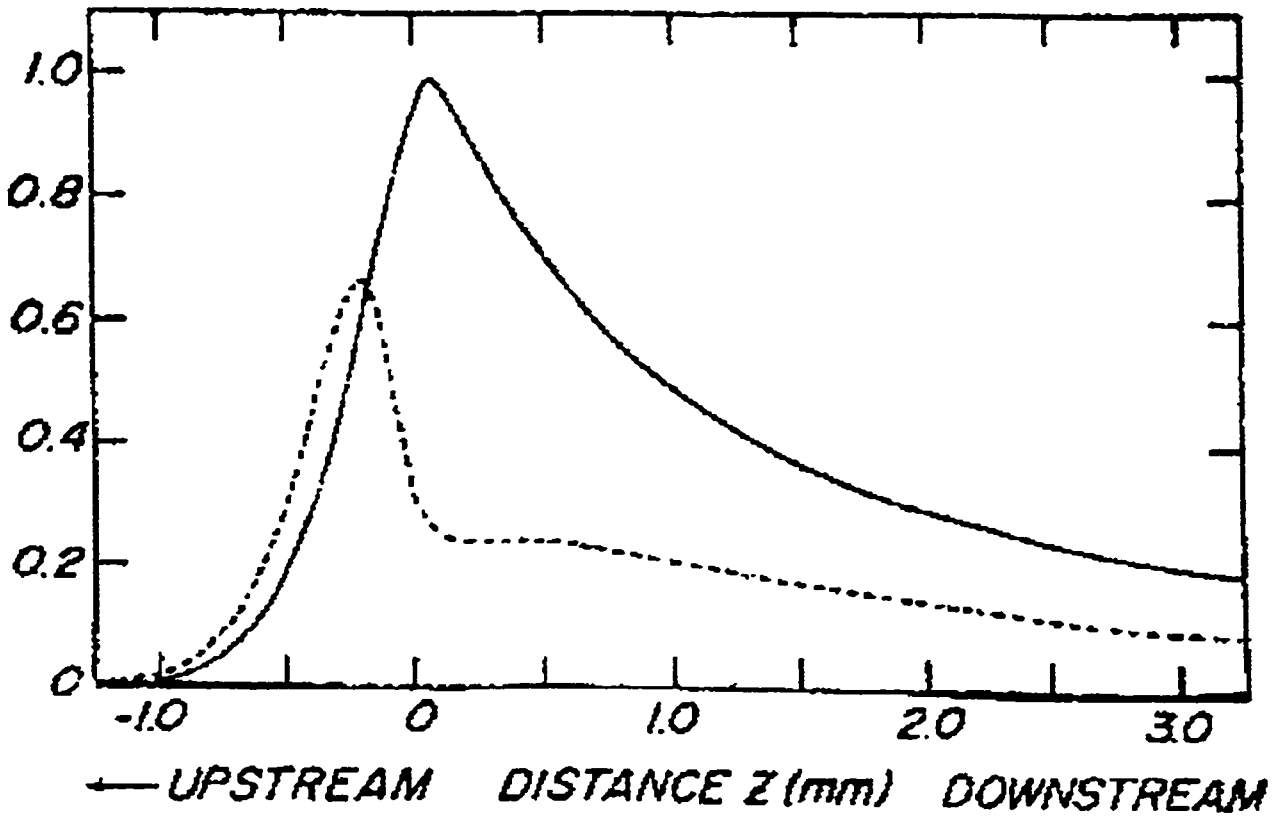


Figure 4.7 Positive and negative ion profiles in a hydrocarbon flame (methane)[51].

(the flame is 6 mm long)

Solid line : normalized total positive ion concentration

Broken line: normalized total negative ion concentration

4.3 EXAMINING THE BEHAVIOR OF DIFFERENT PROBES IN THE FLAME.

It is important to know, how a probe behaves upon insertion in a flame, and how this will affect on the measured voltage. To have a feeling of the behavior of the probes and to choose a suitable probe, five different probes are used to measure the surface voltage and/or current of the flame. These probes are :

- Platinum tube (3.0 mm o.d., 2.7 mm i.d., closed at the end)
- Ti-6Al-4V alloy coated with titanium nitride (TiN) (a plate 2.0 mm hight and 10.0 mm width).
- Ti-6Al-4V alloy (uncoated) (a plate 2.0 mm hight and 10.0 mm width).
- Steel rod, 2.0mm o.d., a gas welding rod *FER G-1* from *Hilco* company.
- Tantalum wire 1.5 mm o.d.

4.3.1 Effect of the Flame Temperature on Some Probes

To see the effect of the flame temperature on some probes, each probe was fitted inside a clay tube which is open from both sides. The tube is 3mm thick. Each probe is inserted for about one hour in the flame. The feed of the flame consists of heptane, benzene and natural gas. The flame is not in contact with the electrodes. It can be seen by the naked eye, that the probe as will as the clay tube become red in the first few minutes after insertion in the flame. The voltage with respect to the burner head (grounded) is measured. The results are

summarized in Table 4.4. Similar results have been obtained using the Bunsen burner, where the fuel is natural gas only.

As can be seen from Table 4.4, the contribution of the heat to the voltage depends on the probe. While it is small and positive for platinum probe, it is larger (the absolute value) and negative in the tantalum case. The contribution of the heat to the measured voltage in the flame remains small to be considered.

4.3.2 Stability of the Probes in the Flame

Five different flame conditions are employed to check the stability of different probes inside the flame. In each of these different flame conditions, the feed consists of heptane, benzene and natural gas. The feed conditions are summarized in Table 4.5.

Table 4.4 Some probes behavior due to the heat of the flame

Probe	maximum voltage developed	Observations on the surface of the probe
Platinum	0.02 volt	Nothing observed
Steel	0.05 volt	corroded surface, covered by a dark brown layer
Tantalum	-0.21 volt	corroded surface, covered by a white tough layer

The stability criteria of the probe is investigated in two aspects:

(a) Visual inspection: The probe is checked if there is any deformation or if any layer has been formed on the surface.

(b) Voltage stability: The voltage has to be stable during the measurement which usually take less than 10 seconds. If the voltage is unstable during the period of interest, this is an indication that the probe is unstable.

For example, Fig. 4.8 shows the voltage development versus time of the platinum probe at various flame conditions. The flame conditions for each curve in Fig. 4.8 are as the following:

Curve A : corresponds to state no. 1 in table 4.1

Curve B : corresponds to state no. 3 in table 4.1

Curve C : corresponds to state no. 5 in table 4.1

As can be seen from Fig.4.8 the voltage may be considered reasonably stable in the range of 5-25 seconds after insertion of the probe in the flame. It take about five seconds for the probe to stabilize in the flame. There were no changes on the surface of the probe during the tested time. Therefore, it can be concluded that, platinum probe is stable in all of the studied conditions. Some probes may be stable in some flame conditions and not stable in others. For example Ti-6Al-4V alloy is not stable in state no 5, table 4.5, while it is stable in states no 1&2, table 4.5. Table 4.6 summarizes all results of different electrodes checked. As can be seen the best probe from the studied probes is the platinum probe.

Table 4.5 Different flame feed

State no.	Air flow liter/min	Natural gas† liter/min	Waste flow‡ ml/min
1	12.8	4.40	1.80
2	26.6	4.40	1.80
3	31.6	4.40	1.80
4	38.8	4.40	1.80
5	44.2	4.40	1.80

† The composition of the natural gas is considered to be 95% methane and 5% ethane. This composition is confirmed by the GC using TCD detector. Other concentrations in the natural gas are very small to considered.

‡ The composition of the waste is always heptane and benzene (4:1 v/v). The density of benzene is 0.875 g/ml and the density of heptane 0.682 g/ml at room temperature (298 K) where the flow was measured.

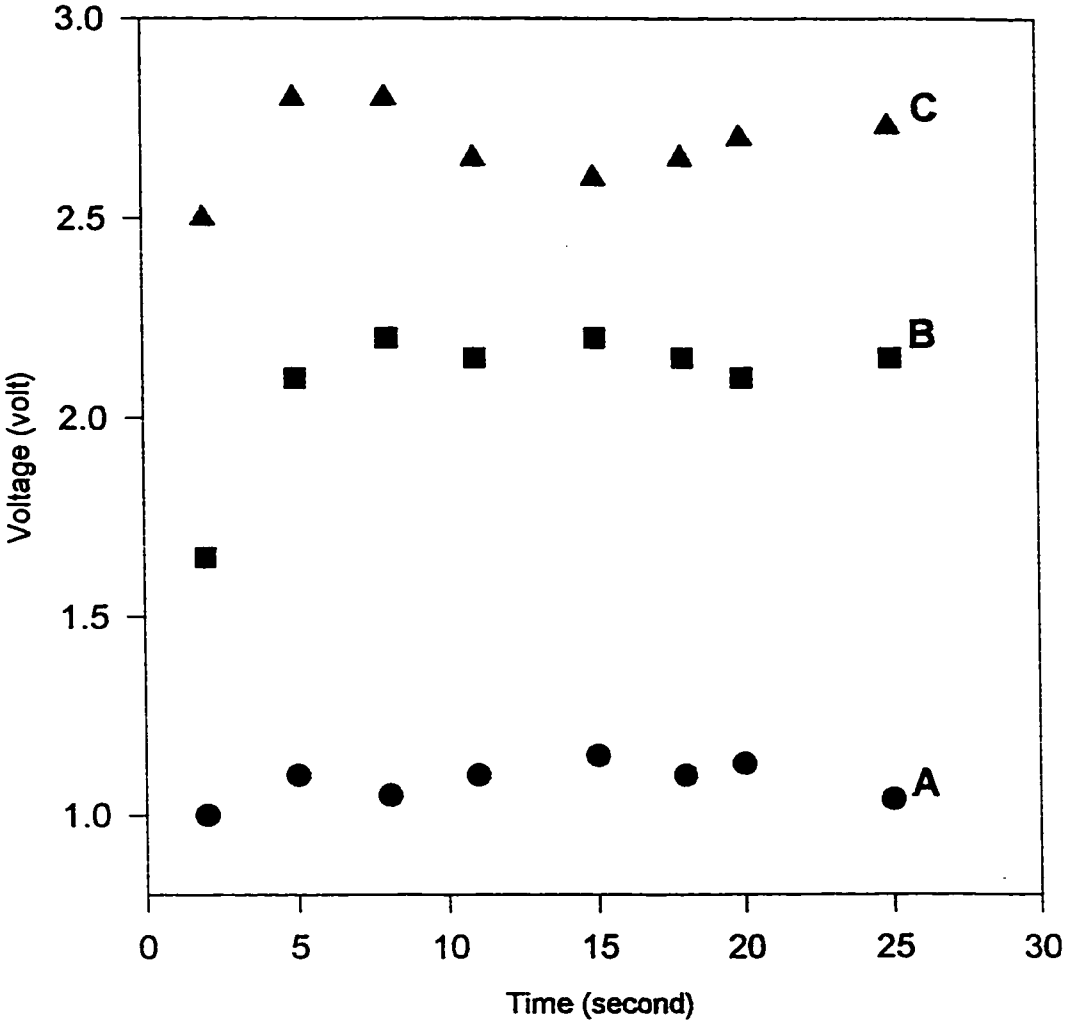


Figure 4.8 Voltage versus insertion time of the platinum probe in the flame.

Curves: A(●): corresponds to state no. 1 in table 4.1, B(■): state no. 3, C(▲): state no. 5.

Table 4.6 Stability of different probes at different flame conditions.

State no*.	Platinum	TiN coated Ti-6Al-4V	Ti-6Al-4V	Steel	Tantalum
1	stable	stable	stable	stable	not bad
2	stable	stable	stable	not bad	not stable
3	stable	stable	stable	not stable	not stable
4	stable	stable	not bad	not stable	not stable
5	stable	not bad	not stable	not stable	not stable

* State no. corresponds to the states given in table 4.5.

The measured voltage of the flame is not the same for all probes used in this work. This difference may be due to the nature of the probe in response to the flame and its chemical stability. Some probes gave the same voltage under same flame conditions, e.g TiN coated Ti-6Al-4V and uncoated Ti-6Al-4V as shwon in Table 4.7.

Full investigation of the mechanisms that could affect the measured voltage is suggested for further work in the area. More sophisticated equipment is needed. For example, to study the types of ions in the flame, an on-line mass spectrometer is required. To study the surface behavior in the flame, X-ray photoelectron spectrometer, microphotography and electrochemical techniques could be required.

Table 4.7 Voltage (volt) of the flame using TiN coated Ti-6Al-4V and uncoated Ti-6Al-4V

State no*.	TiN coated Ti-6Al-4V)	Ti-6Al-4V	Comments
1	0.85 ± 0.06 V	0.89 ± 0.06V	good agreement
2	1.26 ± 0.06 V	1.37 ± 0.06 V	within the error
3	1.40 ± 0.06 V	1.45 ± 0.06 V	good agreement
4	1.84 ± 0.06 V	1.90 ± 0.06 V	good agreement
5	2.4 ± 0.06 V	*	*The surface is changed

* State no. corresponds to flame conditions given in table 4.5.

CHAPTER V

RESULTS AND DISCUSSION

5.1 INTRODUCTION

During this work, a lot of experience has been gained in the area of chemical waste treatment; particularly, the incineration method. Most of the time has indeed been spent on the construction, operation and optimization of the incinerator and the monitoring system. One difficulty in the analysis arises because of the presence of water in the samples to be analyzed. Since water is always there, one should take it in consideration in all of the analysis techniques.

The major results achieved in this work can be summarized as follows:

1- A small scale incinerator was constructed from which highly reproducible (reached less than 1% difference) data was obtained.

2- A novel technique, based on a new interpretation of the charge redistribution in the flame, is proposed and experimented for very fast chemical measurements and fast feedback control.

3- A reliable monitoring system has been constructed. Particular experience has been gained in instrumentation. Operation of gas chromatography and infrared spectrometers with their advantages and limitations in the analysis of the exhaust from hazardous waste incinerators or similar environments, has been extremely useful.

4- Automation was accomplished for many parts of the incinerator. Feedback electronic circuit associated with a flame sensor was made from basic electronic parts.

5.2 THE INCINERATOR

One important result in the present work was building and operating the incinerator. A slight design modification, compared to the commercially available incinerators, is introduced; namely, converting the liquid waste to vapor before the introduction to the burner.

Although the design of the incinerator is research oriented, it can be used for solving real problems. This was a big difficulty in the present work; namely to do fundamental research on a relatively large scale incinerator. The objective in this case is to apply the results and experience from the research on a small scale incinerator to larger systems.

The incinerator built in this work seems to be successful in providing reliable data to be used in fundamental research. The most important criteria in this aspect is the reproducibility of the results for a given steady state. The feed system seems to play a very important role in the reproducibility of the analysis. Converting the liquid waste to vapor before it enters the burner, helped in obtaining reproducible results. The reason lies in preventing localization of the waste in the flame or the chamber. A homogenized feed is introduced to the burner, this gives a stable and constant feed which in turn contributes in obtaining a constant output at certain steady state.

The reproducibility of the built incinerator is some times within 0.5%. This range is the limit of the GC. In the GC, the results are reproducible within 0.5% if automatic sampling loop injection method is used. For more details see section 3.4.2. So this reproducibility is good enough to study any fundamental phenomena that is related to incineration, especially if the aim is to apply it in the real life incineration.

Many parameters have to be simultaneously fixed in the operation of the incinerator operation. e.g. feeding the waste, combustion air, cooling air, heating sampling lines, sample extraction and sample analysis. In addition some conditions must be continuously monitored. If any error happens during operation, feedback control is very necessary to prevent further upsetting conditions, e.g. flame extinguishing during operation. It is not feasible for the operator to check the flame regularly, because the flame could be extinguished at any moment. Therefore, automation has been found necessary in some equipment which are used in the incinerator. The microprocessor of the GC with the associated junction board and software, has been found to be satisfactory in the present work to do the necessary automation. However for complete or more complete automation a computer with a suitable interfacing system and the associated software is needed.

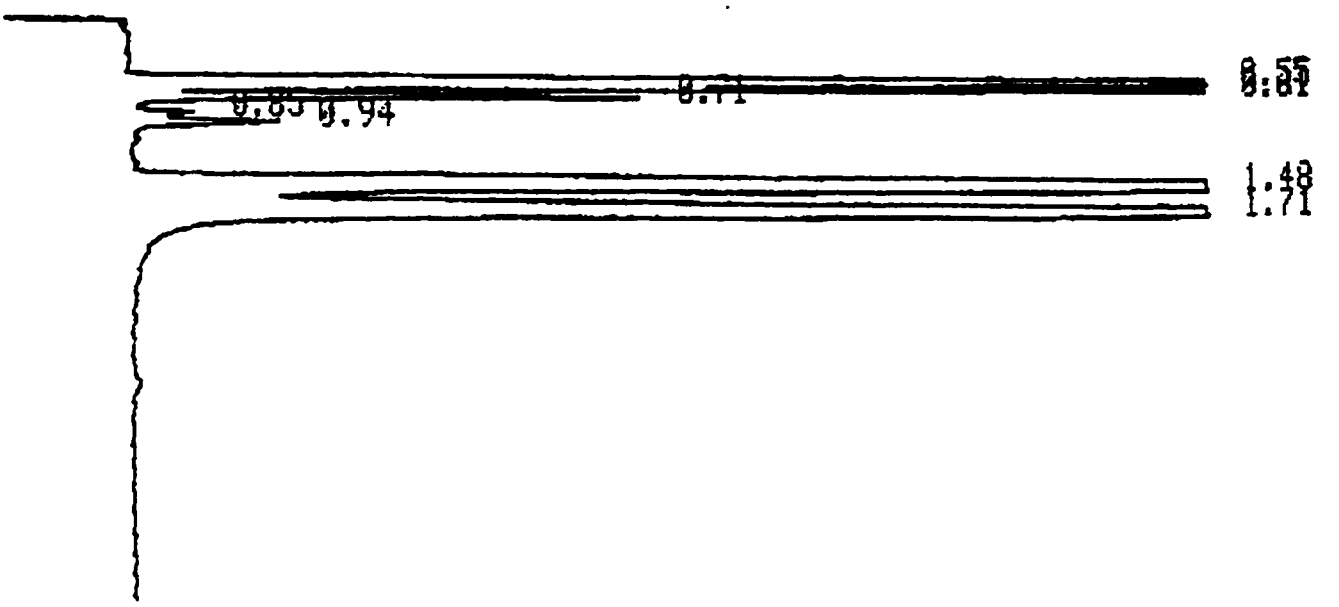
5.2.1 Performance of the Incinerator

The performance of the incinerator is checked by the analysis of the feed using the bypass lines and the analysis of the exhaust from the end of the chamber. To test the incinerator, only liquid waste that contains carbon and hydrogen has been used.

The FID detector of the GC is mass based. So DRE can be directly calculated from the absolute values of the areas of the peaks of the inlet (using the bypass line) and the outlet as follows:

DRE = (peak area of the inlet - peak area of the outlet)/peak area of the inlet.

The GC cannot detect chemicals having peak areas less than 1 in GC arbitrary units. Smaller areas are within the noise level of the instrument. Therefore, if no peak is detected for a certain species, the area is considered as 1 GC units. Fig. 5.1 shows the analysis of the feed as detected by the GC. The feed in this case consists of benzene, heptane (1:4 v/v) mixed with some natural gas. Three components are of interest; namely, methane (retention time, RT, 0.55 min), heptane (RT, 1.48 min), and benzene (RT, 1.71 min). The other small peaks in Fig. 5.1 are some components of the natural gas.



[hP] 5880A INJECTION @ 15:00 JAN 14, 1998
AREA %

RT	AREA	TYPE	AREA %
0.55	17726.20	BH	31.928
0.61	1738.95	HH	3.132
0.71	1280.87	HH	2.307
0.85	164.51	HH	0.296
0.94	466.09	HH	0.840
1.48	22020.30	HH	39.663
1.71	12121.50	HH	21.833

TOTAL AREA = 55518.50
MULTIPLIER = 1

Figure 5.1 A sample GC chromatogram of the inlet of the incinerator

Sample chromatogram of the analysis of the exhaust of the same sample, are shown in Fig. 5.2.

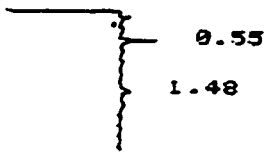
In the middle chromatogram of Fig. 5.2, methane, heptane, and benzene are detected. From the data in Fig. 5.1 and Fig. 5.2, DRE is calculated as the following :

Component	DRE
Methane	(99.66 ± 0.01) %
Heptane	(99.66 ± 0.01) %
Benzene	(99.55 ± 0.01) %

DRE for benzene is slightly lower than that of heptane even though the concentration of benzene (1:4 v/v) is less in the waste feed. This is expected, because benzene is more stable in the incineration process than heptane [6].

The last chromatogram in the GC shows no peaks. The incinerator average temperature is around 930 °C. Assuming the peak areas are 1 GC unite, DREs can be calculated to give the following :

Component	DRE
Methane	>99.99 %
Heptane	>99.99%
Benzene	>99.99%



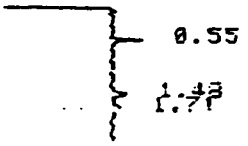
[hp] 5880A INJECTION @ 16:01 JAN 14, 1998
AREA %

RT	AREA	TYPE	AREA %
0.55	73.28	BH	57.527
1.48	54.11	HH	42.473

TOTAL AREA = 127.39
MULTIPLIER = 1

VALVE 7 ON

VALVE 7 OFF



[hp] 5880A INJECTION @ 16:06 JAN 14, 1998
AREA %

RT	AREA	TYPE	AREA %
0.55	59.82	BH	31.552
1.48	75.35	HH	39.744
1.71	54.42	HH	28.704

TOTAL AREA = 189.58
MULTIPLIER = 1

VALVE 7 ON

VALVE 7 OFF

[hp] 5880A INJECTION @ 16:14 JAN 14, 1998
NO PEAKS

Figure 5.2 A sample GC chromatograms of the outlet of the incinerator for performance test

Sometimes DRE is >99.99% for some components and <99.99% for others. This happens if a lower temperature is used, such that easily incinerable compounds are "completely" destroyed and more difficult compounds are destroyed to a lesser extent. Fig.5.3 is a sample chromatogram of the analysis of the outlet of the incinerator when average chamber temperature is 750 °C. From the data in Fig.5.1 and Fig.5.3 the following DREs are calculated :

Component	DRE
Methane	26.95%
Heptane	>99.99%
Benzene	96.56%

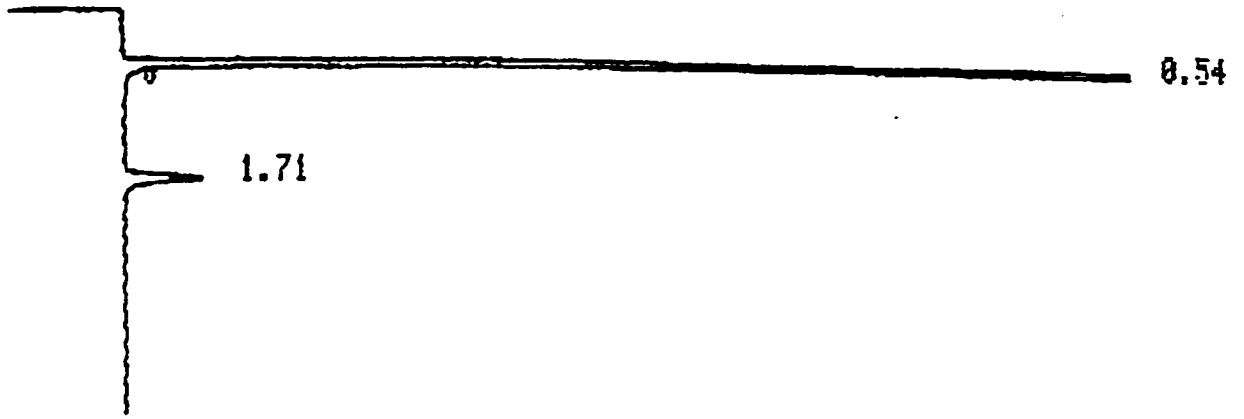
It is to be noted that, methane is not considered as a criteria of stack emission in incineration performance tests [1-5, 8-9]. The lower DRE (26.95) of methane is not because of methane stability against incineration (like benzene) but because methane is generated from other compounds in the feed, which is heptane in the present case. This result shows that in our system, the operating temperature has to be larger that 750 °C to obtain better than 99.99% DRE.

The analysis results could show good performance of the incinerator, but these results could be misleading. This happens if the effect of cooling air (when it is operated) of the

chamber is not taken into consideration. The dilution factor must be considered for the correction of the results. The correction factor can be calculated by analysis of nitrogen before and after the operation of cooling air. The waste must not contain nitrogen. The ratio of nitrogen before and after the operation of the cooling-air is the dilution factor. Here the analysis of nitrogen is done using the TCD of the GC. TCD peak is concentration based; so there is no need for quantitative calibration for this purpose. The usage of the absolute peak areas given by the integrator of the GC, in this case, is adequate.

5.2.2 Higher Destruction at Lower Temperatures

Achieving 99.99% DRE, is generally not a difficult task, because of the thermodynamic driving force of combustion. In the present work, the concentration of the outlet compared to the inlet, using the bypass line, of the waste is calculated and found to give the DRE more than 99.99%. However, more important is how to achieve this percentage.



[hp] 5880A INJECTION @ 14:39 JAN 14, 1998
AREA %

RT	AREA	TYPE	AREA %
0.54	12949.30	BV	96.876
1.71	417.53	VP	3.124

TOTAL AREA = 13366.80
MULTIPLIER = 1

Figure 5.3 A sample GC chromatogram of the outlet of the incinerator showing selective destruction of some waste feed components

For example, incineration of nearly any type of waste at 2000 °C, will give DRE better than 99.9999%. However to achieve and to maintain such high temperature is very expensive. In addition, finding a chamber with suitable refractory materials and good insulation system (if existed) to stand such high temperatures will be very expensive as well. In general, the working temperature in incinerators ranges from 800 to 1200 °C. Attempts have been made to obtain a better DRE at lower temperatures, e.g. some additives like CO, ozone and hydrogen peroxide have been tried [10,16, 19-21]. Catalytic incineration for volatile organic compounds is a completely independent field as incineration technology [1-2, 5, 9]. The operating temperature of catalytic incineration is around 600 °C.

However, a limited number of studies has been done in the area of converting liquid waste into vapor.

The current technology of liquid waste incineration is based on injection of the waste as a spray in the incinerator. This gives acceptable DRE, 99.99% [1-5, 9]. Droplet size of the waste affects the DRE; the larger the size the lesser the DRE. Some problems associated with this method could be serious. Sometimes large droplets could be thrown in the chamber which will affect the performance of the incinerator. DRE is a function of droplet size in liquid injection incinerator. In the present work, the 'droplet size' is in the molecular level which is expected to increase the DRE compared with the other liquid injection designs. Plugging of the nozzle also occurs in this type of feeding systems.

Koshland *et. al.* [52] compared the thermal destruction of gaseous and liquid 1,1,1-trichloroethane. Their experiments suggest "that there is little qualitative but some quantitative variation in the combustion byproduct distribution between liquid injection and

gas-phase injection of 1,1,1-$C_2H_3Cl_3$ for the present experimental conditions. The 1,1,1-$C_2H_2Cl_2$ (a combustion byproduct) concentrations are about 25% higher for liquid injection when compared to gaseous injection". Other researchers studied droplet processes in liquid hazardous waste incineration [53-55]. It can be inferred from their studies that evaporation of the liquid waste incineration prior to its introduction to the burner will increase the DRE.

Soot is formed whenever the fuel/oxygen ratio is high. Soot formation may be an excellent and easy indicator of a poor combustion process. The more soot is formed during the incineration, the worse the combustion processes is. The fuel/oxygen ratio on the surface of the droplet in liquid injection incineration technology is always higher than fuel/oxygen ratio in the evaporation-based technology. For the same fuel/oxygen ratio evaporation-based technology will give lesser soot than the liquid injection technology. Hence the evaporation-based technology will give better DRE. A more detailed quantitative study comparing the rates of soot formation in liquid injection and evaporation based incinerators could be very important in this aspect.

The feeding system and the associated burner are different from the existing designs in the literature. Making use of the heat to vaporize the liquid waste is an idea which deserves more consideration by researchers working in the field. Not only energy is saved, but also problems associated in spraying the waste will be eliminated. Plugging of the burner is a frequent problem in liquid waste incinerator. This problem is eliminated by the present design. However, the rate, if any, of building up the coke inside the heating tubes is not checked in this study.

A problem that may arise in evaporation of the waste, is coke formation inside the heaters. This was one of the problems faced the feeding system of our incinerator during operation. Coke could be formed to the extent of plugging the lines. However, with more suitable design that prevents overheating of the waste and cleaning the feeding system by air after each working day the problem is solved. If the heating pipes are very close to the surface temperature of the chamber (500 - 700 °C), the coke could plug the pipes (1/4") during the operation. However this problem could be minimized if a suitable design of the preheater is done, so that no overheating of the waste occurs.

5.3.3 Further Modifications is Possible

Although the incinerator is designed for clean waste (C,H,O) destruction, it can be easily modified for chlorinated organic compounds. The limiting part, in the present incinerator, that prevents the incineration of chlorinated compounds is the analysis system which is currently not suitable for the analysis of the products of chlorinated compounds incineration. However, modification to make suitable for chlorinated waste is possible. Halogens and halogen-containing compounds can be analyzed using electron capture detector (ECD). ECD is very sensitive for the analysis of halogen-containing compounds. Waste that contain large quantities of sulfur and/or nitrogen or other halogens could be incinerated, provided that the analysis system is modified.

The only liquid waste type that cannot be incinerated in the present incinerator is the waste that contains large quantities of metals or metallic compounds. Some changes must be done in the incinerator hardware itself as well as in the analysis system.

Finally, in the present work DRE reached sometimes more than 99.99%. DRE will be more if a scrubbing system is used, because DRE is also a function of the scrubbing system. In this respect DRE is, at least, as good as that of commercially available incinerators. In the work done, scrubbing system is not used because chlorinated compounds, which produce HCl, have not been used. No chemicals that could produce acid gases have been used.

5.3 A NEW PROPOSED TECHNIQUE

A second result of the work done is the investigation of a technique that could be used for fast chemical measurements and fast feedback control. The proposed technique has the potential of solving the 'infinity loop(s)' challenge at least from the principle point of view. The commercially available techniques do not tackle problems like 'infinity loop(s)' challenge.

In the following sections, results that correlate the voltage of the flame with some exhaust components are presented. Different probes are used to correlate the voltage with some incineration products. An important result from different probes is that, the higher the voltage of the flame the higher the destruction. However, the stability of the probe is important in measuring the voltage. The voltage of the flame is also correlated with CO concentration in the exhaust of the incinerator. This correlation is used to predict CO concentration from the incinerator. In addition, the voltage of the flame is correlated with the air flow rate in the feed.

One important step in all experiments to be carried out is achieving a steady state in the incinerator. The analysis system as well as the temperature monitoring system is used to indicate whether the steady state is reached or not, section 5.4. For each steady state in the incinerator, the voltage of the flame (6cm from the burner head) with respect to the burner head, as shown in Fig.4.1, is measured. The voltage in the flame is the same, as long as the feed is not changing.

The exhaust of the incinerator at a given steady state is analyzed. For each steady state in the incinerator four or five samples from the exhaust are analyzed and averaged. The results of the analysis from the GC is correlated with the measured voltage of the flame at each steady state.

The correlation of an electrical property in the flame with the exhaust from an incinerator, which is related to the destruction, has never been studied. More detailed is given in the literature review section 1.3.

5.3.1 Results Using the Platinum Probe

As mentioned earlier, platinum probe was found to be stable in different flame conditions. The voltage is measured after around ten seconds of insertion of the probe in the flame. Different steady states in the incinerator are obtained by changing the flame conditions. The flame conditions can be changed by changing the composition of the pre-mixed feed. Table 4.5 summarizes the flame conditions used at each point (steady state) studied. The concentrations of some gas components in the exhaust at each steady state are correlated with the voltage and current in the flame. While the voltage is stable in all of the flame

conditions tested, the current was fluctuating in state no. 5, table 4.5. Only the results of the first four steady states are recorded for the current measurements.

Fig. 5.4 shows the relation of the voltage to CO concentration in the exhaust using platinum rod as a probe. The linear regression coefficient is 0.961. Fig. 5.5 shows the correlation of the current versus CO concentration in the exhaust, the linear regression coefficient is 0.914. The same trend is observed compared to the corresponding voltage curve, i.e. the higher the current the higher the destruction.

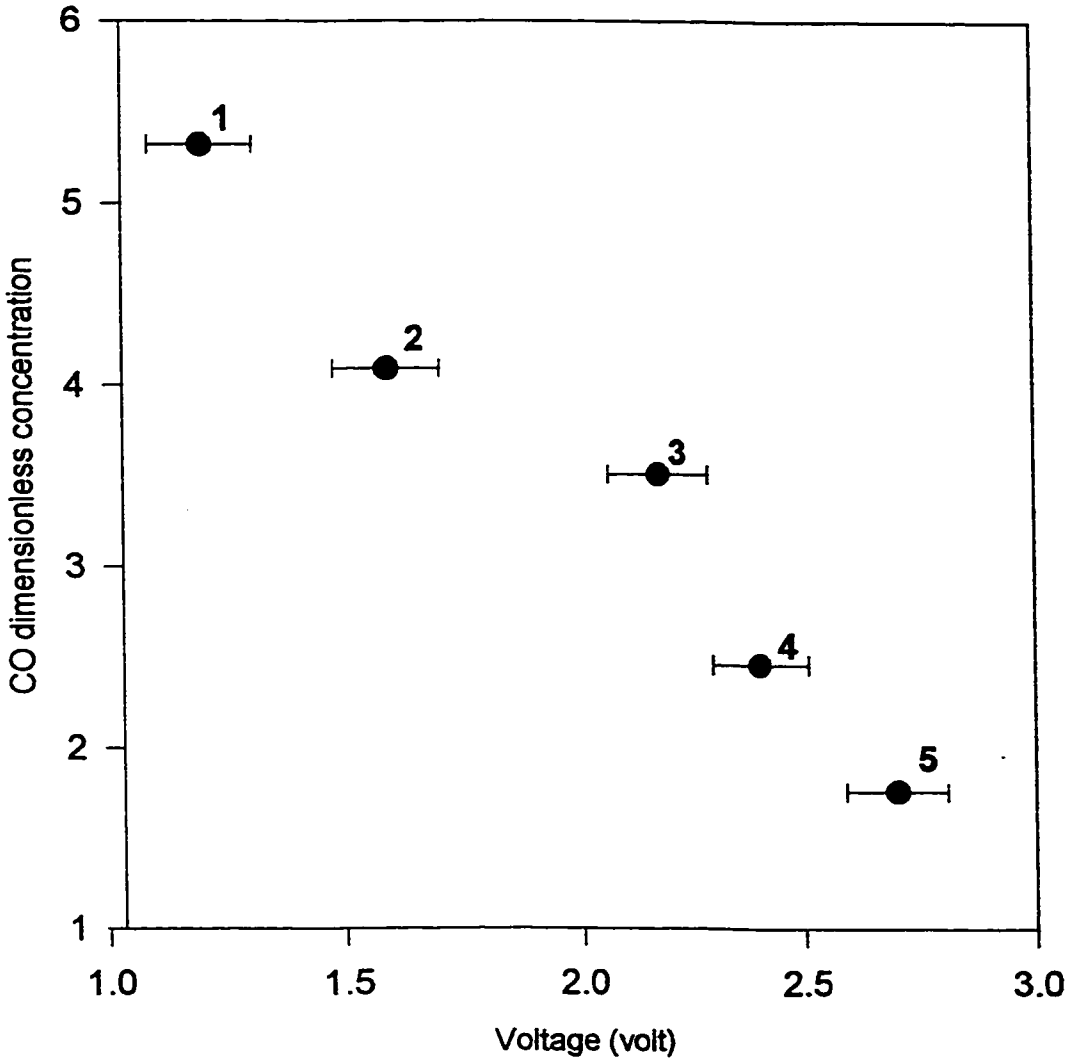


Figure 5.4 CO outlet concentration vs. voltage using platinum probe

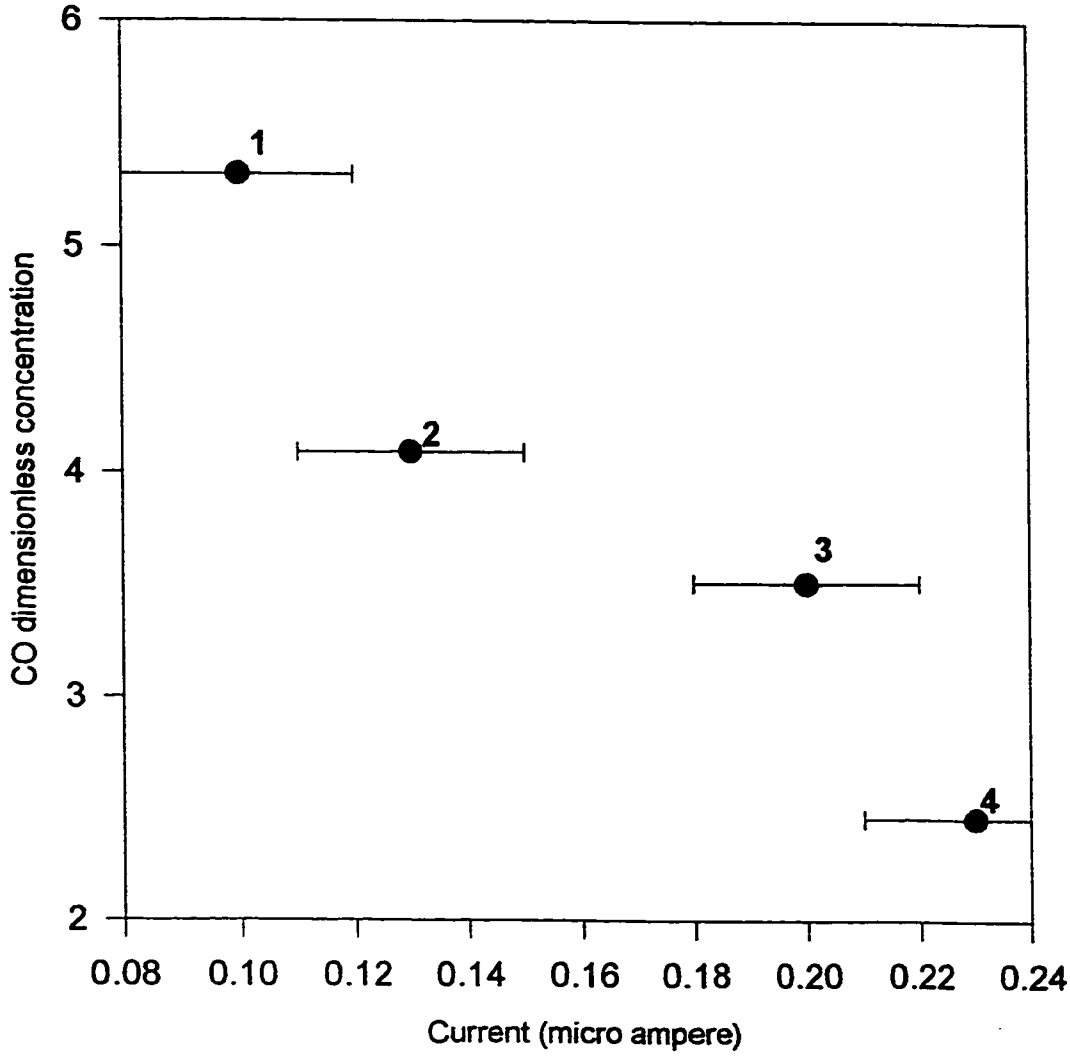


Figure 5.5 CO outlet concentration vs. current using platinum probe

While CO shows linear correlation with the measured voltage, benzene and heptane do not show such relation. Fig. 5.6 and Fig. 5.7 show benzene concentration versus voltage and current respectively. As can be seen, the trend is the same in both curves. At higher voltages, the outlet concentration is less than that of the lower voltages. In this aspect, the higher the voltage the more the destruction of benzene or heptane.

Fig. 5.8 and Fig. 5.9 show the outlet heptane concentration versus voltage and current respectively. As in benzene situation, the relation is not linear. However, at higher voltages the destruction is more complete.

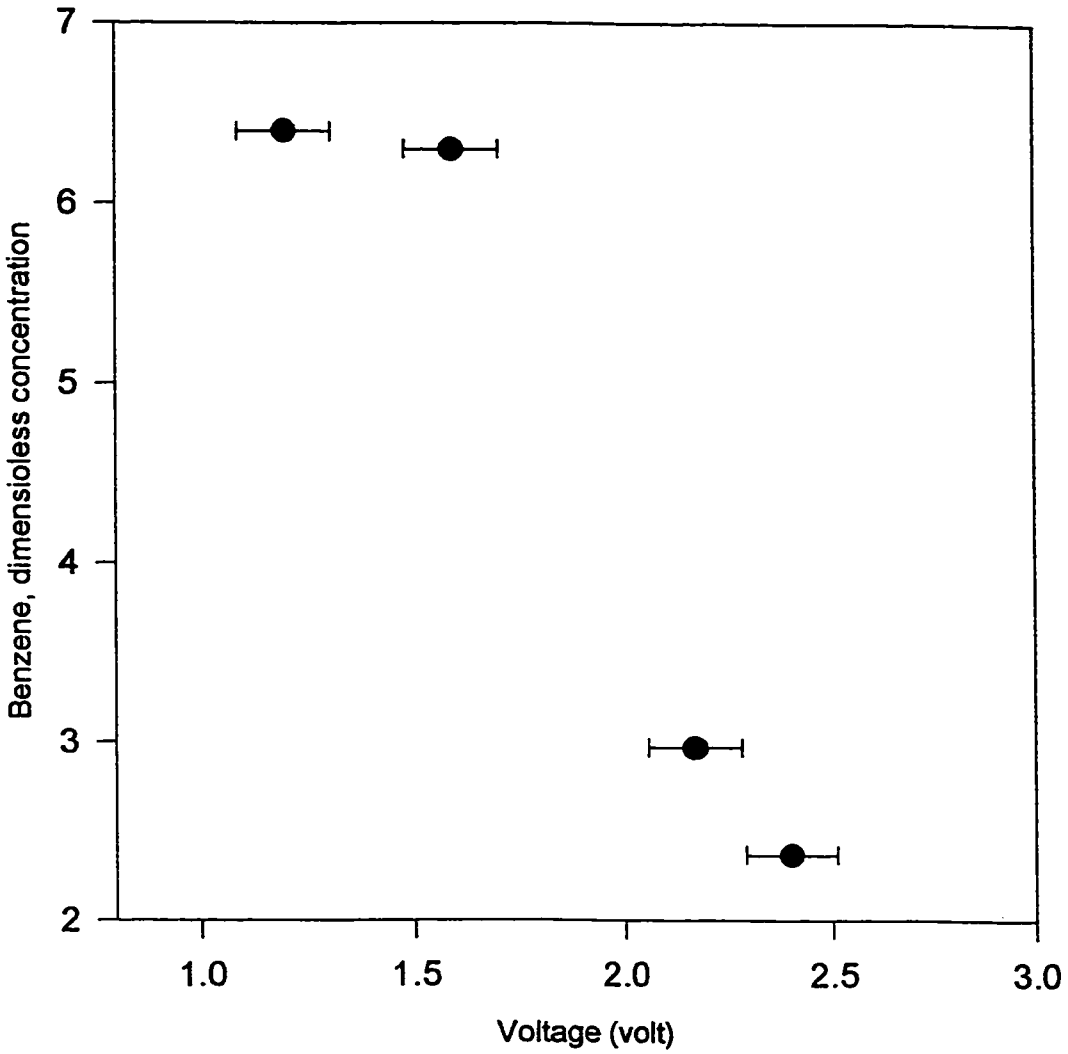


Figure 5.6 Benzene outlet concentration vs. voltage using platinum probe.

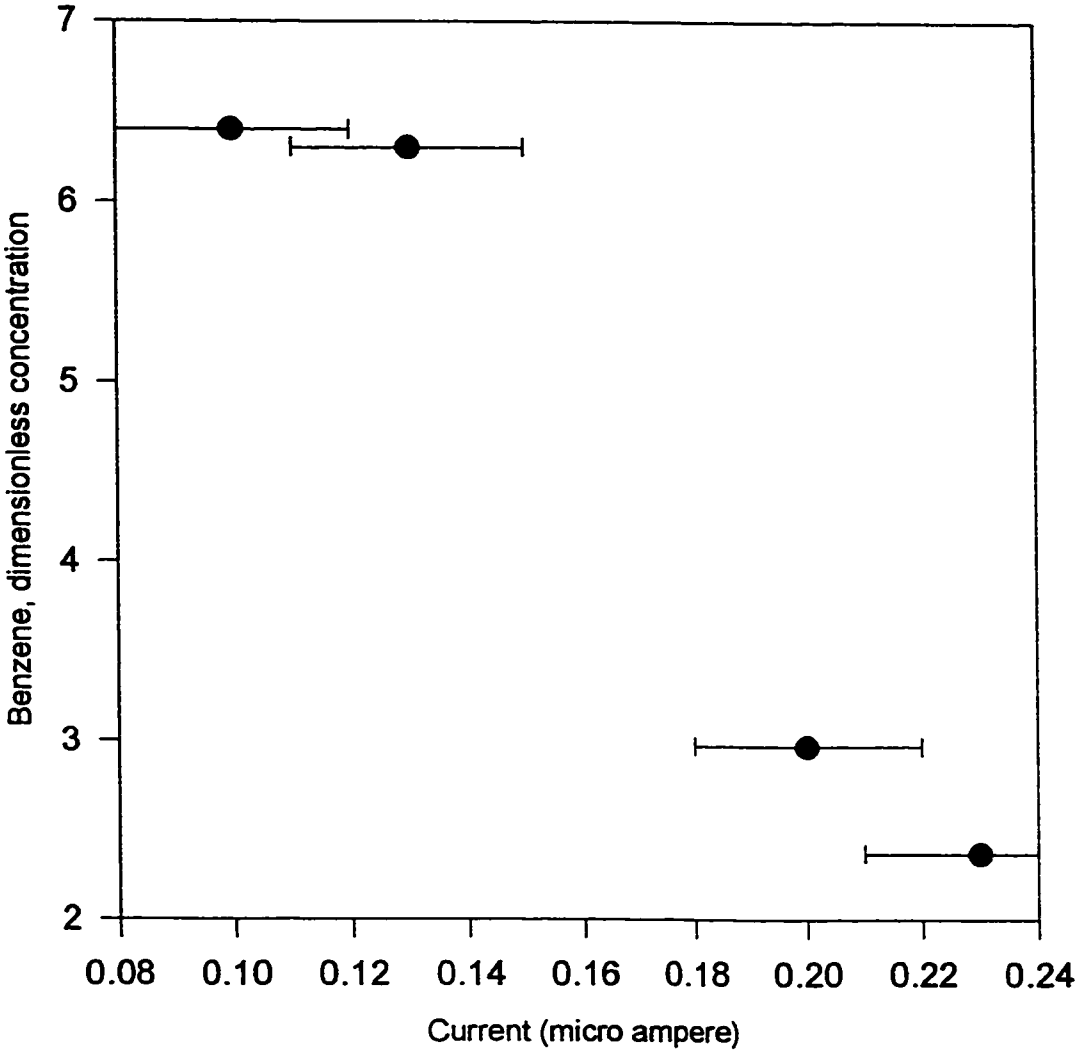


Figure 5.7 Benzene outlet concentration vs. current using platinum probe.

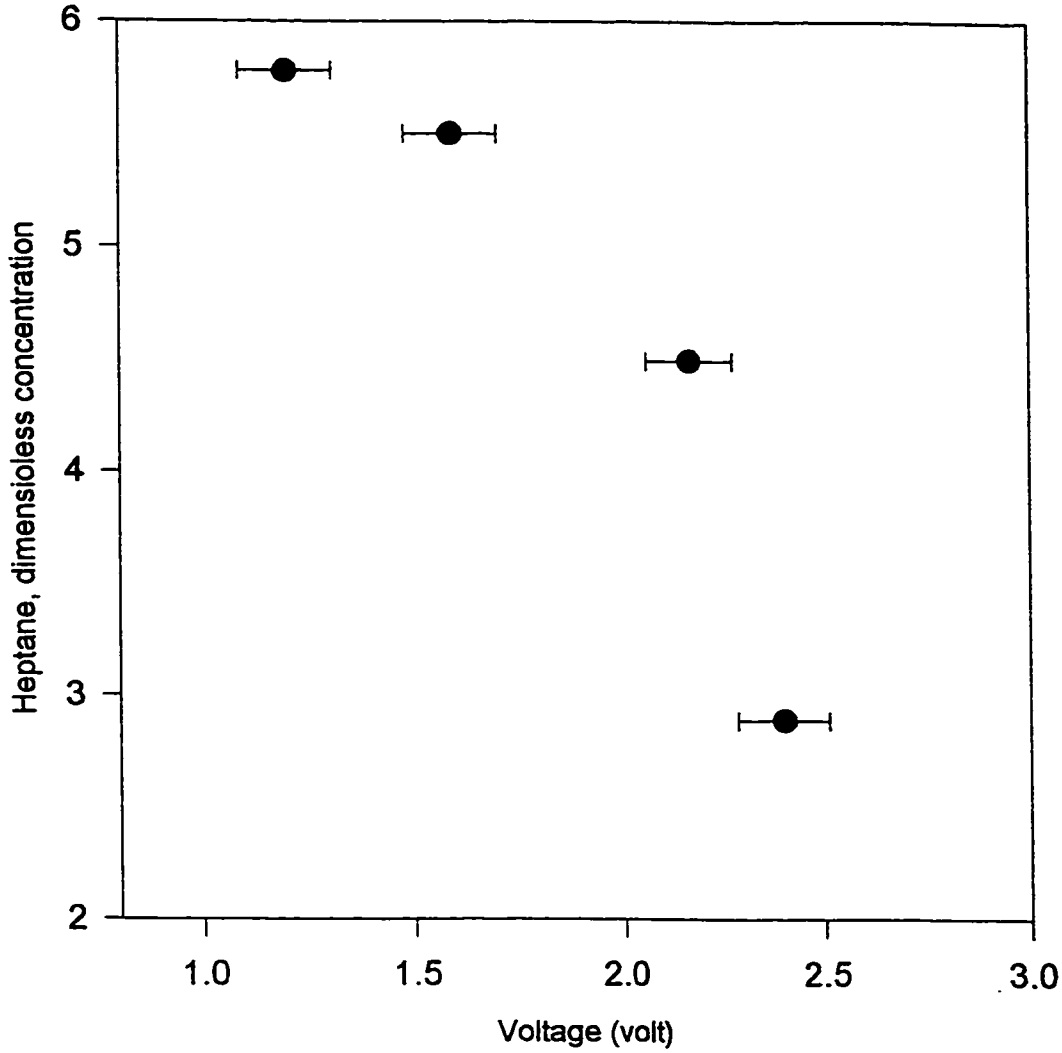


Figure 5.8 Heptane outlet concentration vs. voltage using platinum probe.

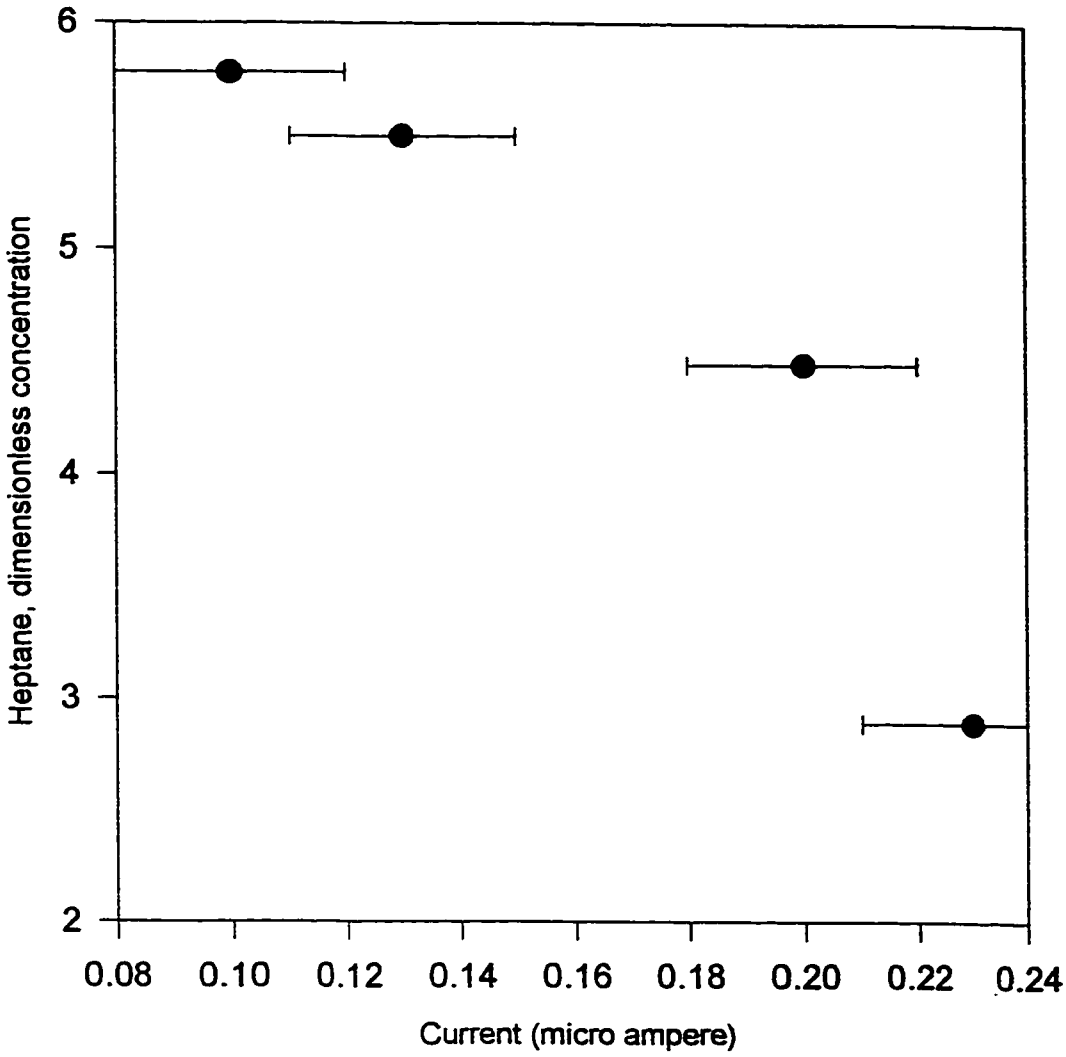


Figure 5.9 Heptane outlet concentration vs. current using platinum probe.

5.3.2 Results Using the TiN Coated Ti-6Al-4V alloy Probe

TiN films are commonly used as coating substance to improve wear resistance and providing corrosion protection on metallic substrates [56]. "The film is deposited using physical vapor deposition technique. A titanium film was sputter deposited onto the substrate by a DC magnetron source in an argon atmosphere. It was then implanted with N^+ ions at an acceleration potential of 50 keV" [56]. This kind of high energy procedure of coating seems resistant, to some extent, in some flame conditions. No surface deformation occurred in the flame at the experimented period. Table 4.6 shows the stability behavior of the TiN coated Ti-6Al-4V alloy at different flame conditions. The feed conditions are as shown in Table 4.5.

Fig. 5.10, Fig. 5.11, and Fig. 5.12 show the voltage versus CO, benzene, and heptane concentrations in the outlet, respectively. As can be seen from Fig. 5.10 the fifth point on the curve (corresponding to state no. 5, table 4.5) is deviated from the linear behavior compared to the curve, Fig. 5.4, where platinum probe is used. This is due to the instability of the probe inside the flame, where the coated surface was slightly deformed, table 4.6.

Fig. 4.13, Fig. 4.14, and Fig. 4.15 represent the concentration of CO, benzene, and heptane versus current, respectively, using TiN coated Ti-6Al-4V alloy. As can be shown, the concentration versus current curves resemble the corresponding concentration versus voltage curves.

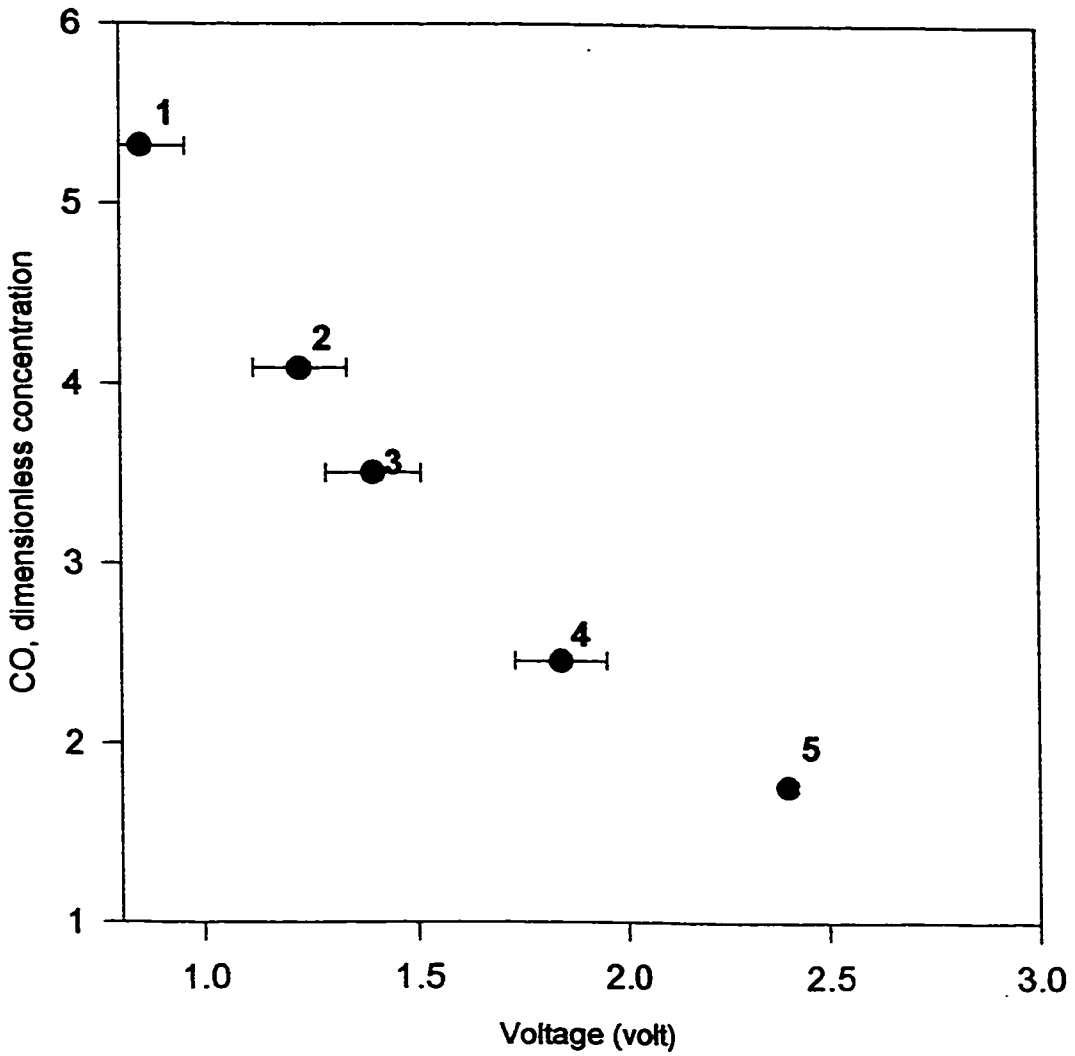


Figure 5.10 CO outlet concentration vs. voltage using TiN coated Ti-6Al-4V probe.

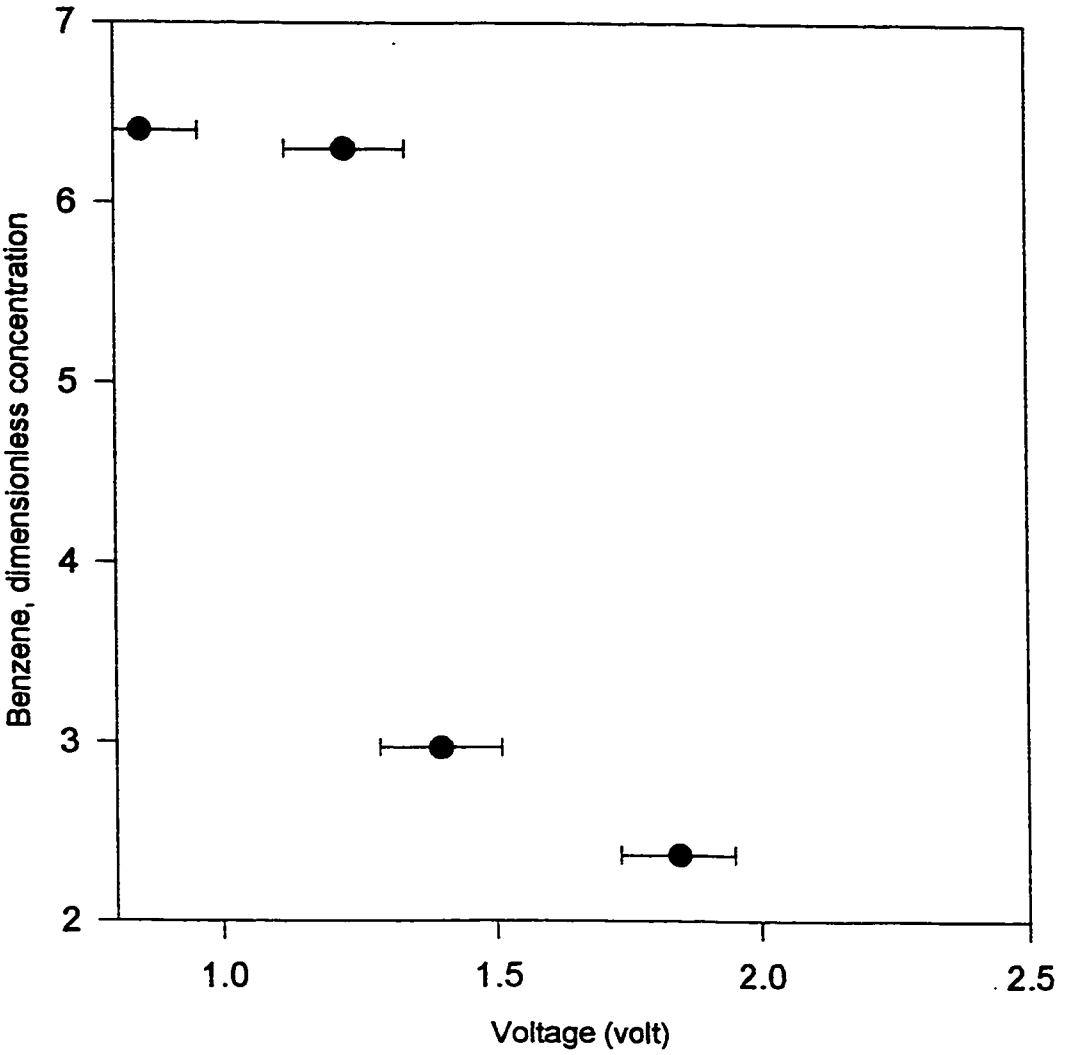


Figure 5.11 Benzene outlet concentration vs. voltage using TiN coated Ti-6Al-4V probe.

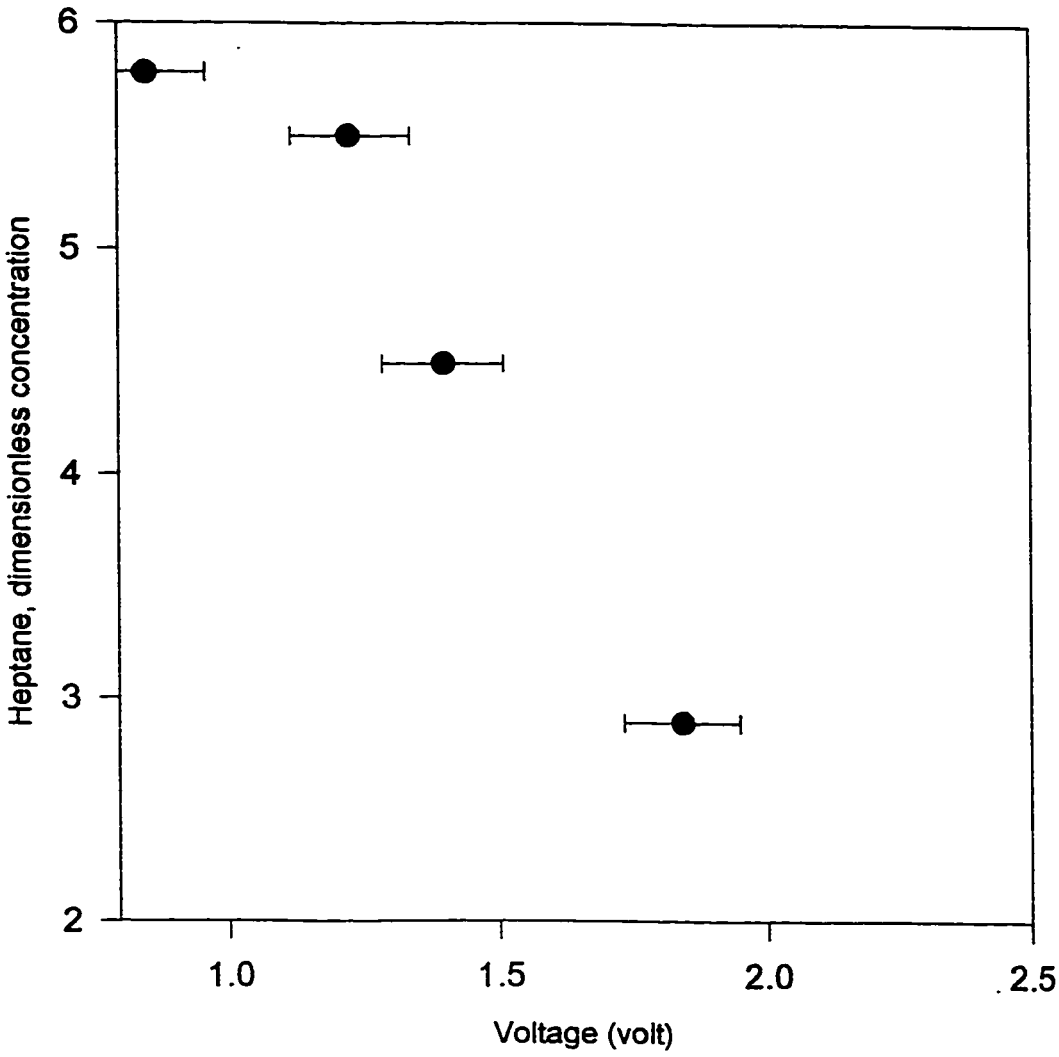


Figure 5.12 Heptane outlet concentration vs. voltage using TiN coated Ti-6Al-4V probe.

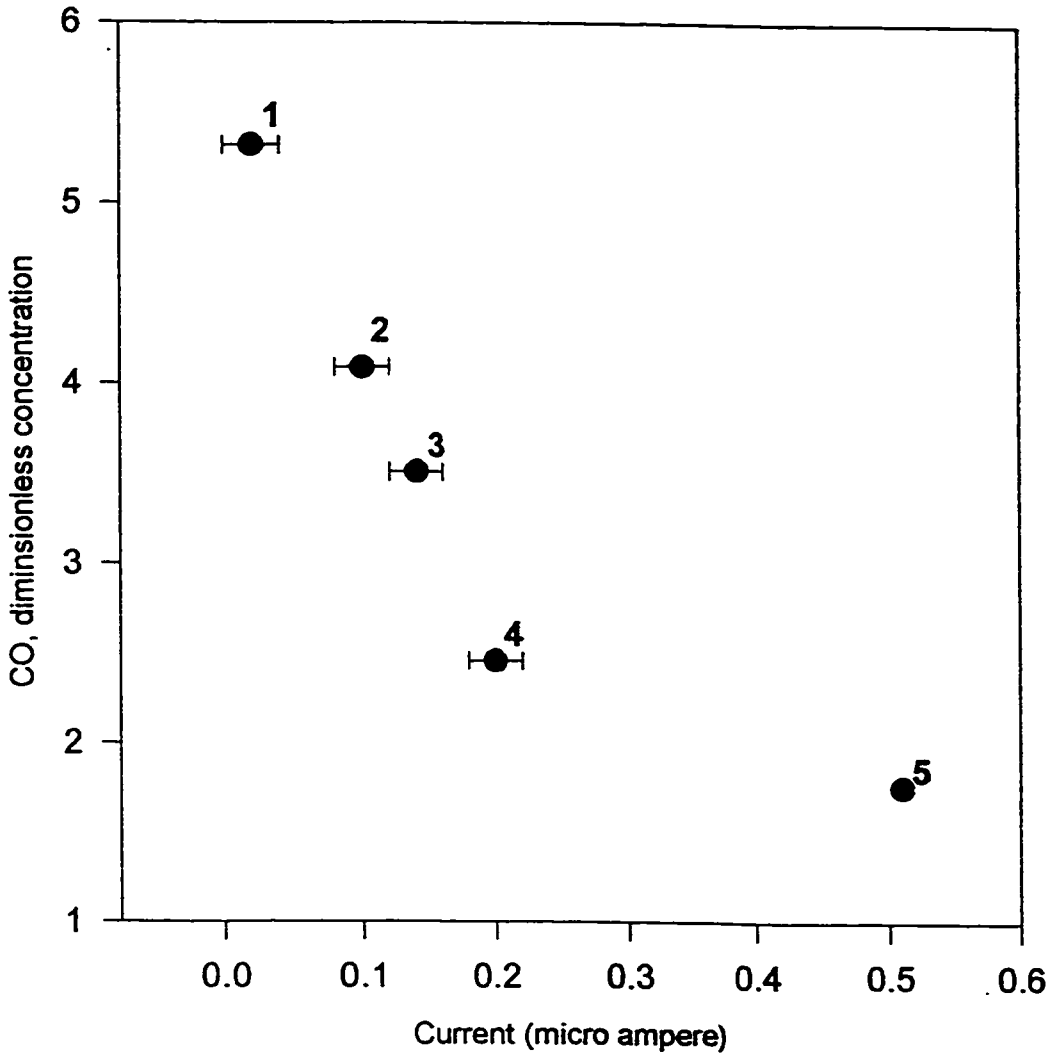


Figure 5.13 CO outlet concentration vs. current using TiN coated Ti-6Al-4V probe.

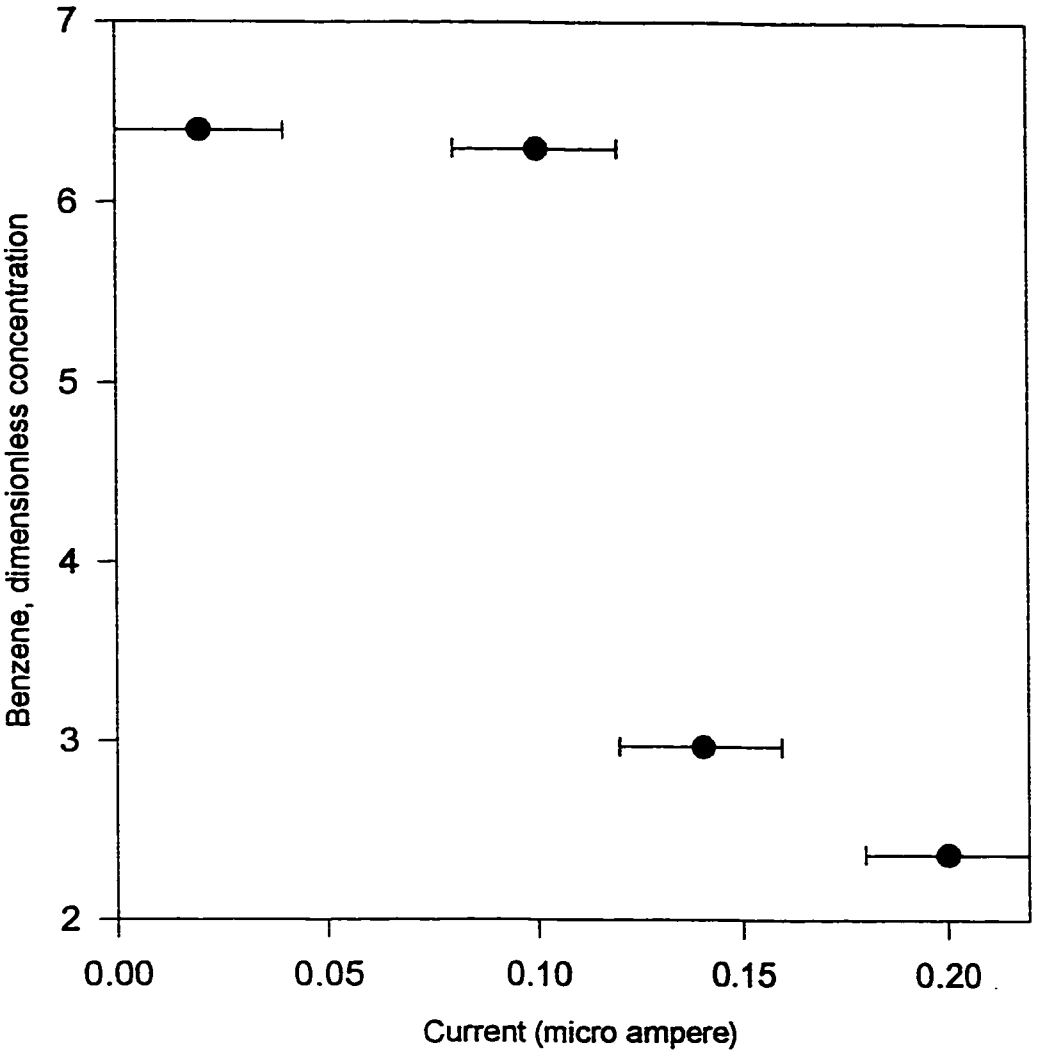


Figure 5.14 Benzene outlet concentration vs. current using TiN coated Ti-6Al-4V probe.

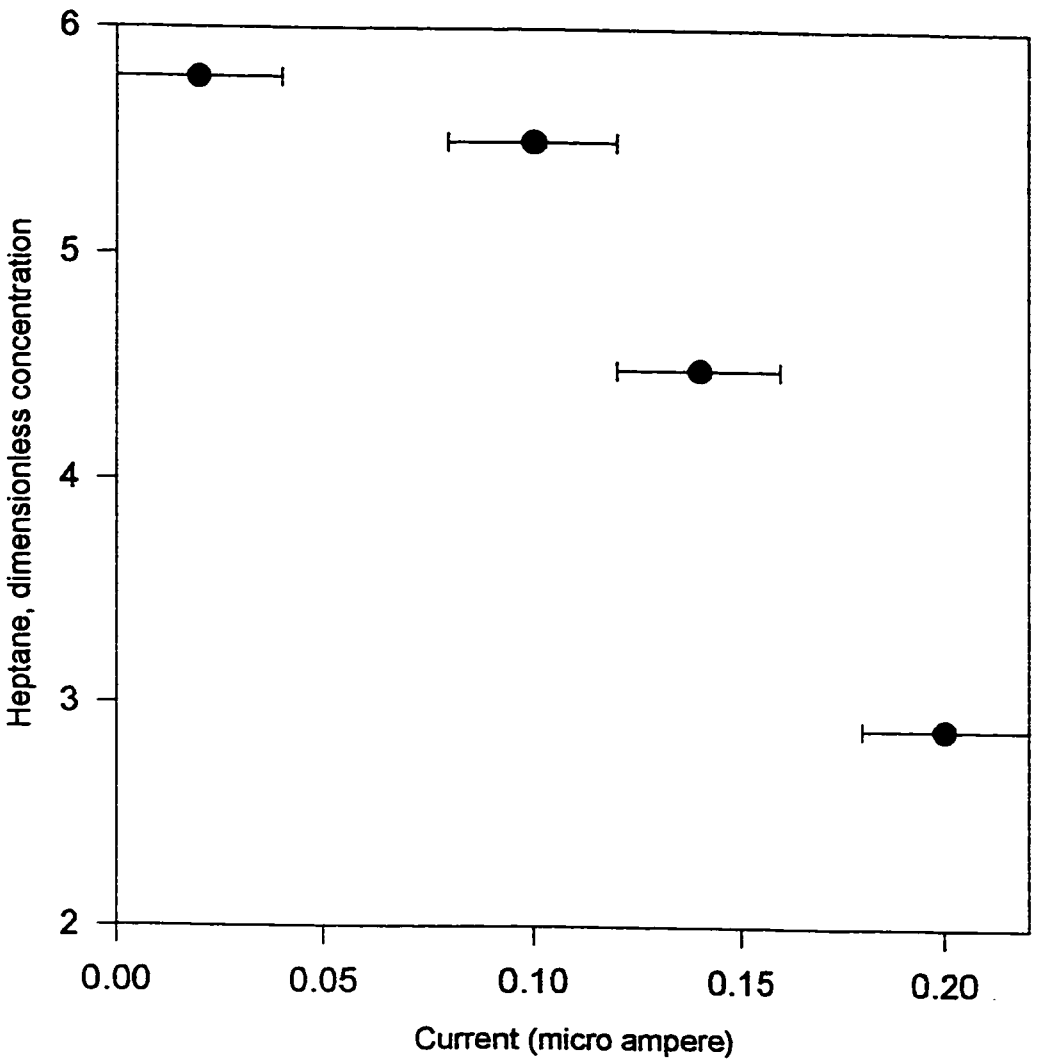


Figure 5.15 Heptane outlet concentration vs. current using TiN coated Ti-6Al-4V probe.

5.3.3 Results Using the Ti-6Al-4V alloy Probe

Ti-6Al-4V alloy is widely used in industry due to its excellent properties, e.g. high toughness-mass ratio [56]. However, it is not always stable in flame conditions, table 4.6. The results of voltage versus concentration are found to be quite similar to the TiN coated alloy, table 4.7. At flame condition number 5, table 4.5, Ti-6Al-4V alloy was found to be completely unstable. The same trend, as in the previous probes, of concentration versus voltage or current is observed. Fig. 5.16, Fig. 5.17, and Fig. 5.18 show the concentration of CO, benzene, and heptane, respectively, versus voltage. Fig. 5.19, Fig. 5.20, and Fig. 5.21 show the concentration of CO, benzene, and heptane, respectively.

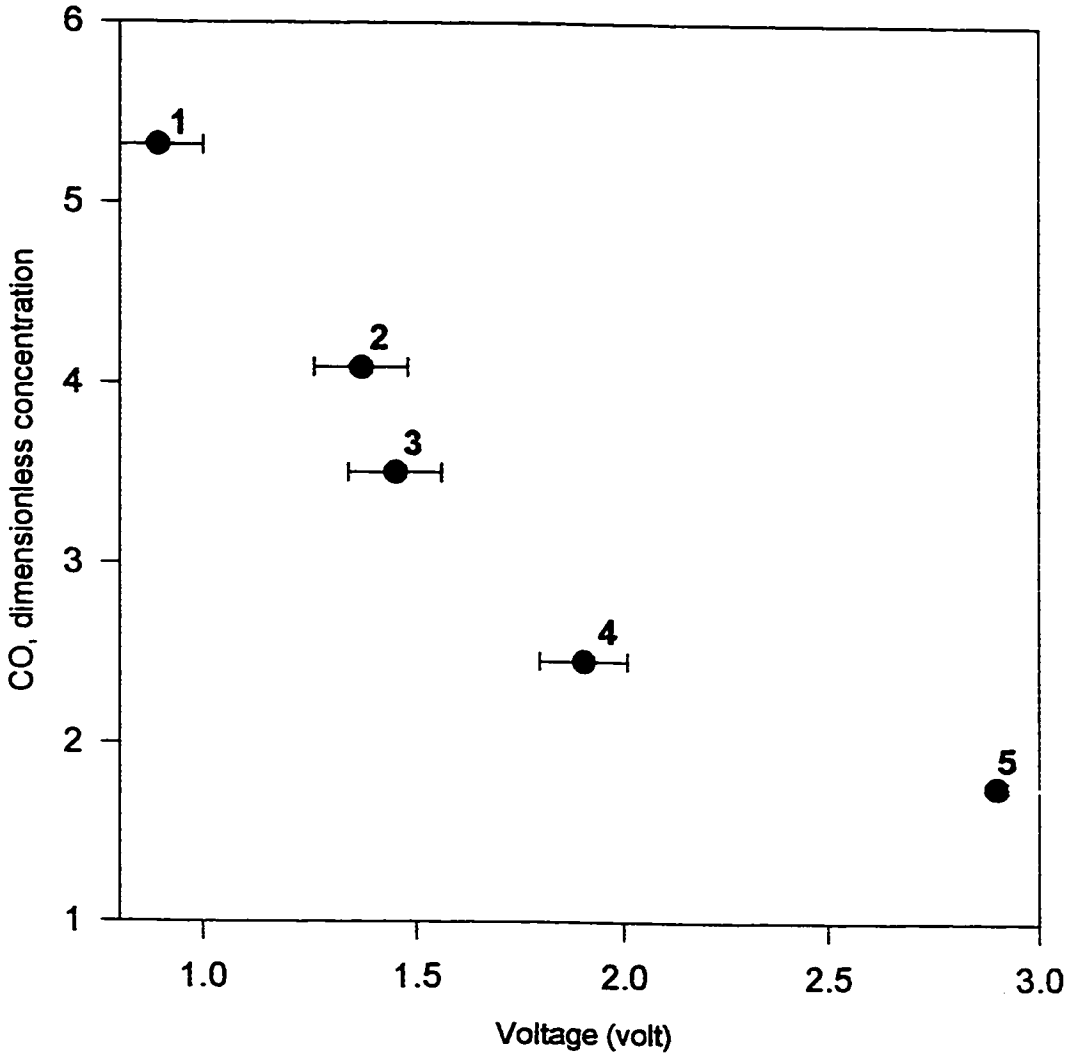


Figure 5.16 CO outlet concentration vs. voltage using Ti-6Al-4V probe.

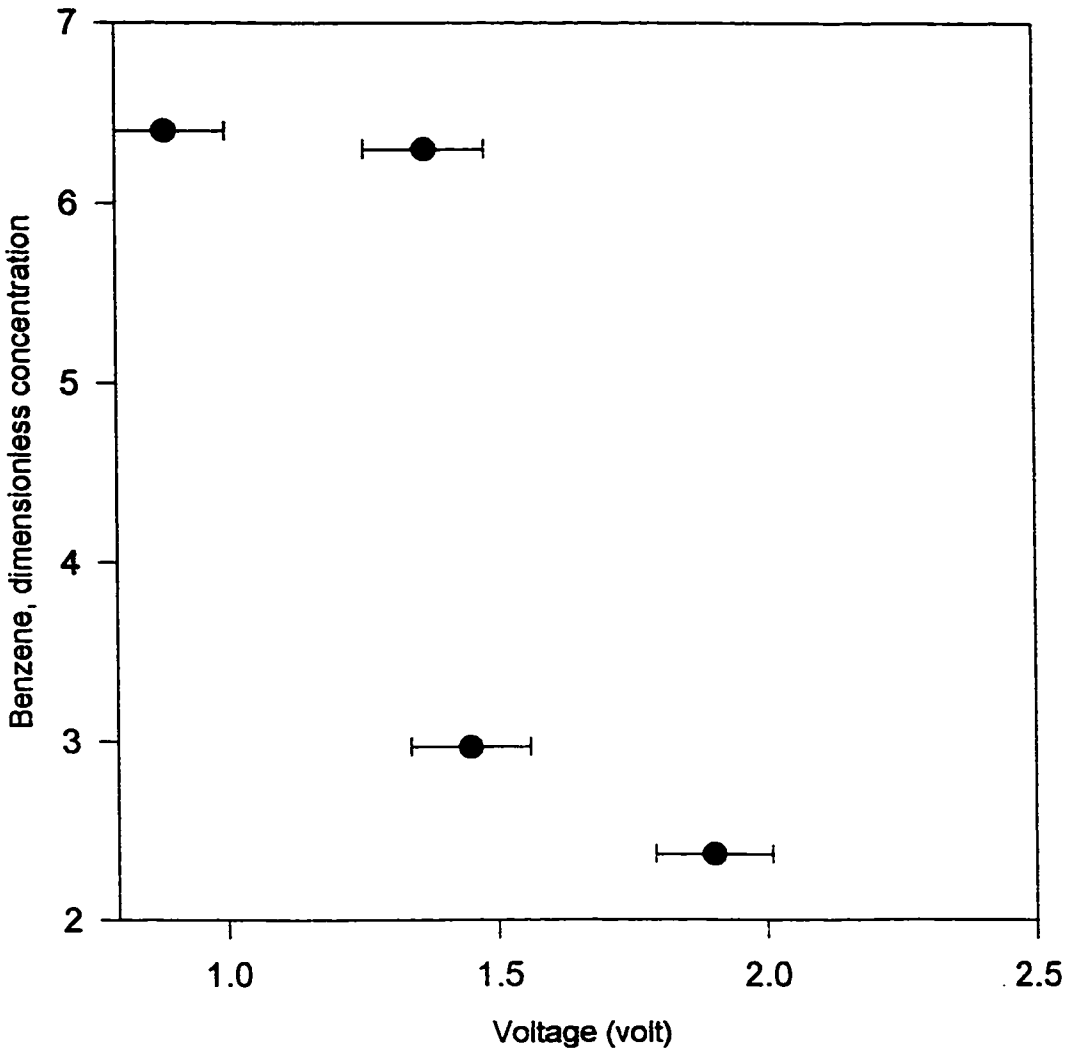


Figure 5.17 Benzene outlet concentration vs. voltage using Ti-6Al-4V probe.

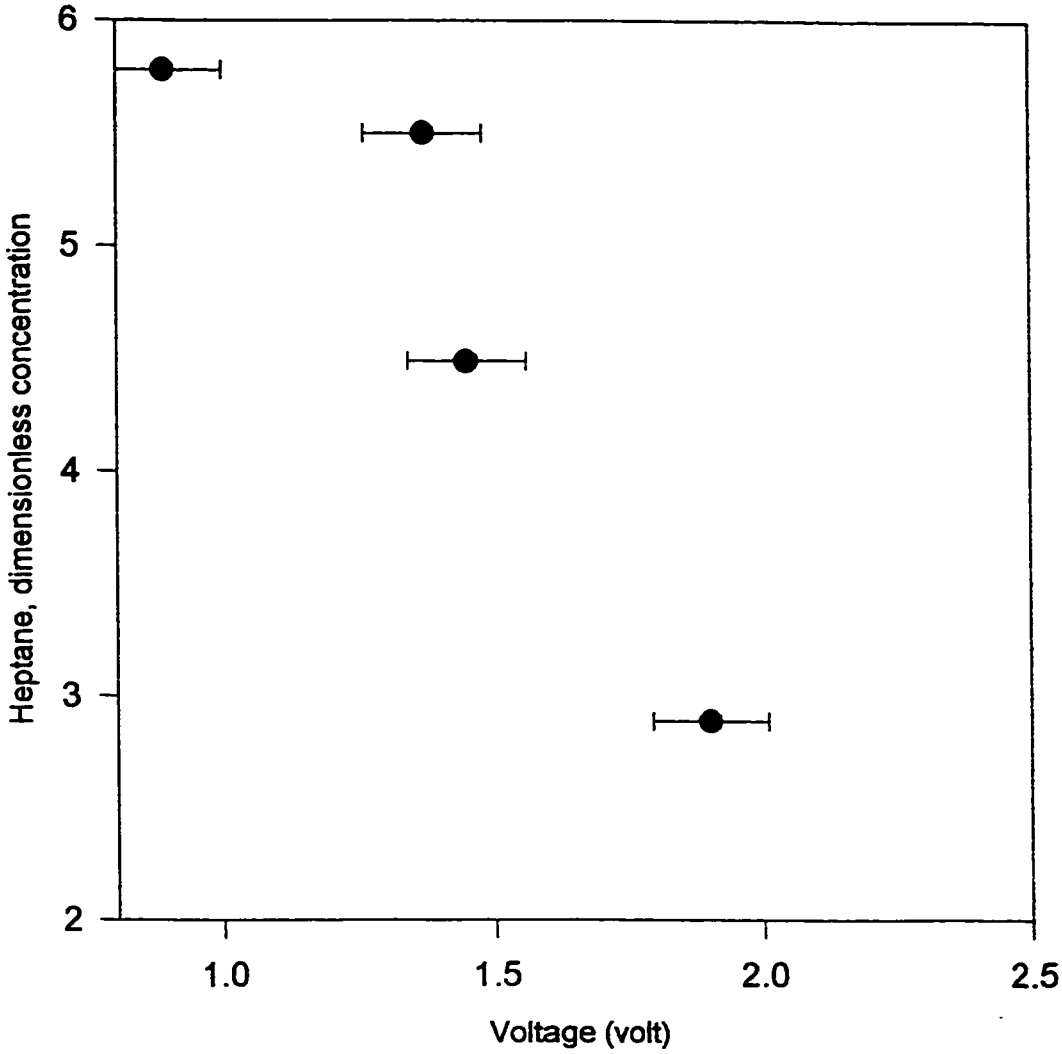


Figure 5.18 Heptane outlet concentration vs. voltage using Ti-6Al-4V probe.

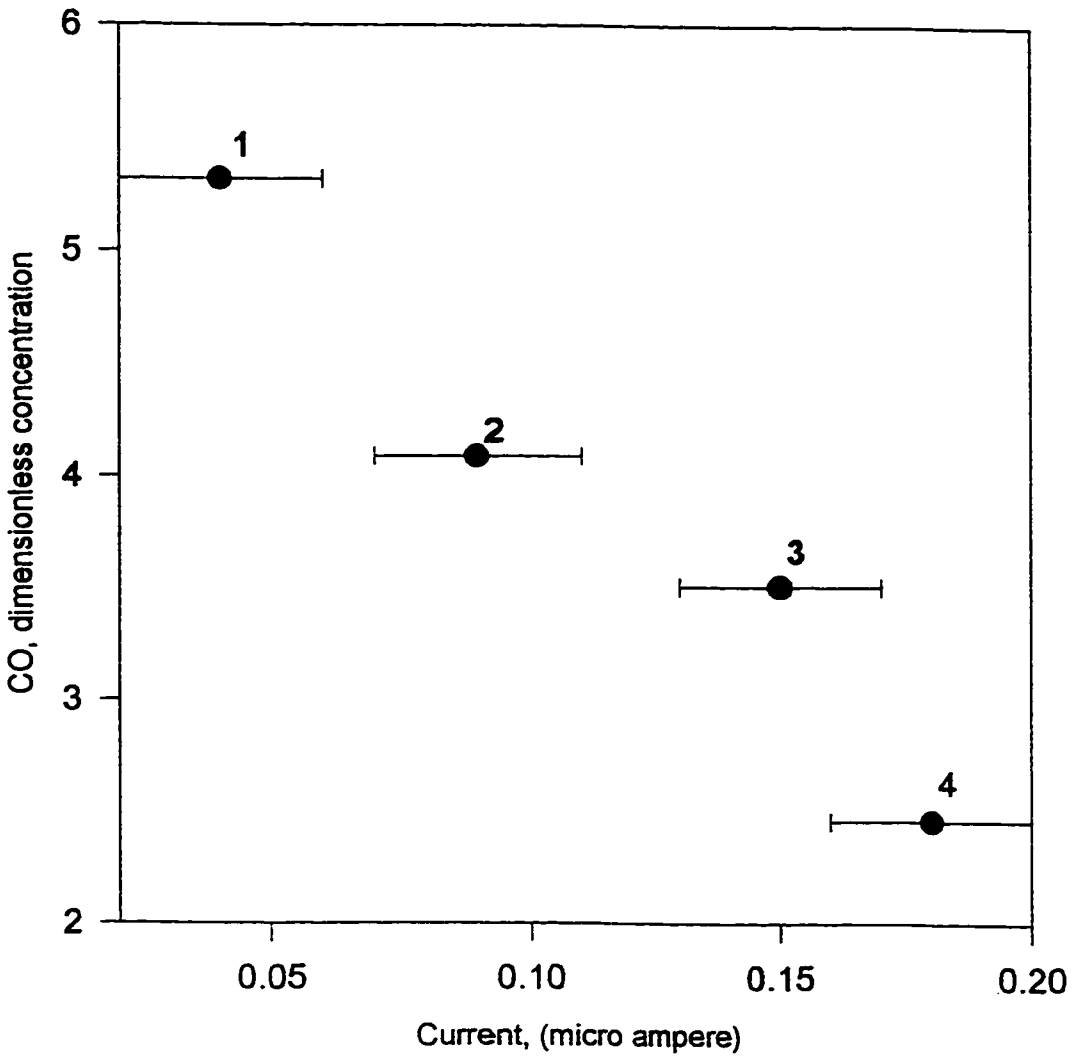


Figure 5.19 CO outlet concentration vs. current using Ti-6Al-4V probe.

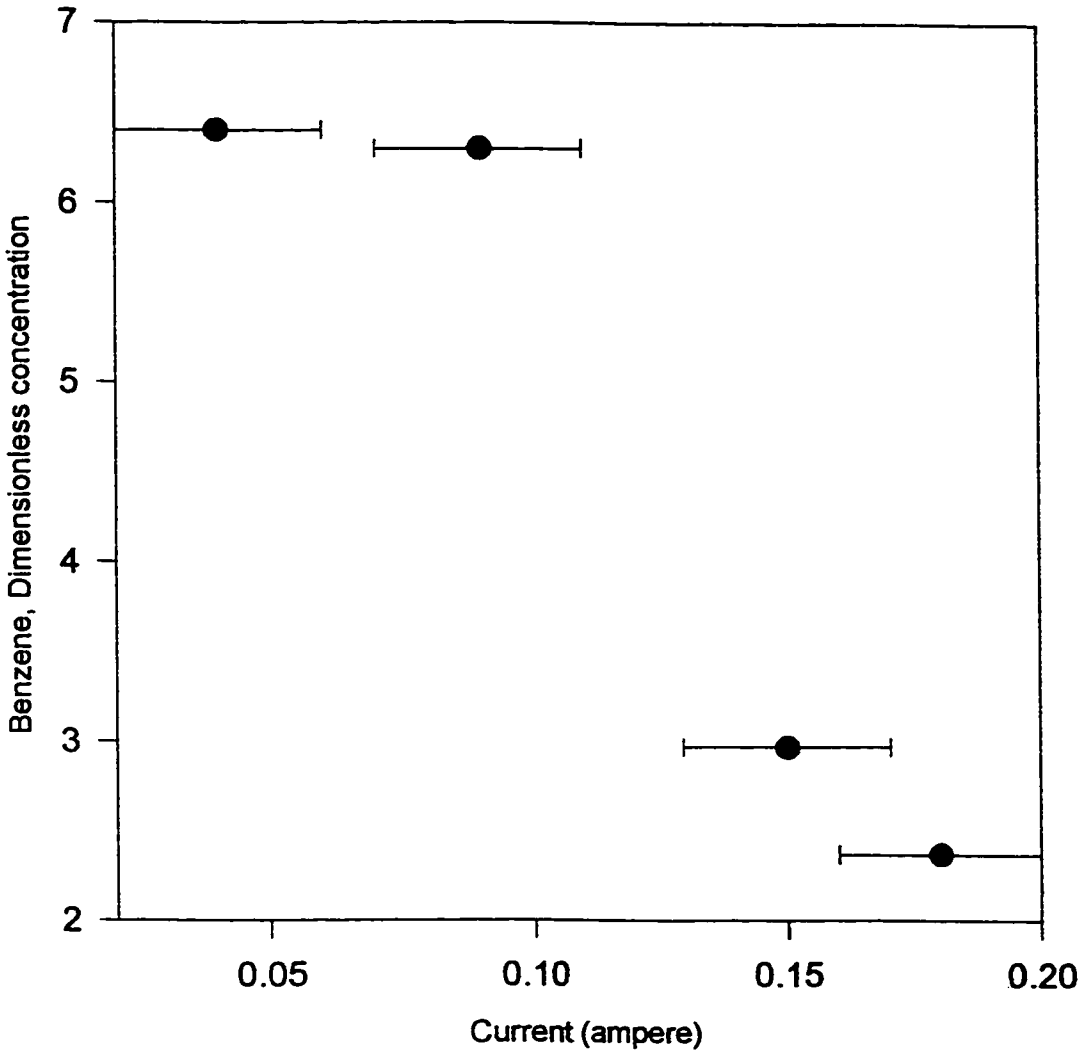


Figure 5.20 Benzene outlet concentration vs. current using Ti-6Al-4V probe.

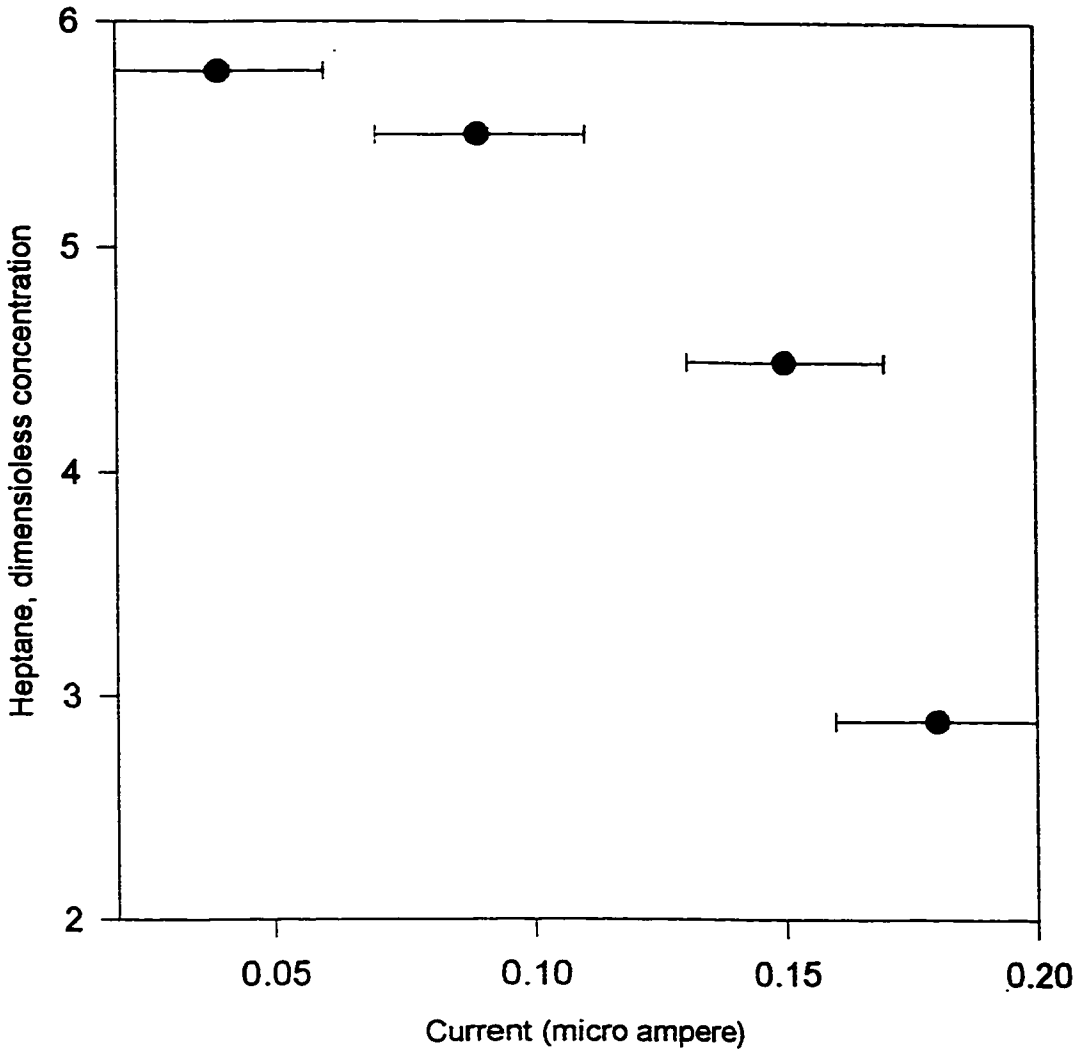


Figure 5.21 Heptane outlet concentration vs. current using Ti-6Al-4V probe.

5.3.4 Results Using the Tantalum Probe

Tantalum probe can not be used as a flame probe. It is a clear example that shows how important the probe chemical stability is. Although the melting point is very high (2996 °C), the chemical reactivity made it an unsuitable probe in flame conditions. Platinum has much lower melting point (1769 °C) than tantalum, but it is chemically inert at the same conditions. So platinum is good candidate to be used as a flame probe, while tantalum is not. Tantalum rod has been found to develop a hard and thick white material on the part of the probe which was in the flame. In addition, the head became very sharp (like a needle), although it was flat before the experiment. Three different tantalum probes have been tried and all have shown the same behavior.

Figure 5.22 shows a bad CO versus voltage correlation. The error is not indicated because it is hard to be determined. The values are the average of four or five readings. There is nothing useful to say about this curve, except that, the conclusion of the invalidity of the tantalum as a flame probe. The negative voltage (-0.18) developed is due to high temperature oxidation in the flame, table 4.4.

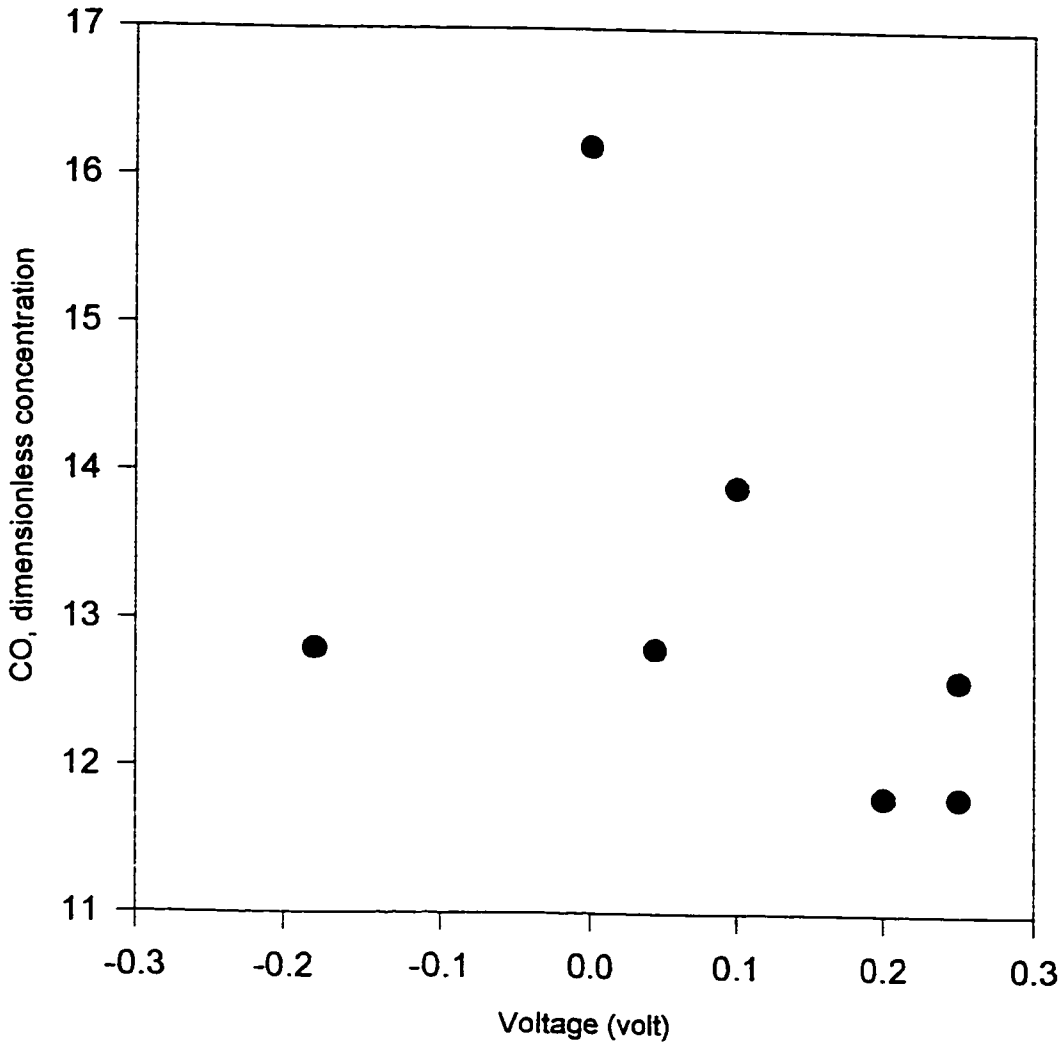


Figure 5.22 CO concentration vs. voltage using tantalum wire as a probe

5.3.5 Results Using the Steel Probe

Steel probe is not stable in flame conditions, table 4.4 and table 4.6. This experiment tells us, how important the procedure of measurements is. Systematic treatment of the probe before each measurement is important to obtain reproducible results of voltage at certain flame conditions. In this aspect, the probe is cleaned prior to each measurement to remove any layer which could have been formed in a previous measurement. The voltage reading is taken after approximately four to five seconds from the instant of inserting the probe in the flame. This time is related mainly to the response time of the voltmeter used, rather than the flame-probe system. Unlike the platinum or the alloys probes, steel probe is externally interfered in measurements. Cleaning and allowing around five seconds for stabilization of the voltage in the flame is arbitrary, however, they were attempted to be consistent as much as possible. The same trend of voltage versus concentration is observed. Fig. 4.23 show CO versus voltage concentration obtained using the procedure just described. The first four flame conditions are used in this experiment only. The fifth state created a lot of disturbance in the voltage, due to the high instability of the probe at that conditions. Same trend is obtained for benzene and heptane.

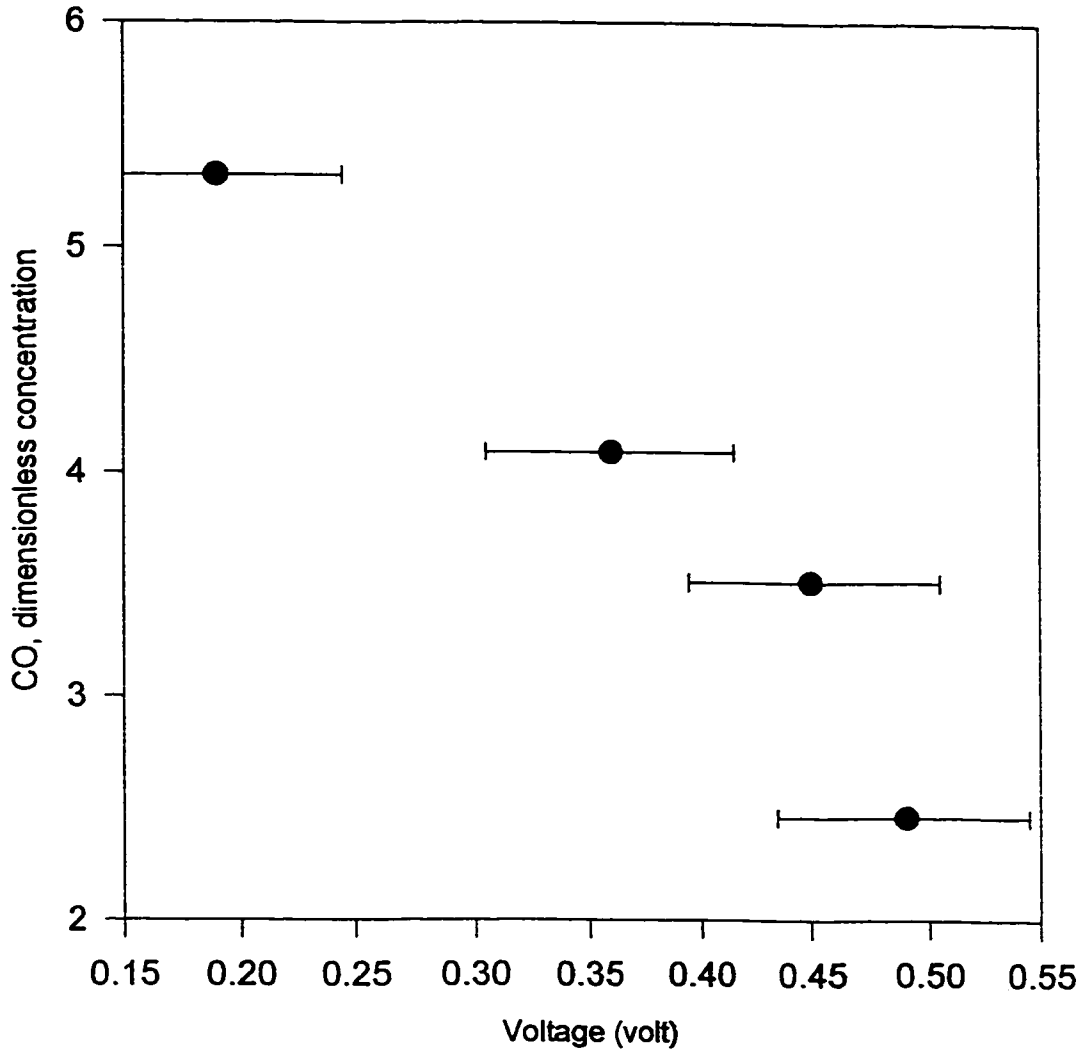


Figure 5.23 CO outlet concentration vs. voltage using steel probe.

5.3.6 Predicted Versus Measured CO Concentrations

The voltage in the flame was found to be the same before and after a steady state is achieved in the incinerator. In this part, the voltage is measured, using platinum probe, just after changing the flame conditions. Two sets of experiments were done, where CO was only analyzed. The first set has exactly the same operating conditions as given in table 4.5. The second set has the operating conditions as shown in table 5.1. Fig. 5.4 is considered as a calibration curve for CO concentration. The voltage is measured and the corresponding CO concentration is recorded. When the steady state is established in the incinerator, the CO is analyzed using the analysis system. Fig. 5.24 shows the predicted and the found concentration for the same measured voltage obtained after the steady state has been established. Fig. 5.24 show the predicted versus the found CO concentration using the flame conditions as illustrated in table 5.1. The numbers of the states in Fig 5.24 correspond to the flame conditions given in table 5.1.

Table 5.1 Flame conditions used to predict CO concentration using the platinum probe.

State no.	Air flow liter/min	Natural gas† liter/min	Waste flow‡ ml/min
1	15.4	4.4	1.80
2	24.3	4.4	1.80
3	30.9	4.4	1.80
4	44.2	4.4	1.80

† The natural gas is considered to be 95% methane and 5% ethane. This composition is confirmed by the GC using TCD detector. Other concentrations in the natural gas could be neglected.

‡ The composition of the waste is always heptane and benzene (4:1 v/v). The density of benzene is 0.875 g/ml and the density of heptane 0.682 g/ml at room temperature (298 K) where the flow rate is measured.

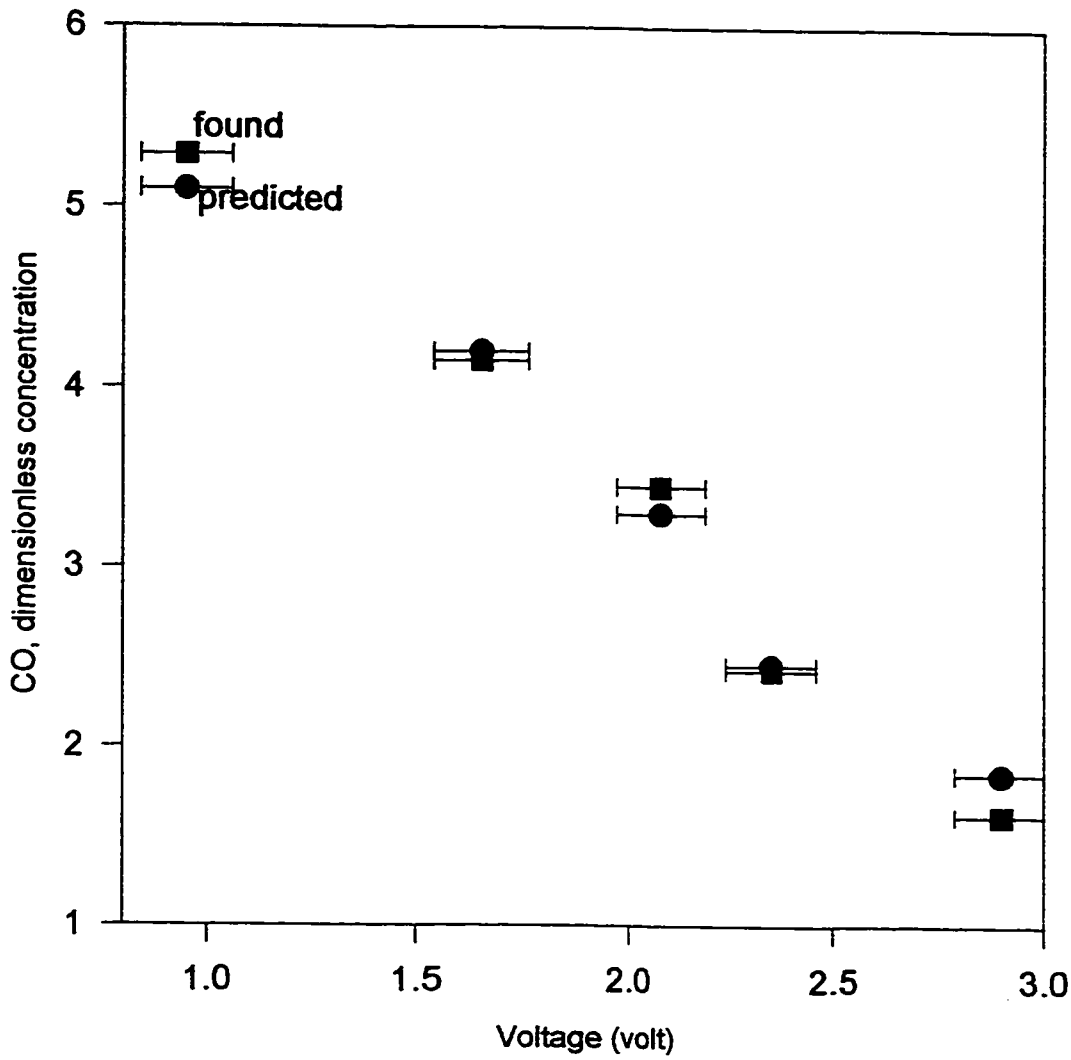


Figure 5.24 The predicted and the found CO concentration for the same measured voltage using the platinum probe. Flame conditions are given in table 4.5.

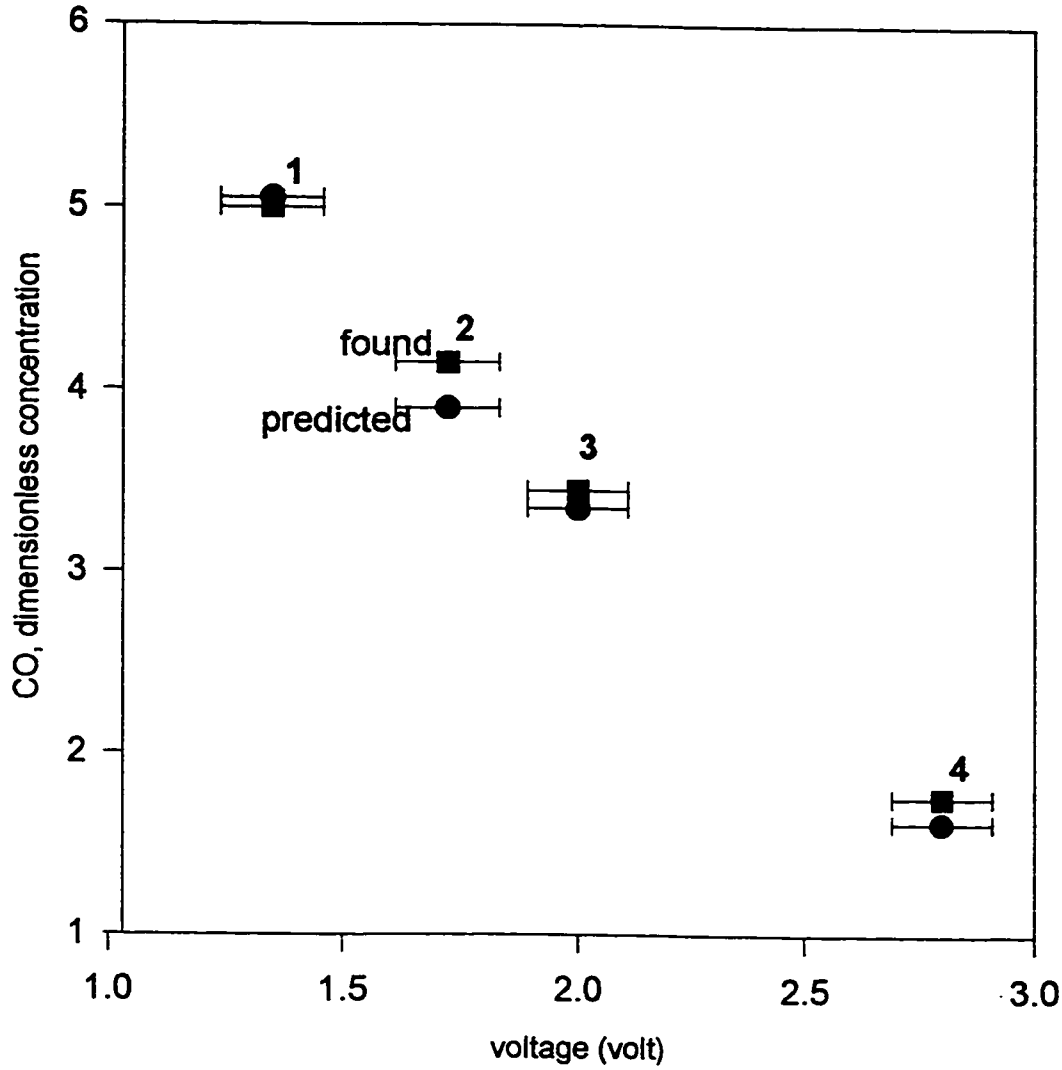


Figure 5.25 The predicted and the found CO concentration for the same measured voltage using the platinum probe. Flame conditions are given in table 4.1.

In this way, measuring the voltage for any flame will give the concentration of CO in the exhaust. Moreover, any upsetting of the flame will change the value of the voltage. Using this method the value of the CO concentration can immediately be predicted even before the steady state is established. This gives a potential to the proposed technique of 'measuring' the concentration of CO much earlier. Therefore, it could be used for very fast feedback control for any upsetting conditions due to flame effects and feed introduction. This is a clear advantage of the proposed technique over the other techniques.

5.3.7 The Relation Between CO and the Voltage

In hydrocarbon flames, "the overall concentration (of ions) remains sufficiently small that these species have no effect on the reaction rate in the flame"[28]. This approach in dealing with the charged species in the flame does not explain the correlation of CO concentration with the measured voltage in this work. This observed correlation implies that the charged species may affect the rate of formation of CO and hence the other elementary reactions that take place in the flame. It is true that the overall concentration of ions is small. However, in a steady state conditions these ions will be consumed fast in some elementary reactions, and therefore their concentration will remain small. Nevertheless, they act as 'a bridge' between some reactants and products. In addition charged species could have catalyzing effect (where small concentrations are sufficient) on CO formation.

As mentioned earlier, the direct linear relation between the voltage and CO dose not mean, at all, that CO is produced through ion-molecule reactions only. Free radical mechanisms that produce CO in the flame could have direct relation with the ion-molecule reactions. In this aspect, CO formation appears as a pseudo ion-molecule reaction. It is important to note that, CO concentration versus voltage can not tell the contribution of each of the two kinds of mechanisms, free radical and ion-molecule, in the CO formation. However, free radical mechanisms alone can not explain the observed CO voltage or current correlation. Ion-molecule reactions that produce CO in the flame could have direct relation with the free radical reactions. In this aspect, CO formation appears as a pseudo ion-molecule reaction. CO concentration versus voltage can not tell the contribution of each of the two kinds of mechanisms, free radical and ion-molecule, in the CO formation.

It is now accepted [29, 31] that chemi-ionization occurs close to the reaction zone as a result of :

$$O + CH \rightarrow HCO^{-} + e$$

The most important process following this reaction is

$$HCO^{+} + H_2O \rightarrow H_3O^{+} + CO.$$

In the known models of combustion, free radical elementary reactions are the only elementary reactions taken into account with reaction rate constants as [21, 28, 57-59]:

$k = A\,T^n \exp(-E/RT)$ or $k = A \exp(-E/RT)$

A : the pre-exponential factor

T : the temperature

E : the activation energy

R : the gas constant

n : order of the reaction.

Table 5.2 shows some elementary reactions for heptane combustion [21]. As can be seen, no charged particles are included in the proposed reactions.

Free radical mechanisms alone cannot explain the observed correlation between the concentration of CO or other chemicals vs. voltage. It is believed that the mechanism of the burning process includes effective steps having ionic species. As a first approximation, the rate constants of any proposed elementary ionic reaction, similar to the

Table 5.2 Some elementary reactions that contribute to heptane combustion process*

1. $C_7H_{16} \rightarrow {}^{\cdot}C_4H_9 + {}^{\cdot}C_3H_7$

2. $C_7H_{16} \rightarrow {}^{\cdot}C_5H_{11} + {}^{\cdot}C_2H_5$

3. $C_7H_{16} + {}^{\cdot}H \rightarrow {}^{\cdot}C_7H_{15} + H_2$

4. $C_7H_{16} + O \rightarrow {}^{\cdot}C_7H_{15} + {}^{\cdot}OH$

5. $C_7H_{16} + {}^{\cdot}OH \rightarrow {}^{\cdot}C_7H_{15} + H_2O$

6. ${}^{\cdot}C_7H_{15} \rightarrow C_2H_4 + {}^{\cdot}C_5H_{11}$

7. ${}^{\cdot}C_7H_{15} \rightarrow C_3H_6 + {}^{\cdot}C_4H_9$

8. ${}^{\cdot}C_7H_{15} \rightarrow C_4H_8 + {}^{\cdot}C_3H_7$

9. ${}^{\cdot}C_7H_{15} \rightarrow C_5H_{10} + {}^{\cdot}C_2H_5$

10. ${}^{\cdot}C_5H_{11} \rightarrow C_2H_4 + {}^{\cdot}C_3H_7$

11. ${}^{\cdot}C_5H_{11} \rightarrow C_3H_6 + {}^{\cdot}C_2H_5$

12. ${}^{\cdot}C_5H_{10} + {}^{\cdot}O \rightarrow C_4H_8 + CH_2O$

13. $C_5H_{10} + {}^{\cdot}OH \rightarrow {}^{\cdot}C_4H_9 + CH_2O$

14. $C_4H_{10} + {}^{\cdot}H \rightarrow {}^{\cdot}C_4H_9 + H_2$

* For the complete set of reactions that comprise heptane combustion and other compounds see [21]

ones shown above for free radical case, can be used. The concentration of ionic species could be approximated using Saha formula [38, 60] :

$$\alpha^2 = (2.4\times10^{-4}/p)T^{2.5}\exp(-E/kT)$$

α : degree of ionization(number of ions/total number particles)

p : pressure in torr.

E : ionization energy in eV.

k : Boltzman constant in eVK^{-1}

T : temperature in K.

Many challenges face the introduction of ionic mechanisms in combustion reactions. One problem is in finding which species are there. Second, what is the concentration of that species? Third, what is the mechanism of recombination that will produce, finally, neutral species ? Fourth, is there an interaction between the free radical reactions and the ionic reactions? Does this interaction produce a net voltage? Particularly that radicals can be considered as tiny magnets and the ions have electrical field. Is there more than one type of particles (ions and radicals) in one reaction?.

Plotting CO concentration vs. voltage gives a good linear fit (e.g. Fig.4.2; correlation coefficient, r = 0.961). On the other hand, heptane and benzene have no such good linear behavior. It is to be noted that CO could be produced from any hydrocarbon combustion reactions. In addition, some important ionic reactions (which are usually not included in

combustion modeling [21, 28, 57-59]) are believed to contribute to the CO production. Some of these reactions are [51] :

$CHO^+ + H_2O \rightarrow H_3O^+ + CO$

$CHO^+ + HCHO \rightarrow CH_3O^+ + CO$

$CHO^+ + HCOOH \rightarrow CH_3O_2^+ + CO$

$CHO^+ + CH_3OH \rightarrow CH_5O^+ + CO$

$CHO^+ + CH_3OCH_3 \rightarrow C_2H_7O^+ + CO$

$CHO^+ + CH_2CO \rightarrow C_2H_3O^+ + CO$

In addition to these reactions, the produced charged species may react to produce CO. In this aspect, charged species are not necessarily produced by direct ionization alone. This is a very important fact because if direct ionization alone is considered, the contribution of charged species to CO production could be small. Several ion-molecule reactions are possible. Taking CHO^+ as an illustrative example, one could show other ways, rather than direct ionization, of producing charged particles [51]:

$CHO^+ + X \rightarrow HX^+ + CO$ (proton transfer)

$CHO^+ + X \rightarrow X^+ + HCO$ (charge transfer)

$CHO^+ + X \rightarrow$ other products (rearrangement)

$CHO^+ + X + M \rightarrow CHO^+.X + M$ (Clustering)

$CHO^+.X + Y \rightarrow CHO^+.Y + X$ (switching).

Considering the above ion-molecule reactions, one could explain, qulitatively, the observed linear behavior of CO concentration versus the measured voltage. For example let's take the elementary reaction

$A^+ + B \rightarrow D^{(+)} + CO$

as a representative reaction of CO formation through ion-molecule reactions. The rate of formation (v) of CO in this reaction can be written as :

$v = k\,[A^+]\,[B]$

where k is the rate constant of the reaction. The concentration of A^+ ions could be considered as constant, because the voltage is constant at a given steady state. The concentration of the B species is also expected to be constant at a given steady state. The integrated form of the rate equation for CO can be written as :

$[CO] = k_1\,t + \text{constant.}$

The same equation could be derived for the consumption of the ions (A^+) to give :

$[A^+] = -\,k_1\,t + \text{constant.}$

The sum of both the integrated forms gives :

$[A^+] + [CO] = \text{constant}$, or

$[CO] = -\,[A^+] + \text{constant}$

As can be seen, the higher the A^+ (or charged species), the lower the concentration of CO. In other words the higher the voltage the lower the CO. This is a simplified scheme that

explains, at least qualitatively, the observed linear relation between the CO concentration at the exhaust and the measured voltage of the flame.

A simpler interpretation is possible. As stated earlier, chemi-ionization in the flame is mainly related to HCO^+. The voltage of the flame is proportional to the concentration of HCO^+ ions. In each of the steps in the above ion-molecule reactions, each HCO^+ ion is consumed for every one CO molecule produced. In kinetic terms this is equivalent to :

$$-d[HCO^+]/dt = + d[CO]/dt$$

At any given time this relation gives :

$$[CO] = - [HCO^+] + \text{constant}$$

Therefore, it is expected that a plot of [CO] versus the voltage of the flame is linear with a negative slope.

5.3.8 Voltage Versus a Feed Component

At higher voltages the destruction of the waste is more compared to the corresponding lower voltages (e.g. Fig. 5.6 and Fig. 5.8). As can be noticed from table 4.5 and table 5.1, the air flow rate is higher at higher voltages. So, a relation between the inlet air and the voltage is expected. An important fact is that, the air flow rate is a feed property not an outlet property of the incinerator. Fig. 5.26 and Fig. 5.27 shows the relation between the

air flow rate and the measured voltage using the platinum probe. Without waiting the results of the analysis, the flame conditions as measured by the voltage, could give at least qualitative information about the destruction process. This is could be used as the key of fast feedback control of the combustion process.

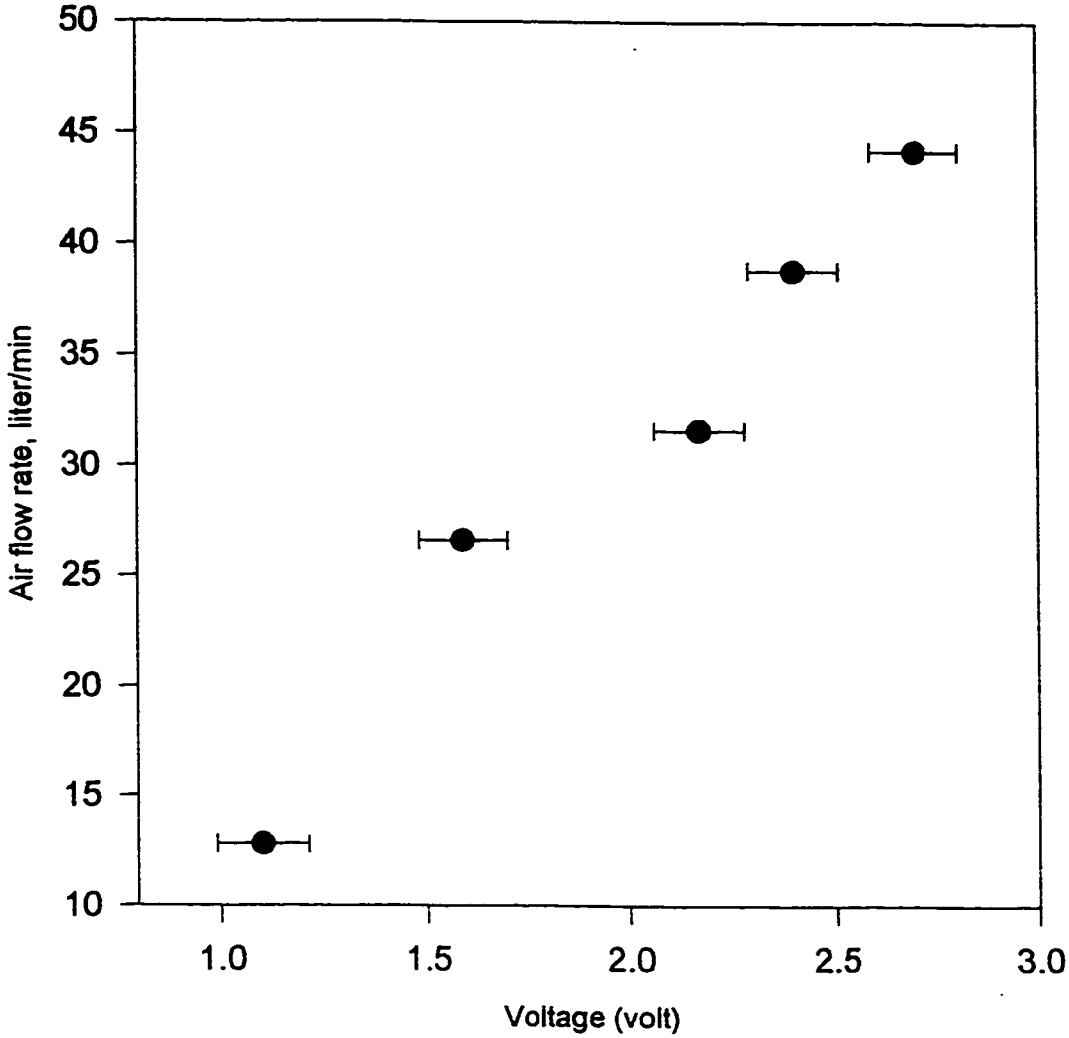


Figure 5.26 Voltage of the flame versus air flow rate (table 4.5) of the feed using the platinum probe.

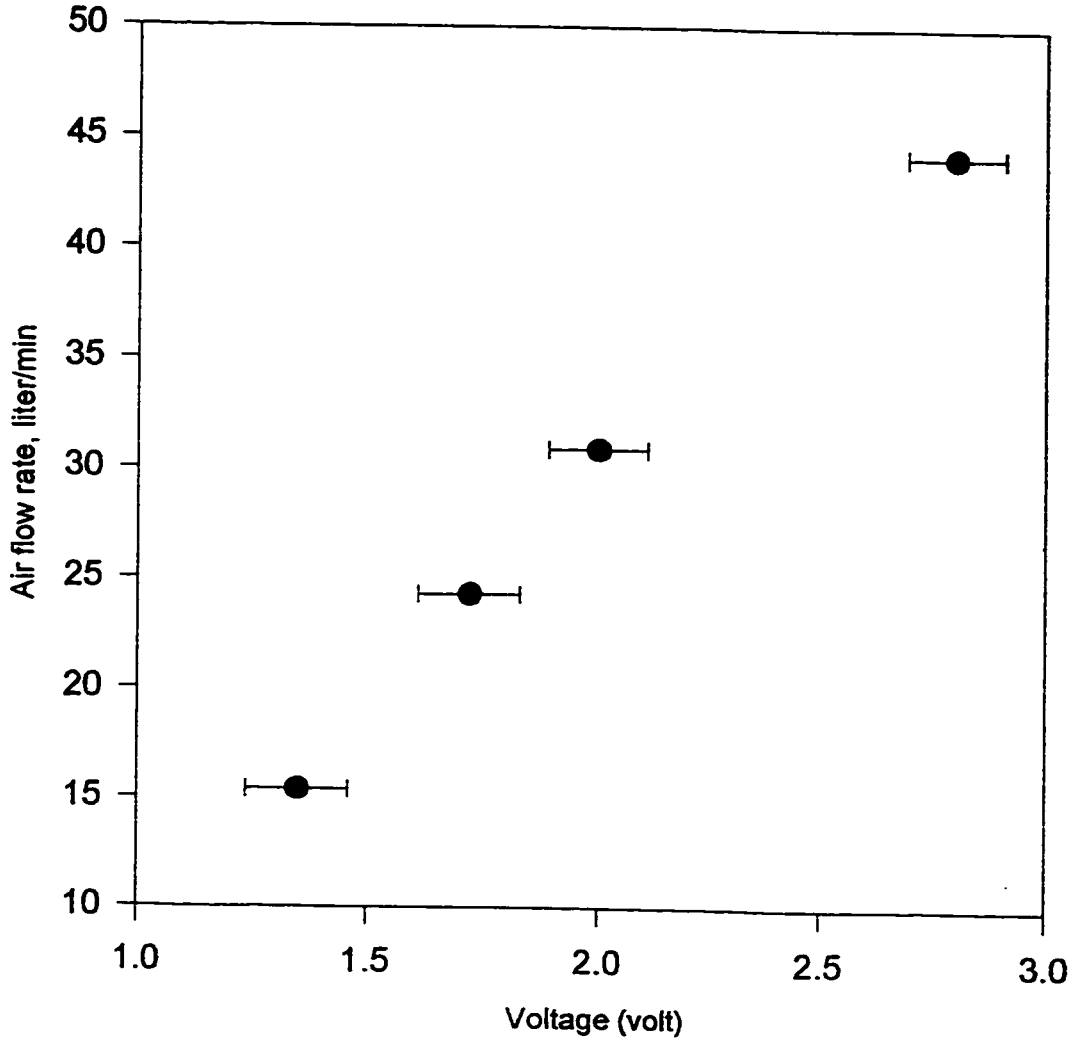


Figure 5.27 Voltage of the flame versus air flow rate (table 5.1) of the feed using the platinum probe.

5.3.9 Closing Remarks

Heptane and benzene have no direct relation, like CO, versus voltage. However, high voltage can be correlated with higher destruction of these compounds. This kind of correlation is proportional with the DRE of each compound, which is one of the most important criteria of incinerator performance.

Irrespective of the mechanism of the combustion process that produced this voltage, measuring the voltage in this way is a fast indictor of the combustion process in the flame which could be related to the combustion products.

Thus, the proposed technique has three advantages :

(i) It provides fast information about the combustion process.

(ii) The concentration of some exhaust gases can be predicted based on the voltage measured.

(iii) Fast feedback control of any upsetting conditions in the flame could be done.

However, research work on the mechanism of the combustion process and the flame-probe interaction is very important for designing a suitable probe for this purposes. One major problem is to find a probe that can stand in the flame for long enough time without changing its chemical and physical properties. However the problem becomes less significant if the change in the properties of the probe is minimum. Moreover, the problem can also be reduced if the probe can remain in the flame for a short time (about one minute) without change in its properties. The measurements of the voltage usually takes

much less time than one minute. As a proposed solution in this case, the probe could be moved automatically back and forth in the flame for voltage measurements.

No doubt a better voltage measurement system will enhance the reproducibility and the accuracy of the measured values. A microprocessor associated with data acquisition system for sampling and averaging each measurement would reduce the noise and enhance the reproducibility.

One should remember that the measured potential does not only depend on the probe-flame system, but also on the resistance of the wiring system between the probes and the voltmeter. Since the signal is voltage (not current) so the wiring system will affect the recorded values.

5.4 THE MONITORING SYSTEM

One of the achievements of this work is assembling and operating the monitoring system for incineration purposes. The monitoring system consists of the temperature monitors, waste flow rate monitor and the exhaust gas analysis system. Waste flow monitor is simply a rotameter (#3 of Fig. 2.2) to measure and show how steady the flow of the waste is. Temperature monitors (See section 2.5 for the hardware of the temperature monitoring system) are either with an analog or a digital output. The digital thermometers for the surface temperature of the chamber, the analysis heated lines and the exhaust temperature are interfaced with a chart recorder. The history of the temperature development will be clear during the preparation for the operation or during the operation itself. This kind of monitoring is important for confirming and monitoring a steady state if needed. When

some upsetting conditions happen, the temperature monitoring system could indicate the error, e.g. the damage of some heating tapes, the unexpected increase or decrease of the temperature of the chamber or an increase in the temperature of the exhaust gas. Around half hour is needed to record five or six samples for each datum. Any upsetting conditions could be reflected by the temperature monitoring system as well as the gas analysis system. So the recorded results from the GC will be questionable if the temperature monitoring system does not confirm the steady state. In this work, the temperature monitoring system used to be checked before and after each steady state.

Fig. 4.9 shows a sample of a steady state that is verified by the temperature monitoring system. Four locations are monitored and recorded using the chart recorder interfaced with the digital thermometers. Curve A indicates the temperature history of the outer surface of the chamber. Curve B indicates the temperature of the sampling port. Curve C indicates the temperature of a certain location of sampling lines before entering the GC. Curve D is room temperature monitoring. Peaks X and Y in curve B indicate a large increasing of the temperature of the sampling ports upon fast flushing of the sampling lines using the main vacuum lines. Tails of these peaks are due to extraction of the sample using the vacuum pump connected to the GC. It has been observed that curve B has to retain its flat base after the extraction of the sample; otherwise, the results are not reproducible

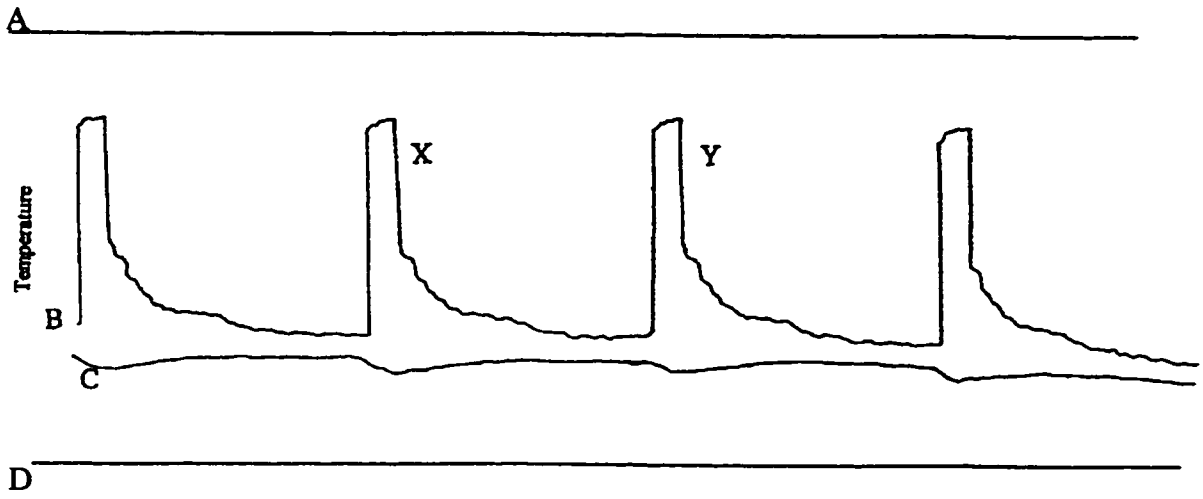
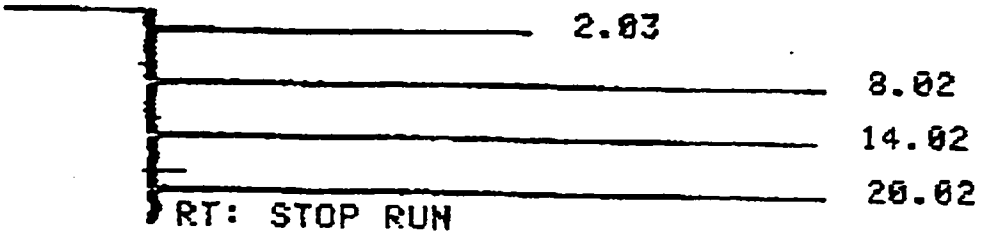


Figure 5.28 A sample of the temperature monitoring system output

When the flat base line is not retained, it is an indication that the steady state has been affected by external disturbances. Indeed the time between two peaks (from the end of the peak to the beginning of the other peak) is the time for checking the validity of the steady state. Each peak represents a set of analysis data for the given steady state. The presence of a flat temperature base line for long enough time (20 minutes), is an indication that the steady state has most probably been established. Any disturbance in the heating lines will be indicated in curve C and any fluctuation in room temperature will be shown by curve D. In the present work oxygen, nitrogen, carbon monoxide, carbon dioxide (if needed), and individual hydrocarbons could be analyzed in 7 minutes using GC only with a suitable plumbing system and suitable programming of the GC. As mentioned earlier (section 3.4.2) high reproducible result were obtained from the analysis system of the incinerator. Fig. 5.29 shows a sample chromatogram of a steady state where only methane is predicted in the exhaust of the incinerator. Appendix E shows the GC program that used for this experiment. The samples are automatically injected in the GC and analyzed during the run time of the GC. Notice that, as mentioned earlier (section 3.4.2), the first sample is different from the others. The first sample used to be discarded in all of the analysis done. The reproducibility for the other three samples is within $\pm 0.5\%$. The average of these three peaks is taken as the result of that analysis.



[hp] 5880A INJECTION @ 21:16 DEC 27, 1997
AREA %

RT	AREA	TYPE	AREA %
2.03	563.66	BV	15.289
8.02	1044.21	PH	28.323
14.02	1033.95	HH	28.045
20.02	1044.93	HH	28.343

TOTAL AREA = 3686.75
MULTIPLIER = 1

Figure 5.29 A sample chromatogram that demonstrate the reproducibility of the analysis system of the incinerator

Halogens and halogen-containing compounds can be analyzed using electron capture detector (ECD). ECD is very sensitive for the analysis of halogen-containing compounds. Infrared spectroscopy is another candidate for gas analysis. Indeed some gas analyzers are nondispersive (using fixed wavelength filters) infrared analyzers. These gas analyzers are single component analyzers. If a variable wavelength infrared gas analyzer is used, many components could be analyzed. Variable wavelength gas analyzers are more feasible for research. Miran 80 gas analyzer is tested and some experiments were done using it, see section 2.5 for more details. Low detection limits have been achieved. However it is not used in the present work, because GC has been found to be satisfactory for our purposes. One important difficulty in using such IR analyzer in the analysis of incineration exhaust gas, is the presence of water vapor. Working at a lower pressure, high temperature (100 °C), and/or using proper filtration system could make Miran 80 or similar gas analyzers much more feasible for industrial use as well as for research purposes.

CHAPTER VI

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

During this work, the incinerator is built from single component available in the University or outside. The chamber, the insulation, the feeding system and the cooling system is designed and constructed in the laboratory and the University workshop. The monitoring system is assembled after collection of the necessary components from different places in the University.

A novel technique based on the correlation of the voltage developed in the flame with the DRE has been introduced. It can be considered as an active sensor for the incineration process. Although the exact reasons of the voltage in the flame are not fully understood, the correlation of the measured voltage with the concentration of some exhaust components has been observed. Therefore, this technique is a good candidate for further development and industrial use.

Designing and constructing an incinerator seems as a matter of art as well as science. Thermodynamic driving force for combustion is enough for complete destruction of the liquid organic waste. However, the conventional thermodynamic parameters especially temperature and residence time (or the volume) are not enough for complete operation of the incinerator. For example, control of upsetting conditions does not need thermodynamic data to be done. In this work, the basic design parameters depend solely on the conventional parameters of thermodynamics of combustion. e.g. temperature of the chamber and residence time of the waste. These parameters are enough to design an

incinerator of any scale. This does not mean that other indirect parameters are excluded in the design.

One could introduce a catalyst in the incinerator which could decrease the temperature of operation in some parts of the incinerator. Additives could be introduced to overcome on some conventional thermodynamic parameters, e.g. temperature and volume.

A monitoring system that gives a reliable data is assembled. This monitoring system can be used for many kinds of studies related to the incineration.

This work shows that, monitoring systems could be constructed in an efficient way and much cheaper than the commercial ones.

For the incinerator to work properly, an efficient monitoring and controlling systems must be installed. Any upsetting conditions in the incinerator performance must be reflected as fast as possible on the control system. However, the analysis procedures followed commercially are not capable of such fast response, because of the lag time between the waste introduced and the analysis. In this work this problem is attacked completely in a different way. The fact that around 99% of the waste is destructed in the flame region gave the hint of trying to control the incinerator using flame properties. If flame properties are badly changed, the effect on this 99%, will have a pronounced effect on the required DRE which must be at least 99.99%.If the technical problems are reduced e.g. the stability of the probe in the flame, the proposed technique may contribute strongly in solving the control problems in incineration technology.

6.2 RECOMMENDATIONS

Two main items were of interest in this work, the design and control. Accordingly further work is recommended in the following :

1- The effect of evaporation of the liquid waste on DRE and PIC of several compounds compared to liquid injection method.

2- The effect of evaporation of liquid waste on dioxin formation in incinerators compared to liquid injection methods.

3- The effect of evaporation of the liquid waste on soot formation in incinerators compared to liquid injection incinerators.

4- Studying suitable designs for converting the liquid waste to vapor waste by using the heat generated by the incinerator itself.

5- Finding a suitable probe that could stand long times in the flame without changing its physical or chemical properties.

6- More correlation studies of the voltage of the flame and other waste compounds, e.g. halogenated compounds, polychlorinated biphenyls (PCBs).

7- The effect of different probes on the measured voltage.

8- The interaction of the probe with some feed components or the flame, if any.

9- Reducing the noise associated with the voltage in the flame.

10- Examining more closely the flame properties for more destruction in the flame and for control purposes.

11- Studying in more detail the ion-molecule mechanism and the role of the ions in combustion reactions.

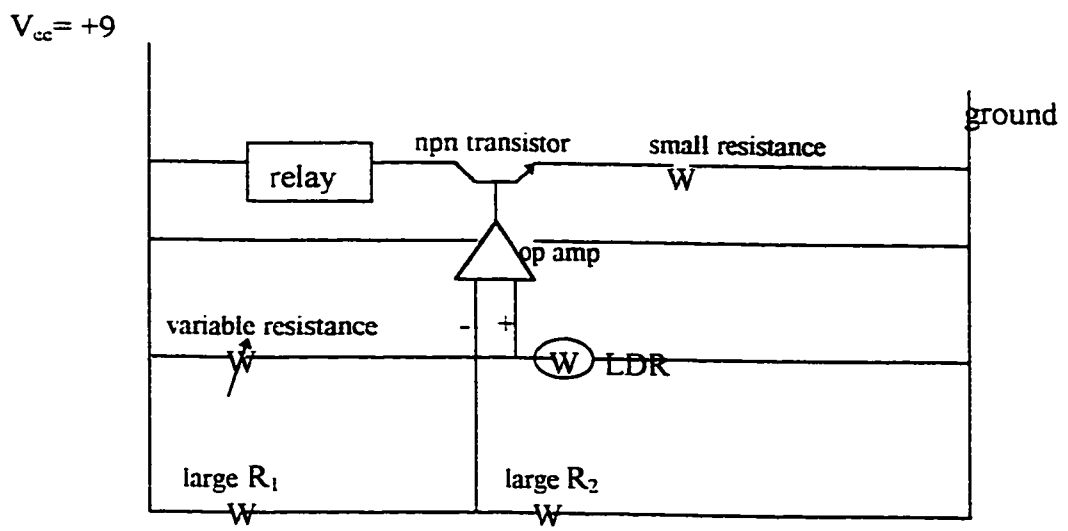
12- Studying the role of metals in the ion-molecule reactions and their effect on DRE or CO formation.

13- Including the ion-molecule reactions in the modeling of combustion reactions.

APPENDIX A

THE DESIGN OF THE FLAME SENSOR

The flame sensor developed is basically a voltage comparator circuit connected to a light dependent resistance (LDR). The basic element in the sensor is the LDR. It is fixed in the center at the end of a cylindrical tube. The pilot flame light is reflected from a mirror, fixed near the flame, to the LDR. Upon reflection of the light the resistance drops in the LDR. By adjusting the variable resistance in the comparator circuit, the circuit will activate if the resistance of the LDR is very high, i.e. the flame is extinguished. Upon activation the electromechanical relay will activate such that the chemical pump will be off (connected to normally closed terminals of the relay) and an alarm will be on.
The electronic circuit is shown below:



R_1=R_2

APPENDIX B

CHAMBER DESIGN CALCULATION

The derivation of the design equations(eq. 1-2 given in chapter two) is shown here.

Abbreviation used :
V : volume of the chamber (liters)
F : flow rate of the liquid waste (liter/hour)
ρ: density of the waste (g/ml)
n_c: number of carbon atoms in a molecule.
MM : molar mass
N(X) : number of moles of X/hour
N_t: total number of moles of gases/hour
τ: residence time of the chemicals in the chamber in (second)
Q: Flow rate of gases inside the chamber (m^3/hour)
Re: Reynolds number
v: the velocity of gases(m/s)
μ : dynamic viscosity($kg.ms^{-1}$)
ν : kinemetic viscosity ms^{-2}

Suppose a representative waste consists of heptane, benzene and Toluen. The density of such mixture could be taken as 0.8 gr/ml. and $n_c = 7$
Let CO_2 be the bases of calculations:

$$N(CO_2) = F(L/hr)\ \rho(gr/ml)\ 1000\ (ml/L)\ n_c\ mol/MM \qquad (B1)$$

Taking heptane (MM=100 gr/mol)for stoichiometric calculations

$$C_7H_{16} + 11\ O_2 \rightarrow 7\ CO_2 + 8\ H_2O$$

Using B1, $N(CO_2)$ can be written as :

$$N(CO_2) = F\ (.8)\ (1000)\ (7)/100 = 56\ F \qquad (B2)$$

$$N(H_2O) \cong N(CO_2)$$

$$N(N_2) = .79/.21[N(CO_2) + .5N(H_2O)]$$
$$= 5.6\ N(CO_2)$$

$$N_t = 2N(CO_2) + 5.6N(CO_2) = 7.6\ N(CO_2) \qquad (B3)$$

substituting of B2 in B3 gives

$N_t = 428F$

using $PV = nRT$ (considering ideal gas behavior)

$Q = \dot{V} = nRT/P = 428F(8.314)\ (1200K)/1.03x10^5 pa = 41.5\ F\ m^3/hr.$ (B4)

now the residence time in seconds is

$\tau = V/Q(3600)$

rearranging for V and substitution of B4 gives

$V = 11.5\ \tau\ F$

To calculate the preferable diameter of a cylindrical chamber, let's take Re > 2300 to have mixing of the flue gases.

$Re = \rho\ v\ D / \mu$ or
$Re = v\ D/\ \nu$, where $\nu = \mu / \rho$ (B5)

now

$Q = (area)\ v$ (B6)

substituting B6 for v in B5 gives

$Re = Q\ D/\ (Area)\ \nu$

$Re = 4Q\ /\pi D\ \ \nu$; rearranging for D gives

$D = 4Q / \pi\ \nu Re$ (B7)

With $\nu = 163 \times 10^{-6} m^2 s^{-1}$ for combustion gases at 1200K and by substitution of B4 in (B7) the diameter of the cylinder is

$D = 90\ F / Re$

The maximum liquid flow rate -can be found from the design equation with low residence time(.2-.3 s)- could be 4
with F = 4 and $Re \geq 2300$, $D \leq 15.6$ cm.

Insulation Design Calculation

The following data is needed for the design of the insulating materials :

k : Thermal conductivity (W/mK):
k_{ss} of the stainless steel = 14.9
k_c of the clay = .387, prepared and measured in the lab.
k_g of the glass wool = .142 measured in the lab.
D_o: Out side diameter of the chamber = .159m
D_i: Inside diameter of the chamber = .152 m
0.065 m. Thickness of the glass wool used. We were limited to this thickness because of the availability of the material.
110 Degrees is the maximum allowed temperature drop in the chamber.

$m_g = Q \rho_g = 41.5 \times 0.4975/3600 = 5.7351 \times 10^{-3}$ kg s^{-1}(F=1 as will be taken in the heat exchanger design, because of the space problems).
T_{ss} : The temperature at the surface of the stainless steel = 1200 K
T_o : The temperature at the outer surface of the insulation = 400 K
C_{pg}: The heat capacity of the gases at 1100 K. = 1.141 kj/kg K
R_t : The total heat resistance
R_{ss}: The heat resistance of stainless steel.
R_c: The heat resistance of clay
R_g: The heat resistance of glass wool
L : the length of the chamber = 0.60 m
X : is the diameter of the chamber with the clay.

We supposed that the k values are constant over the temperature range.

Now, substituting the appropriate values give :

$$Q = m_g C_{pg} \Delta T_g = 719 \text{ W}$$

$$Q = (T_{ss} - T_o)/ R_t \qquad \text{(B8)}$$

$R_t = R_{ss} + R_c + R_g$, where

$R_{ss} = \ln(D_o/D_i)/2\pi k_{ss} L = 8 \times 10^{-4}$

$R_c = \ln(X/D_o)/2\pi k_c L = \ln(X/.159)/1.46$

$R_g = \ln(X+0.13)/X)/2\pi k_g L = \ln(1+0.13/X)/.535$

substituting all of the values in B8 and solving for X we found X = 0.31 m
knowing that D_o = .159 m this gives the thickness of the clay = 7.5 cm.

APPENDIX C

HEAT EXCHAGER DESIGN CALCULATION

The heat exchanger design is chosen to be a shell and tube design. One main reason for this design is the easiness of fabrication compared with other designs. Two tubes of 4.8cm od.(d_o) and 3.8cm id(d_i). are chosen centered in a shell of 16.5 cm id.(D_i)
Because of the limitation of the space, the flow rate(F) of the liquid is taken to be 1 l/hr, so a shorter heat exchanger is needed.
In addition to the previous notations used in appendix B, the following notations are used here:

T: Temperature (K or C)
C_p: Heat capacity (j/kg K)
k: Thermal conductivity coefficient (W/m K)
h : Heat transfer coefficient (W/m^2 K)
m_g : Mass flow rate of the gases(kg s^{-1})
m_w: mass flow rate of water(kg s^{-1})
Pr: Prandtl number
Nu: Nusselt number
L: The length of the heat exchanger

Data given for calculation:

$\dot{Q}$= 41.5 F m^3/hr. (B4)
Initial T of the gas from the end of the chamber (T_{ig}) = 900 K
Outlet T of the gas from the heat exchanger (T_{og}) = 450 K (to prevent condensation of water in the exhaust duct)
Initial T of the water entering the heat exchanger (T_{iw}) = 300 K
Outlet T of the water (T_{ow}) = 320 K

For the gas side, the following data is needed (taking the mean T of the gas 700 K)

$\rho = 0.4975$ kg m^{-3}
$\mu = 338.8\text{x}10^{-7}$ Nsm^{-2}(kg m^{-1}s^{-1})
$C_p = 1.075\text{x } 10^3$Jkg^{-1}K^{-1}
$k = 52.4\text{x}10^{-3}$ W m^{-1}K^{-1}
Pr = 0.695

the properties of water at 310 K are

$\rho = 992.3$ kg m^{-3}

$\mu = 653.1 \times 10^{-6}\ Nsm^{-2} (kg\ m^{-1}s^{-1})$
$C_p = 4.179 \times 10^3 Jkg^{-1}K^{-1}$
$k = 0.6286\ W\ m^{-1}K^{-1}$
$Pr = 4.34$

The energy balance for the heat exchanger is

$$\dot{m}_g C_{pg} \Delta T_g = \dot{m}_w C_{pw} \Delta T_w \qquad (C1)$$

assuming $F = 1$

Eq. B4 gives $\dot{Q} = 41.5\ m^3/hr$

taking

$$\dot{m}_g = \dot{Q} \rho_g = 41.5 \times 0.4975/3600 = 5.7351 \times 10^{-3}\ kg\ s^{-1}$$

using eq.C1

$$\dot{m}_w = .03319\ kg\ s^{-1}$$

Let's calculate the heat transfer coefficients for water and gas sides.

For water side :

the hydraulic diameter (D_h)
$D_h = 4\ A_{cross\text{-}section}/P_{wet\ circumference}$

$$D_h = 4(\pi/4)(D_i^2 - 2d_o^2)/\pi(D_i + 2d_o)$$

with $D_i = 16.5$ cm, $d_o = 4.8$ cm

$D_h = 8.67$ cm

$$Re = \rho v D_h / \mu \qquad (C2)$$

$$\rho v = \dot{m}_w / Area \qquad (C3)$$

$$Area = (\pi/4)(D_i^2 - 2d_o^2) = 178 \times 10^{-4}\ m^2$$

substituting C3 in C2 and the appropriate values

$Re = (\dot{m}_w/Area)\, D_h/\mu = 247$; laminar flow.

Now for laminar flow

$$Nu = 1.86(Re\, Pr\, D_h/L)^{1/3}(\mu/\mu_s)^{0.14} \qquad (C4)$$

μ_s (at the surface of the inner tube) at T = 600 K is 0.06×10^{-3} kg $m^{-1}s^{-1}$
assuming $D_o/L = .05$ and substituting the appropriate values eq.C4 gives

$Nu = 9.8 = h\, D_h/k$ or

$$h = Nu\, k/D_h \qquad (C5)$$

substituting the appropriate values, C5 gives

$h_w = 71$ W m^{-2} K^{-1}

For the gas side

$Re = \rho\, v\, D / \mu$ where $D = D_h = d_i$, substituting eq. A6 for v

$Re = \rho\, (\dot{Q}/Aear)\, D_h/\mu$, Area : the surface area inside the tube.

with Area = $(\pi/4)(3.8^2 \times 10^{-4})$ and $\dot{Q} = 41.5/2 \times 3600$
Re = 2840 for one pipe; the flow is turbulent .

For turbulent flow

$Nu = .023\, Re^{.8} Pr^{.3}$, substitution of the appropriate numerical values
Nu = 11.93

Using eq.C5 with the appropriate numerical values

$h_g = 16.5$ W m^{-2} K^{-1}

Now let's calculate the total heat resistance (R_t) of the system :

$$R_t = R_{conduction} + R_{convection\ of\ gas} + R_{convection\ of\ water} \qquad (C6)$$

$R_{cond} = \ln(d_o/d_i)/2\pi k_{ss} L$;
$k_{ss} = 14.9$ $wm^{-1}K^{-1}$(ss : stainless steel), substituting the numerical values gives

$R_{cond} = 2.495 \times 10^{-3}$ /L

$R_{conv.g} = 1/ A_i h_g$ (A_i : the surface area inside the tube)
$R_{conv.g} = 1/2\pi$ di L , or
$R_{conv.g} = .2544/L$

$R_{conv.w} = 1/ A_o h_w$, (A_o : the outer surface area of the pipe), or
$R_{conv.w} = .0467/L$

substituting all R values in C6 gives :

$$R_t = (2.495\text{x}10^{-3} + .2544 + .046)/ L = .3036/L \qquad \text{(C7)}$$

now

$$m_g C_{pg} \Delta T_g = \Delta T_{lmtd}/R_t ; \qquad \text{(C8)}$$

ΔT_{lmtd} : logarithmic mean temperature difference

$$\Delta T_{lmtd} = [(T_{ig} - T_{ow}) - (T_{og} - T_{iw})]/\ln[(T_{ig} - T_{iw})/(T_{og} - T_{iw})]$$

substituting the numerical values :

$\Delta T_{lmtd} = 318$ K

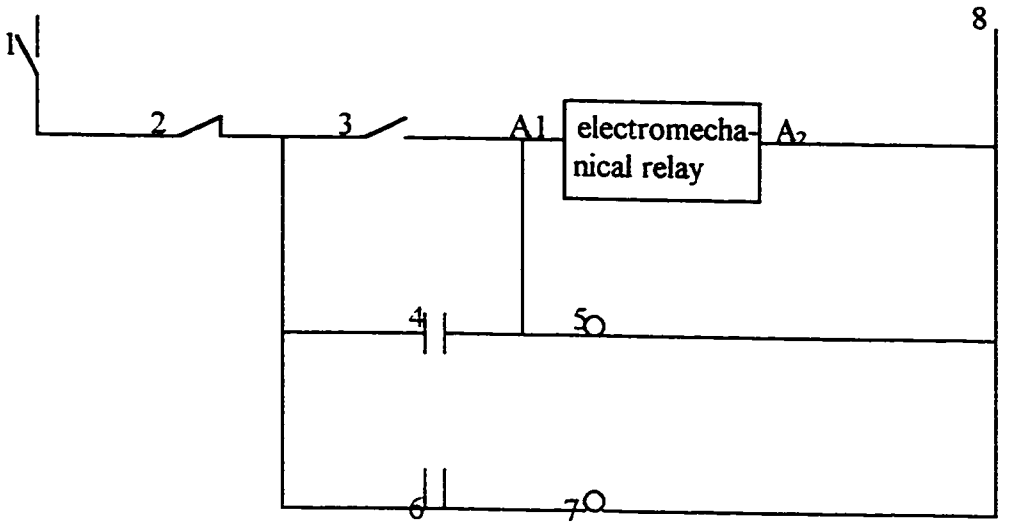
substituting C7 in C8 and substituting the appropriate value and solving for L, gives L = 2.6 m.

APPENDIX D

CONTROL CIRCUITS

Control can be done either manually (hand mode) or automatically (auto mode) by the GC. In addition to the feed back control of the pilot flame (see appendix A), other six equipment can be controlled as well. Candidate equipment in the incinerator for automation could be the liquid waste pumps, heated sampling lines, analysis sampling pump, air supplier and any valve of the system.

Hand mode control circuit



A_1, A_2 - the terminals of the solenoid of the relay.
1- main power line, 24 V ac, and emergency switch.
2- On-Off normally closed switch; red color.
3- On-Off normally open switch; green color.
4- normally open terminals of the relay.
5- green light indicator.
6- normally closed terminals of the relay.
7- red light indicator.
8- the ground.
The above circuit is repeated six times.

Auto mode control circuit

The same basic unit shown above is used for auto mode operation, except that switch # 3 is connected to a junction board in the GC to activate it according to the program needed.

APPENDIX E

A SAMPLE OF GAS CHROMATOGRAGH PROGRAM

Definitions:

valve1 : The relay of the sampling loop valve that is connected to GP5%SP-1200/1.75% Benton34, 6'*1/8"column.
valve2 : The relay of the sampling loop valve that is connected to 13X molecular sieve 4'* 1/8" column.
valve7 : The sampling pump relay that is connected to the outlet of the sampling loops.

The program:

```
run time 0.05  valve1 on
run time 0.05  valve2 on
run time 0.10  valve1 off
run time 0.10  valve2 off
run time 0.15  valve7 on
run time 4.00  valve7 off
run time 6.05  valve1 on
run time 6.05  valve2 on
run time 6.10  valve1 off
run time 6.10  valve2 off
run time 6.15  valve7 on
run time 10.00  valve7 off
.
.
.
```

The sentences are repeated each 6 min for the desired time.

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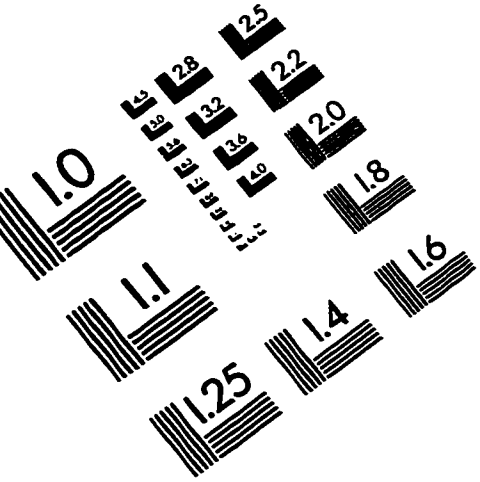
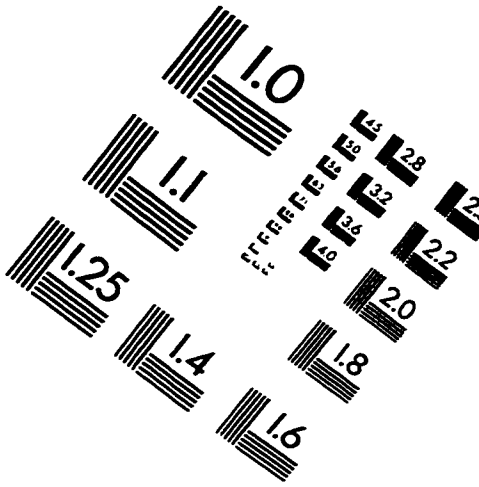
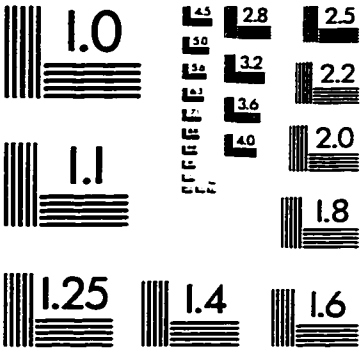
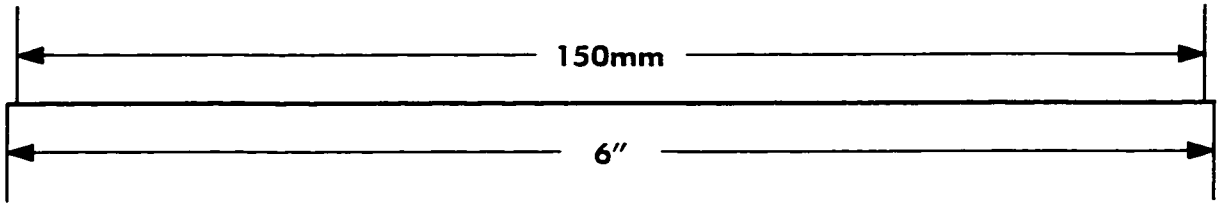
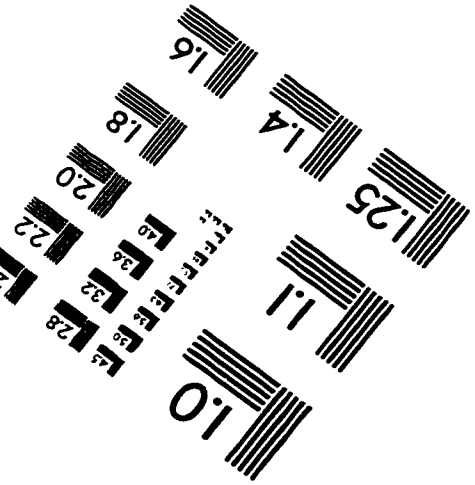
IMAGE EVALUATION TEST TARGET (QA-3)











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