MODELING AND SIMULATION OF ENERGY PRODUCTION PROCESSES FROM THE INCINERATION OF POLYCHLORINATED BIPHENYL WASTES IN ROTARY KILNS

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DEDICATION

To My Family

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Special thanks to all professors at the mechanical engineering department in the University of Jordan.

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LIST OF ABBREVIATIONS AND SYMBOLS

Roman Letters	
A	Area, m^2
C	Species hold up, kg
C_p	Specific heat at constant pressure, J/kg K
C_v	Specific heat at constant volume, J/kg K
D	Internal combustion chamber diameter, m
E	Radiation Energy, W
F	Factor: 1 for undammed kilns; greater than 1 for dammed kilns
$\overline{GS}$	Gas-wall surface exchange area, m^2
H	Convective heat transfer coefficient, $W/m^2 K$
H	Enthalpy, J/kg
K	Thermal conductivity, W/m K
l	Free mean path of a photon inside the combustion chamber, m
L	Internal combustion chamber length, m
M	Holdup inside the kiln, kg
N	Rotational speed of kiln, rps
Nu	Nusselt number
P	Pressure in the gas, atm
PM	Molecular weight, kg/kmol
Pr	Prandtl number
Q	Heat, W
R	Reaction rate, kg/s

Re	Reynolds number
S	Kiln slope (degrees from horizontal)
Sc	Schmidt number
Sh	Sherwood number
T	Temperature, K
U	Internal energy, J
v	Velocity, m/s
V	Combustion chamber volume, m^3
W	Flow rate, kg/s
y	Mole fraction
Superscripts	
bulk	Bulk phase
g	Gas phase
in	Inlet property
out	Outlet property
s	Solid phase
Subscripts	
a	Air Phase
Air	Air phase
bf	Burning fraction
c	Cold fluid
CH_4	Methane
CW	Carbon dioxide and water vapor phase
dr	Destruction rate
e	External property

ex	Exchanged action
f	Flue gas
gas	Gas phase
h	Hot fluid
H_2O	Water and water vapor
i	Stream components
ki	Kiln property
Ln,n	Log mean property
N_2	Nitrogen
O_2	Oxygen
r	Renewal property
ra	Radiation energy
ref	Reference state
solid	Solid phase
tot	Total property
w	Wall
Waste	Waste
Greek Letters	
β	Volume expansivity
γ	Geometry coefficients
Δ	Difference operator
ε	Emissivity
η	Boiler efficiency
μ	Stoichiometric coefficient for waste combustion, $kmolO_2$/kmol waste where the waste refers to the combustible fraction and the O_2 consumption refers to CO_2 formation

ξ	Heat Exchanger efficiency
ρ	Density, kg/m^3
σ	Stefan Boltzmann constant, $W/m^2\,K^4$
τ	Gas transmittance
Φ	Dynamic angle of response for the solid material inside the rotary kiln
ω	Fraction

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ABSTRACT

The goal of this work is to present a dynamic model for the incineration of one kind of hazardous wastes, namely, Polychlorinated Biphenyls (PCBs) in a rotary kiln. The model is written using Matlab and can account for variations in composition and process conditions. The effects of excess air and the number of chlorine atoms in the structure of the PCBs on the incineration process are included. The results show that the latter has a significant effect in determining the operating temperature and the amount of utilized energy.

Models written in Mathcad for heat recovery systems are used. Their effect in the process efficiency is investigated. The use of them in large capacity steam power plant shows an effective increase in the overall efficiency of the plant by saving noticeable amount of heat in the boiler.

It is found that the incineration temperature of PCBs is around 1200 K, depending on the number of chlorine atoms and excess air. The heat of combustion can be recovered and used to improve the efficiency of steam power plant. The incineration process is improved by heating the fuel air mixture by the hot gases produced from the rotary kiln.

Finally, the model validity is investigated by comparing the results with experimental data available from commercial units under ordinary feeding conditions, and comparable results were obtained. In addition, the economical analysis is performed for the modified power plant. It is found that 2.7 million JD of annual saving is possible in terms of fuel used to produce steam, with payback period of about 6 years.

CHAPTER ONE

Introduction

1.1 Background:

Energy production processes from new energy sources is one of the most important processes not only on the national level but also on the international one. One of the reasons for that is the increase in the fuel prices, in addition to the negative impact on the environment i.e. gas emissions. Currently, the world witnesses an increase in the industrial developments which demand more energy on one hand and produce environmental problems on the other hand that is air, water, and soil pollution, besides hundreds of tonnes of industrial wastes.

International conventions, which state laws and regulations to protect the environment will some how retard the industrial revolution all over the world by demanding standards for the industrial outputs to the environmental elements. So the problem of coexistence of sustainable industry and safe environment is one of challenges in the scene of fuel prices and availability.

So studies all over the world to produce cheap and clean energy meanwhile produce less harmful wastes and even use wastes to produce energy through waste treatment technology. This can be achieved by applying what is called waste-to-energy (WtE) principle and sometimes it is called (energy-from-waste (EfW)). One of these studies is the production of energy from hazardous wastes that results from the industrial activities. Thus, this thesis will present a method used to produce energy from the incineration in rotary kilns of one type of hazardous wastes, namely, Poly Chlorinated BiPhenyl (PCBs).

1.2 Rotary Kiln Incinerator:

Incineration is one of waste thermal treatment methods in which the wastes are combusted at high temperatures. Waste incineration has the following advantages:

1. Volume reduction, especially for solids with a high combustible content

2. Detoxification, especially for combustible carcinogens, pathologically contaminated material, toxic organic compounds, … etc

3. Environmental impact mitigation, by destruction of all undesired secondary effluents or byproducts which would create further significant pollution problems

4. Energy recovery, which is the most important advantage, especially when large quantities of waste are available.

Incineration of waste materials converts the chemical energy in the wastes into thermal energy (that can be used to generate electricity). So one of the outputs of the incineration processes is the heat but other outputs are gases and particullate matter, and a smaller amount of solid residue (ash). However, other advantage of using incinerators to convert hazardous wastes into gases, heat, and other matters is the possibility to segregate the outputs into desired and undesired, of course energy is the desired out put and others are not. Therefore, the gaseous and particulate emissions are (in new designs) stored in underground reservoirs such as empty oil wells and effluent gases are treated before they can be emitted to the atmosphere by the flexible design of the incinerator which will allow the addition of gas treatment units.

Modern incinerators (Stehlik, et al. 2000) burn wastes in high-efficiency furnaces/boilers to produce steam and/or electricity and incorporates modern air

pollution control systems and continuous emissions monitors. An incinerator is a furnace for burning refuse, modern incinerators include pollution mitigation equipment such as flue-gas cleaning. There are various types of incinerator plant design:

1. Simple

2. Fixed or moving grate combustion

3. Rotary-kiln

4. Multiple/stepped hearth

5. Fluidized bed

Below is a brief description of the above mentioned incinerator:

1. Simple incinerators

The older and simpler kinds of incinerators were brick-lined cell with a metal grate over a lower ash pit, with one opening in the top or side for loading and another opening in the side for removing incombustible solids, called clinkers. Many small incinerators formerly found in apartment houses have now been replaced by waste compactors.

2. Fixed or moving grate combustion

These are large fixed hearth incinerators, with a moving grate. The moving grate enables the movement of waste through the combustion chamber to be optimised to allow a more efficient burn. These incinerators are typically used for combustion of Municipal wastes.
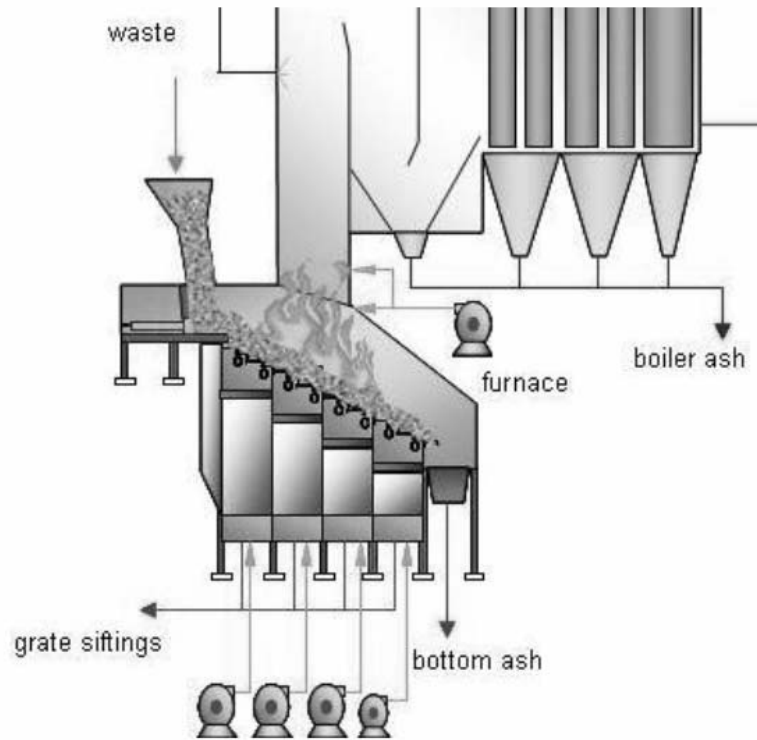
Figure 1.1. Moving Grate Incinerator, (Council of the European Union directives 96/61/EC: article 16 (2)).

3. Rotary-kiln

The rotary-kiln incinerator is used by municipalities and by large industrial plants. The design of incinerators has two chambers: a primary chamber and secondary chamber. The primary chamber in a rotary kiln incinerator consists of an inclined refractory lined cylindrical tube. Movement of the cylinder on its axis facilitates movement of waste. In the primary chamber, there is conversion of solid fraction to gases, through volatilization, destructive distillation and partial combustion reactions. The secondary chamber is necessary to complete gas phase combustion reactions.

The clinkers spill out at the end of the cylinder. A tall flue gas stack, fan, or steam jet supplies the needed draft. Ash drops through the grate, but many particles are carried along with the hot gases. The particles and any combustible gases may be combusted in an afterburner. To control air pollution, the combustion product gases are further treated

with acid gas scrubbers to remove sulfuric acid and nitric acid emissions, and then routed through bag houses to remove particulates before the gases are released into the atmosphere.
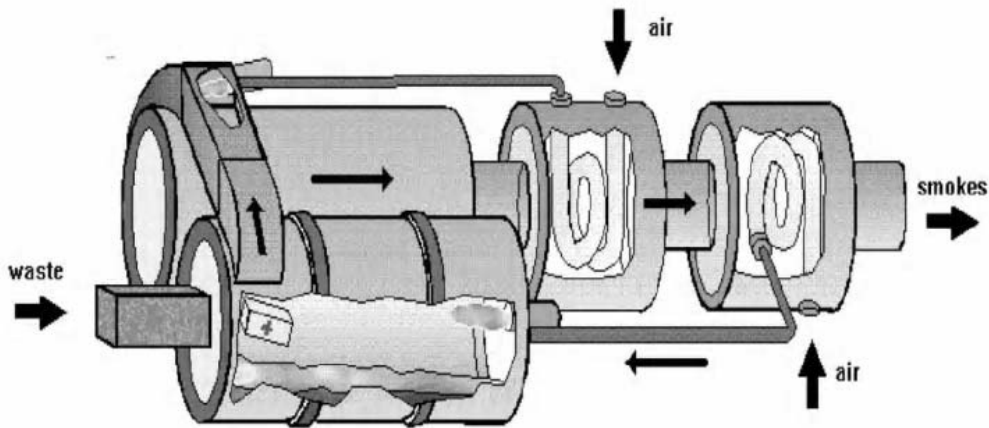
Figure 1.2. Rotary Kiln Incinerator, (Rovaglio, et al., 1998).

4. Multiple/stepped hearth

Where waste is transported through the furnace by moving teeth mounted on a central rotating shaft.

5. Fluidized bed

A strong airflow is forced through a sand bed The air seeps through the sand until a point is reached where the sand particles separate to let the air through and mixing and churning occurs, thus a fluidized bed is created and fuel and waste can now be introduced.

The sand with the pre-treated waste and/or fuel is kept suspended on pumped air currents and takes on a fluid-like character. The bed is thereby violently mixed and
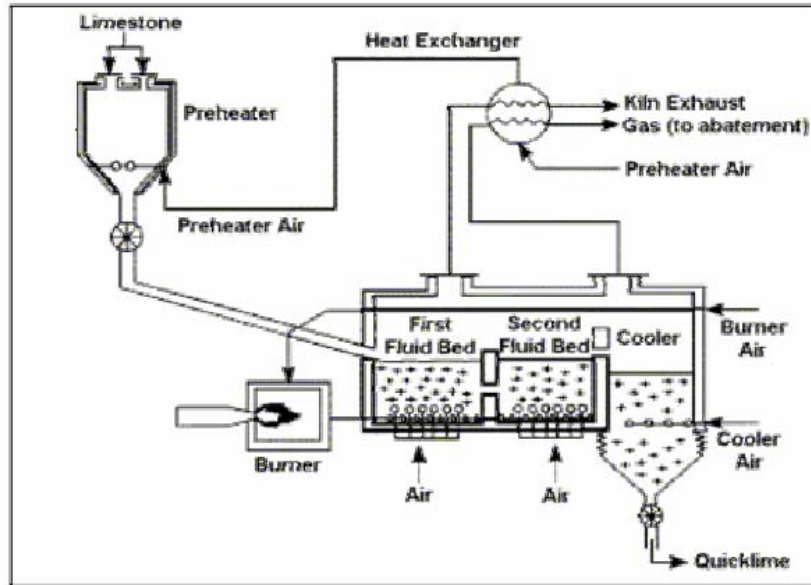
Figure 1.3. Fluidized Bed Incinerator, (Council of the European Union directives 96/61/EC: article 16 (2)).

agitated keeping small inert particles and air in a fluid like state. This allows all of the mass of waste, fuel and sand to be fully circulated through the furnace.

1.3 Use of Thermal Energy:

The heat produced by the rotary-kiln incinerator can be used to generate steam which may then be used to drive an electric generator (Otoma, et al. 1997). The typical range of net electrical energy that can be produced is about 500 to 600 kWh per ton of waste incinerated. Thus, incinerating about 2,200 tones per day of waste will produce about 50 MW of electrical power (Rovaglio, et al., 1998)

The energy production processes mostly generate wastes specially when it includes a combustion process. This work deals with the energy production from the incineration of hazardous wastes which implies a decrease of the amount of wastes in general. This will contribute mainly to the Best Available Technology (BAT) for energy production and to the Best Environmental Practices (BEP), since it will control the rate of

pollutants generation mainly in the gas phase. Next section will introduce the types of pollutants expected in the incineration processes.

1.4 Pollution

Incineration has a number of outputs such as the fly ash and the emission to the atmosphere of combustion product gases and particulate matter. Concerns over $PM_{2.5}$ or 2.5 micrometer size particles are of specific concern.

Modern incinerators emit less air pollution than coal plants, but more than natural gas plants. The U.S Environment Protection Agency (U.S. Environment Protection Agency, 2004) has characterized modern incinerators as "producing electricity with less environmental impact than almost any other source of electricity".

a. Gaseous emissions

The combustion product gases exhausted to the atmosphere by incineration are a source of concern. The main pollutants in the exhaust gases include acid gases such as hydrogen chloride, sulfur dioxide, nitrogen oxides (referred to as NO_x), and carbon dioxide.

The most publicized concerns from environmentalists about the incineration of municipal solid wastes (MSW) involve the fear that it produces significant amounts of dioxin and furan emissions to the atmosphere. Dioxins and furans are considered by many to be serious health hazards. Older generation incinerators that were not equipped with modern gas cleaning technologies were indeed significant sources of dioxin emissions. Today, however, due to advances in emission control designs and stringent

new governmental regulations, modern waste-to-energy incinerators emit virtually no dioxins (Rahuman, et al., 2000).

The quantity of pollutants in the emissions from large-scale incinerators is reduced by a process known as scrubbing as well as other processes.

b. Solid outputs

Incineration produces fly ash and bottom ash just as is the case when coal is combusted. The total amount of ash produced by municipal solid waste incineration ranges from 15% to 25% by weight of the original quantity of waste, and the fly ash amounts to about 10% to 20% of the total ash (Dyke, 1998). The fly ash constitutes more of a potential health hazard than that of the bottom ash because the fly ash contains toxic metals such as lead, cadmium, copper and zinc as well as small amounts of dioxins and furans. The bottom ash may or may not contain significant levels of health hazardous materials. In the United States, and perhaps in other countries as well, the law requires that the ash be tested for toxicity before disposal in landfills. If the ash is found to be hazardous, it can only be disposed of in landfills which are carefully designed to prevent pollutants in the ash from leaching into underground aquifers, but in testing over the past decade, no ash from a U.S. modern waste-to-energy plant has ever been determined to be a hazardous waste; In the UK, fly ash is classed as hazardous and must be disposed of in a hazardous waste designated landfill but Incinerator Bottom Ash (IBA) is under investigation by the Environment Agency.

c. Other pollution issues

Odor pollution can be a problem with old-style incinerators, but it is claimed that odors and dust are extremely well controlled in a modern incinerator (Otoma, et al.,

1997). They receive and store the waste in an enclosed area with a negative pressure with the airflow being routed through a boiler which prevents unpleasant odors from escaping into the atmosphere. However, not all plants are implemented this way, resulting in complaints. Figure 1.4 shows a plant where integrated process of hazardous waste incineration with pollution monitoring and disposal.
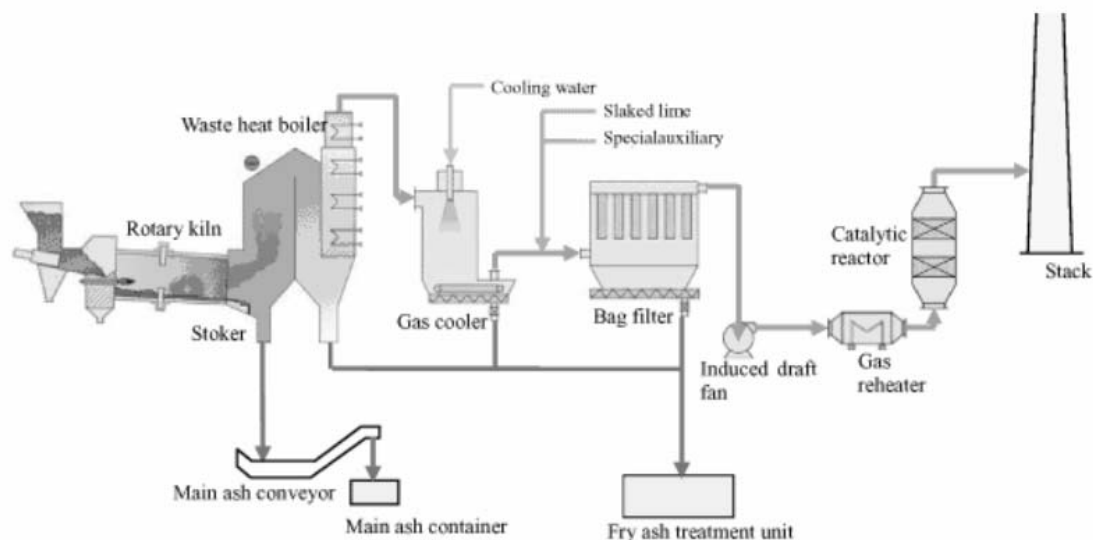
Figure 1.4. Plant Used for Hazardous Waste Incineration with Pollution Prevention and Monitoring Techniques, (Otoma, et al., 1997).

An issue that affects community relationships is the increased road traffic of waste collection vehicles to transport municipal waste to the incinerator. Due to this reason, most incinerators are located in industrial areas.

It is important here to mention that the combined heat and power plant is the cleanest method for energy generation. If compared to other techniques in terms of its participation to the global carbon dioxide (CO_2). Kyoto protocol targets to minimize the CO_2 emissions as it key source for global warming and climate change greenhouse effect. Many governments have actions to reduce the emissions. Table 1.1 (Murphy and

McKeogh, 2004) summarizes and compares the electrical power generated and carbon

dioxide emissions for different electrical sources.

Table 1.1. Greenhouse Gas Production per Unit of Electrical Power from Different Sources (Murphy and McKeogh, 2004)

Source of electricity	g CO_2/kWh
Coal	890
Oil	720
Natural gas	480
Solid waste incineration	220
Bio gas	198
Solid waste gasification	115
Solid waste incineration (CHP)*	58
Wind	0

*CHP: Combined Heat and Power Plant

1.5 Polychlorinated biphenyls (PCBs) Definition:

Polychlorinated biphenyls (PCBs) are a class of organic compounds PCBs classified

as persistent organic pollutants. PCBs contain 1 to 10 chlorine atoms attached to

biphenyl and a general chemical formula of $C_{12}H_{10-x}Cl_x$ (Figure1.3 in the next page

shows the structure of the PCBs), Most PCBs were manufactured as:

1. Cooling and insulating fluids for industrial transformers and capacitors

2. Stabilizing additives in flexible PVC coatings of electrical wiring and electronic

   components.

PCB mixtures have been used for a variety of applications. These applications include dielectric fluids for capacitors and transformers, heat transfer fluids, hydraulic fluids, lubricating and cutting oils, and as additives in pesticides, paints, carbonless copy (NCR) paper, adhesives, sealants, plastics, reactive flame retardants, capacitors, insulating fluids in transformers, vacuum pump fluids, hydraulic fluids, and as a fixative for microscopy. They were also used in surgical implants. However, PCBs production was banned in the 1970s due to the high toxicity of most PCB congeners and mixtures. Research indicating they were likely carcinogens having the potential to adversely impact the environment and therefore undesirable as commercial products.
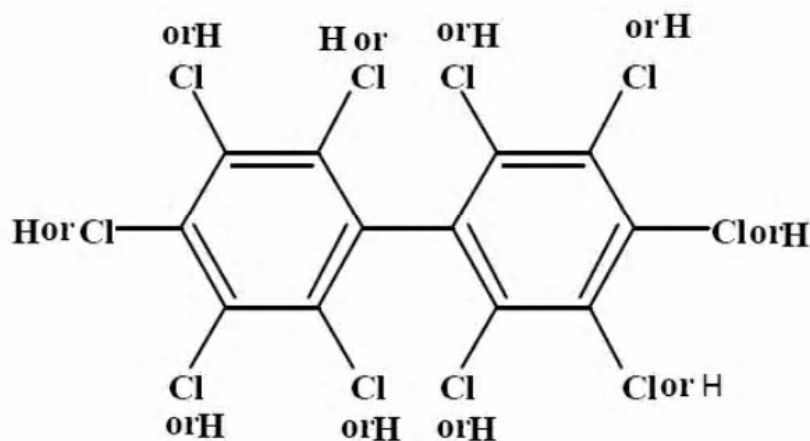
Figure 1.5. PCBs Chemical Structure, (Rahuman, et al., 2000).

Most of the 209 different PCB solutions are colorless, odorless crystals. Commercial PCB mixtures are clear viscous liquids (the more highly chlorinated mixtures are more viscous, for example, its viscosity may reach that of sticky resins. PCBs have low water solubility and low vapor pressures at room temperature, but they have high solubility in most organic solvents, oils, and fats. Other physical and chemical properties vary widely across the class.

Examples of PCBs are PCB-resistant materials include Viton, polyethylene, polyvinyl acetate (PVA), polytetrafluoroethylene (PTFE), bytyl rubber, nitrile rubber, and Neoprene. Table 1.1 gives the known members of PCBs family.

Table 1.2. Examples of PCBs Component with Identifying cas Number and Number of Chlorine Atoms Present, (Rahuman, et al., 2000)

PCB	CASRN[*]	Cl Substituents
Biphenyl	92-52-4	0
Monochlorobiphenyl	27323-18-8	1
Dichlorobiphenyl	25512-42-9	2
Trichlorobiphenyl	25323-68-6	3
Tetrachlorobiphenyl	26914-33-0	4
Pentachlorobiphenyl	25429-29-2	5
Hexachlorobiphenyl	26601-64-9	6
Heptachlorobiphenyl	28655-71-2	7
Octachlorobiphenyl	55722-26-4	8
Nonachlorobiphenyl	53742-07-7	9
Decachlorobiphenyl	2051-24-3	10

* Chemical Abstract Service Registration Number

1.6 PCBs Methods of Destruction:

PCBs are very stable compounds and are not easily degradable. They may be destroyed by chemical, thermal, and biochemical processes (Rahuman, et al. 2000). Though it is extremely difficult to achieve full destruction. And the risk of creating extremely toxic dibenzodioxins and dibenzofurans through partial oxidation. Because of the high thermodynamic stability of PCBs. All degradation mechanisms are difficult to sustain. Intentional degradation as a treatment of unwanted PCBs generally requires high heat or catalysis. Environmental and metabolic degradation generally proceeds quite slowly relative to most other compounds.

Microbial and chemical treatment of PCBs are possible but in this work incineration process will be discussed. Even PCBs do not ignite themselves; they can be combusted under extreme and carefully controlled conditions. The current regulations require that PCBs are burnt at a temperature of 1200°C for at least two seconds, in the presence of fuel oil and excess oxygen. A lack of oxygen can result in the formation of dioxins, or the incomplete destruction of the PCBs. Such specific conditions mean that it is extremely expensive to destroy PCBs on a tonnage scale, and it can only be used on PCB containing equipment and contaminated liquid. This method is not suitable for the decontamination of affected soils.

The Jordanian national records for PCBs show that there are approximately 15 tons of PCBs in liquid form mixed with other types of oils. And there is 2290 ton of copy paper and black/colored ink that includes PCBs. It should be mentioned here that this quantity of inks and papers is the amount imported to Jordan in one year which is the year 2000. This is an indication about how severe is the problem of PCBs in Jordan which need a cooperative work to safely dispose them. It is worthwhile to notice that Jordan approved many international environmental conventions which demand the safe disposal of such pollutants and hazardous chemical wastes. In the next paragraph, there is a brief list of the conventions that Jordan is a member.

1.7 International Environmental Conventions:

The Hashemite Kingdom of Jordan signed international conventions that have a relation to environment. One of these conventions is concerned in safe management and disposal of hazardous wastes. The ministry of Environment as Jordanian focal point has signed the following international conventions that are related to hazardous wastes:

1. Stockholm Convention on Persistent Organic Pollutants (POPs) on 18th January 2002.

2. Basel Convention on Trans boundary movement of hazardous wastes on 23th June 1989

3. Rotterdam Convention on prior informed consent procedure for hazardous chemicals and pesticides in international trade (PIC) on 22nd July 2002.

The presence of pilot projects to study the incineration process is necessary, as it is difficult to anticipate the behavior of reacting species during combustion process due to the special properties of the hazardous wastes. So this work will present a model that describes the physical properties of one type of hazardous wastes (PCBs) which should be banned by Stockholm convention, and the safe disposal of them (by incineration) needs experimental work.

The importance of such a model is to anticipate the behavior of the incineration process and to characterize the species that participate in it. From the wastes and emissions point of view. This will reduce the number of experiments used, simplify the incineration process, and find the amount of pollutants produced whether it is either in solid phase or in gaseous one. For the validity of the model, the results obtained will be compared to published ones obtained experimentally before it will be extended to different types of wastes.

CHAPTER TWO

Literature Survey

2.1 Introduction:

As the world searches for new energy sources, researches started to find alternatives, one of them is biogas and municipal waste incineration. However, the incineration of hazardous wastes was not started and adopted formally until 1990s where new design of burners and incinerators was presented. The motivation for that were the large quantities of hazardous wastes as a result of developments in industry. The following work was found in the published literature concerning the subject of the thesis.

2.2 Previous Studies:

Rovaglio et al. (1998) presented a dynamic model which is able to follow large variations in process conditions and to be of practical value from a control point of view. Their work dealt in particular with the development of a dynamic model. The model describes the behavior of a rotary kiln (primary combustion chamber with heterogeneous combustion) as well as the corresponding afterburner system (secondary combustion chamber with homogeneous combustion). A heat recovery system is followed to complete the hot section of a typical incineration plant. They found that the model was valid for certain conditions and was comparable with some experimental data available.

Yang et al. (2003) developed mathematical simulations as well as experiments for the combustion of wood chips. The incineration of simulated municipal solid wastes in a bench-top stationary bed and the effects of devolatilisation rate and moisture level in the fuel were assessed. The assessment is performed in terms of ignition time, burning rate, reaction zone thickness, peak flame temperature,

combustion stoichiometry and unburned gas emissions at the bed top. It was found that devolatilisation kinetic rate has a noticeable effect on the ignition time, peak flame temperature, CO and H_2 emissions at the bed top and the proportion of char burned in the final stage (char burning only) of the combustion. However, it had only a minor effect on the other parameters. Reaction zone thickness ranges from 20 to 55 mm depending on the moisture level in fuel and an increase in the moisture level causes a shift of the combustion stoichiometry to more fuel-lean conditions.

Yang et al. (2004) studied again the combustion of biomass and municipal solid wastes as one of the key areas in the global cleaner energy strategy. They studied theoretically the ability to reveal features of the detailed structure of the burning process inside a solid bed, such as reaction zone thickness, combustion staging, rates of individual sub-processes, gas emission and char burning characteristics.

They found that these characteristics are hard to measure by conventional experimental techniques. Therefore in their work, mathematical simulations as well as experiments have been carried out for the combustion of wood chips. The incineration of simulated municipal solid wastes in a bench-top stationary bed and the effects of primary air flow rate and moisture level in the fuel have been assessed. Over wide ranges. It is found that volatile release as well as char burning intensifies with an increase in the primary air flow until a critical point is reached. A further increase in the primary air results in slowing down of the combustion process. A higher primary airflow also reduces the char fraction burned in the final char-burning-only stage, shifts combustion in the bed to a more fuel-lean environment and reduces CO emission at the bed top. An increase in the moisture level in the fuel produces a higher flame front temperature in the bed at low primary air flow rates.

Cherng et al. (1998) studied the formation of hexavalent chromium Cr(VI) during waste incineration processes because of its carcinogenic characteristic. They simulated the formation of Cr(VI) species under various operating temperatures and input waste compositions during incineration by a thermodynamic model. The results showed that the major hexavalent chromium species are $CrO_2Cl_2(g)$ and $CrO_3(g)$. Chlorine and oxygen can increase the formation of Cr(VI) species; while hydrogen, sulfur, sodium, and calcium can inhibit. The input waste composition has greater effect on the formation of hexavalent chromium species than operating temperature.

Ficarella and Laforgia (2000) developed an incineration units (kiln and afterburner) for hazardous wastes in terms of design and fluid-dynamic. Optimization has been carried out together with definition of a new design methodology. An extensive theoretical and experimental analysis had been carried out on a hazardous waste incineration pilot plant to test the methodologies and to optimize the entire system in terms of reduction of the polluting emissions and higher combustion efficiency. In particular, the combustion chamber and the afterburner had been thoroughly studied. A computer code for multiple chemical reactions occurring in an afterburner chamber of an incineration system was developed, based on the equations presented in the work, to evaluate the decomposition rate of dioxins (one of the POPs) for different chamber geometries. They found that Dioxins emission depends both on the thermal efficiency of the combustion chamber (temperature and excess air) and on the turbulent mixing (associated with CO amount). As for the afterburner, temperature was not the most important parameter of the destruction efficiency of dioxins, while, on the contrary, the level of turbulent mixing and the residence time proved to be significant.

Sahlin et al. (2004) investigated the recent reduction of amounts of waste to landfills in Sweden will result in a large increase in waste incineration with recovery of energy, used primarily for district heating. The aim of their study was to investigate what changes in the usage of other fuels and technologies for district heat production would be caused by this increase. A questionnaire was sent out to the largest district heating companies, and simulations in an energy systems model were carried out.

They found that the increased waste incineration reduced the demand for other fuels, especially biomass, for district heat production. The effects include reductions in operating hours as well as the avoidance or postponement of investments in new plants for district heat production. Increased waste incineration will also lead to a greater use of district heating in Sweden.

Assefa et al. (2005) performed a technology assessment of thermal treatment technologies for wastes in the form of chains of technologies. The Swedish assessment tool, ORWARE, was used for the assessment. The scenarios of chains of thermal technologies assessed were gasification with catalytic combustion, gasification with flame combustion, incineration and land filling. The land filling scenario was used as a reference for comparison. The technologies were assessed from ecological and economic points of view. The results are presented in terms of global warming potential, acidification potential, eutrophication potential, consumption of primary energy carriers and welfare costs.

It was found that from the simulations, gasification followed by catalytic combustion with energy recovery in a combined cycle appeared to be the most competitive technology from an ecological point of view. On the other hand, this alternative was more expensive than incineration. A sensitivity analysis was done

regarding electricity prices to show which technology wins at what value of the unit price of electricity (SEK/kWh).

Within this study, it was possible to make a comparison both between a combined cycle and a Rankine cycle (a system pair) and at the same time between flame combustion and catalytic combustion (a technology pair). To use gasification just as a treatment technology is not more appealing than incineration, but the possibility of combining gasification with a combined cycle is attractive in terms of electricity production pair).

Barna et al. (2000) studied the reuse of waste materials which required the development of assessment methods for the long-term release of pollutants (source term) from wastes (or materials containing wastes) in contact with water. These methods depend on the scenario conditions: characteristics of the materials (especially physical structure and composition), contact with water. The scenario they studied was a water storage reservoir for fire fighting. The reservoir construction is made of a mixture of hydraulic binders and air pollution control (APC) residues from a municipal solid waste incinerator (MSWI). The modeling of the source term was performed in five steps ranging from the physico-chemical characterization of the material to the validation of the proposed model by means of field simulation devices. They presented the first steps of the methodology: physico-chemical characterization of the source term, identification of the main transfer mechanisms and laboratory scale modeling of the source term. During the physico-chemical characterization,

It has been shown that the solidified waste shows a high basic capacity. A relative decrease in pH during leaching favours retention of the main pollutants. During the first leaching sequences, the dynamic leaching tests show that the release

of pollutants such as cadmium, arsenic, zinc and lead is extremely low but that the release of alkaline species (sodium and potassium) and chloride is very high from the beginning. The release of calcium remains very high even after 3600 hours of leaching. Identification of the main transfer mechanisms concludes that the release of soluble pollutants is the combined result of difusional transfer of pollutants in the solution and the physico-chemical specificity of the species. The modeling based on these features enables a good simulation of the release but reveals a deviation from the experimental results after 500 h for alkaline species and 1000 h for Ca and Cl leaching.

Stehlik et al. (2000) developed a software system for simulating processes for thermal treatment and/or incineration of various types of wastes. The software product is based on modeling for performing a mass and energy balance. They provided the structure of the software and the use the simulation program as demonstration through a case study (incinerator for thermal treatment of various kinds of both industrial and municipal wastes). Flow sheet generation, input data specification, calculation and results of simulation are presented. Various fields of application (design, simulating existing operation, investigation of parametric sensitivity, supporting tool for decision-making) are mentioned. They compared their system with various professional packages for the simulation of chemical/petrochemical and other industrial processes; they found that the results were comparable.

Huai et al. (2007) presented a mathematical model for the combustion of municipal solid waste in a novel two-stage reciprocating grate furnace. Numerical simulations were performed to predict the temperature, the flow and the species distributions in the furnace, with practical operational conditions taken into account.

It was found that the calculated results agree well with the test data, and the burning behavior of municipal solid waste in the novel two-stage reciprocating incinerator can be demonstrated well. The thickness of waste bed, the initial moisture content, the excessive air coefficient and the secondary air are the major factors that influence the combustion process, which is if the initial moisture content of waste is high, both the heat value of waste and the temperature inside incinerator are low, and less oxygen is necessary for combustion. The air supply rate and the primary air distribution along the grate should be adjusted according to the initial moisture content of the waste. A reasonable bed thickness and an adequate excessive air coefficient can keep a higher temperature, promote the burnout of combustibles, and consequently reduce the emission of dioxin pollutants. When the total air supply is constant, reducing primary air and introducing secondary air properly can enhance turbulence and mixing, prolong the residence time of flue gas, and promote the complete combustion of combustibles.

Murphy and McKeogh (2004) investigated four technologies which produce energy from municipal solid waste (MSW): incineration, gasification, generation of biogas and utilization in a combined heat and power (CHP) plant, generation of biogas and conversion to transport fuel. Typically the residual component of MSW (non-recyclable, non-organic) is incinerated producing electricity at an efficiency of about 20% and thermal product at an efficiency of about 55%. This is problematic in an Irish context where utilization of thermal products is not the norm. Gasification produces electricity at an efficiency of about 34%; this would suggest that gasification of the residual component of MSW is more advantageous than incineration where a market for thermal product does not exist.

Gasification produces more electricity than incineration, requires a smaller gate fee than incineration and when thermal product is not utilized generates less greenhouse gas per kWh than incineration. Gasification of MSW (a non-homogenous fuel), however, is not proven at commercial scale. Biogas may be generated by digesting the organic fraction of MSW (OFMSW). The produced biogas may be utilized for CHP production or for transport fuel production as CH_4-enriched biogas. When used to produce transport fuel some of the biogas is used in a small CHP unit to meet electricity demand on site. This generates a surplus thermal product. Both biogas technologies require significantly less investment costs than the thermal conversion technologies (incineration and gasification) and have smaller gate fees. Of the four technologies investigated transport fuel production requires the least gate fee. A shortfall of the transport fuel production technology is that only 50% of biogas is available for scrubbing to CH_4-enriched biogas.

Marias (2003) presented a new development in the study of a rotary kiln incinerator. The modeling of the furnace has been divided into two parts. A model describing the physico-chemical processes which occur within the burning bed of municipal solid waste (assumed to be a mixture of wood, cardboard and PVC) has been set. This model mainly relies on the assumptions of plug flow and macroscopic pyrolysis kinetics of burning waste. The second model was C.F.D. that has been used to describe the processes occurring within the gaseous phase of the kiln and of the post combustion chamber (turbulence, combustion, radiation). A data processing tool has been built to automate the data exchanges between the two parts of the model. It was shown that the component concentration may affect the incineration process besides the geometry of the rotary kiln itself and finally, the effect of radiation must be taken into account.

Yang et al. (2003) studied the use of the rotary kiln for chemical waste incineration as a chemical reactor. This concept has been explored through computational fluid dynamics (CFD) modeling as an off-line tool. CFD has been used in simulation and prediction of fluid flow and the related transport phenomena, but without link to process control. The generation of the CFD database and integration of the CFD predictions to the actual process control situation are discussed in their work. It was found that the use of rotary kiln incinerator as a chemical reactor is controlled in a feedback manner. To optimally control such systems, a well-structured database should be built to assist in the control in the feed forward manner.

2.3 Current Research:

This work concentrates on modeling and simulating an integrated process describing the physical and chemical processes involved in the production of heat. Starting from wastes, including the emissions in both gas and solid phases. It is integrated because all steps will be simulated including not only energy production, but also combustion process and environmental issues. Mainly studying the kinetics and rate of species production from combustion process. Since almost all of the studies dealt only in one aspect of the process.

The previously derived models are made as simple as possible which gives some deviations from the experimentally obtained results. So this study will be directed toward presenting more complicated model but more accurate and real one. The operating conditions will be examined in addition to the efficiency of energy recovery systems. Thus the current work presents:

1. Theoretical mechanism for the incineration of hazardous substances (difficult to anticipate-wide variations in the constituents) PCBs where the number of

chlorine atoms varies form (1 to 10). The model developed by (Rovaglio, et al., 1998) was simulated and adapted to PCBs subsequently. The results of the model were compared with experimental values reported by (Rovaglio, et al., 1998).

2. The physical properties of PCBs will be estimated if they were not available.

3. The variation of temperature with time inside the incinerator will be evaluated.

4. The evaluation of energy recovery with the above items will lead to integrated study.

5. Matlab code that estimates the above mentioned items will be developed instead of using commercial available software.

6. The heat produced from the incineration process will be used in a regenerative cycle to improve its efficiency, by using two types of heat exchangers. Further heat will be recovered by another heat recovery system (cross flow heat exchanger). And the recovered heat is used in the plant to improve incineration efficiency. ShahCF.mcd models are used to design the heat exchangers used in the steam power plant..

7. New and modified steam power plant, where modeling and simulation is used to describe the process and study process variables.

CHAPTER THREE

Theoretical Model

3.1 PCBs Incineration:

The general procedure for PCBs incineration is to mix the oils containing PCBs with sand to form a solid structure. The structure consists of combustible fraction in which oils are the main component. In addition to some elements that can be described as incombustible fraction, and water content (moisture). Within the dry solid, it is necessary to distinguish between a combustible or burning fraction. Which gives rise to gas products. An inert fraction representing what will be also the final solid ash amount. A formal stoichiometry must be associated with the combustible fraction of the solid waste in order to account for the heterogeneous combustion. Thus the general stoichiometric relationship can be used to describe the structure of the feedstock to the incinerator (Rovaglio, et al., 1998):

$$C_mH_nO_pS_qN_xCl_y + v_{o2}O_2 \rightarrow mCO_2 + \frac{n-y}{2}H_2O + qSO_2 + \frac{x-\alpha}{2}N_2 + \alpha NO + yHCl \quad (3.1)$$
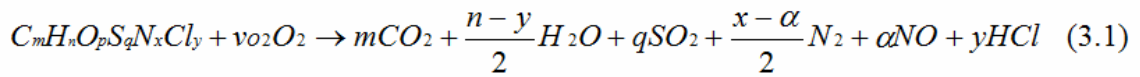
However, the following general expression and chemical reaction for PCBs incineration can be modeled as follows:

$$C_{12}H_{(10-n)}Cl_n + \frac{29-n}{2}O_2 \rightarrow 12CO_2 + (5-n)H_2O + nHCl \quad (3.2)$$
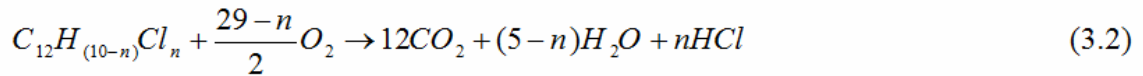
As in the case of the heterogeneous combustion, carbon mono-oxide (CO) is assumed to be the main oxidation product of carbon. The total combustion to CO_2 takes place in the gas phase. Furthermore, waste compounds containing nitrogen are decomposed to give N_2 and NO according to the following equation (Rovaglio, et al., 1998):

$$N_2 + O_2 \rightleftarrows 2NO \quad (3.3)$$

which evaluates the α (in equation 3.1) fraction as a function of kiln temperature and excess oxygen.

The theoretical model (Rovaglio, et al., 1998) is used throughout this work and will be solved using Matlab. Mass and energy balances for both solid and gas phases are presented, the resulting equations will be solved simultaneously to get the required temperatures, flow rates, energy produced, and gas phase concentrations.

3.2 Solid Waste Mass Balance:

The solid waste undergoing the heterogeneous combustion passes through the rotary kiln incinerator for a certain contact time θ (retention time), while the effect of the mechanical agitation induced by rotation consists of the renewal of the surface area exposed to hot gases containing oxygen. On this area, both volatilization and combustion processes take place. The bulk solid phase movement along the rotary kiln is not different in nature from that of similar units.

The solid movement in the rotary kiln in the transient conditions is related to both gas and solid flows are assumed to be fast with respect to mass and energy dynamic balances. In agreement with the aforementioned assumption, the mass balance for the solid phase reads as follows:

$$\frac{dM_{Solid}}{dt} = W_{Waste}(1 - \omega_{H2O}) - R_{dr} - W_{out}^{S} \tag{3.4}$$

The evaluation of A, the interface area for solid oxygen contact which is important sometimes to evaluate the rate of mass destruction, requires the knowledge of both gas- and solid phase motions inside the rotary kiln. This area is a function of the kiln geometry and the operating conditions. The maximum possible interface area depends also on particle diameter and solid angle of repose; if it is possible to estimate the average renewal surface velocity [Ar(m^2/s)] then:

$$A = A_r\theta \tag{3.5}$$

where :

$$\theta = \frac{1.77\sqrt{\Phi}\ FL}{SDN}$$ is the residence time for the solid material inside the rotary kiln

(Rovaglio, et al., 1998). The residence time θ varies depending on the parameters shown in the defining equation such as the square root of the dynamic angle of repose for the solid material inside the rotary kiln Φ, the type of the rotary kiln whether dammed or undammed F generally its value changes from 1 or greater, internal diameter and length of the combustion chamber D and L respectively, kiln slope S, and the rotational speed N. Generally, the value of the retention time of the solids inside the rotary kiln is 15-60 minutes depending on the parameters above. Figure 3.1 shows the control volume where conservation equations are applied.

Air: 10 - 11 Vol. % O_2

Emissions : CO_2
                N_2
                O_2
                H_2O

material
fuel   **Burning**   Ash
air   (dry process)

air
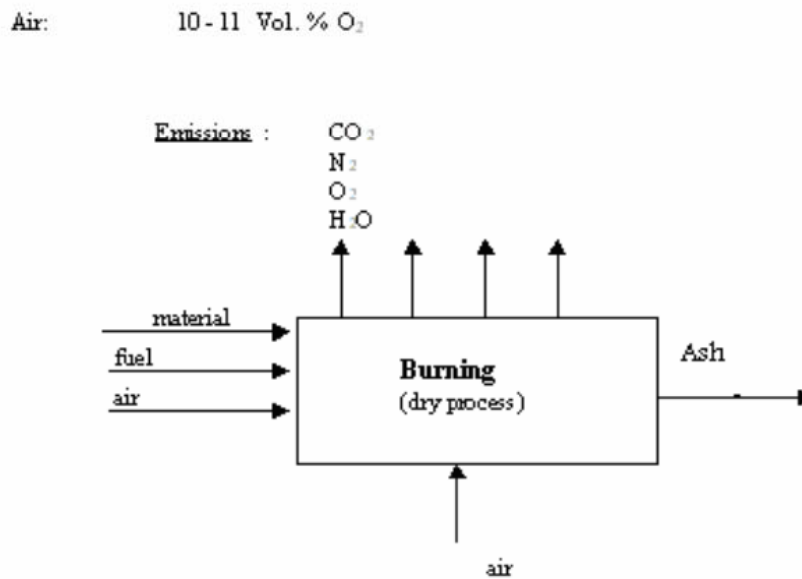
**Figure 3.1. Control Volume where Conservation Equations are Applied,
(European council directives, 96/61).**

The destruction rate R_{dr} can be derived based on the assumption of complete waste destruction:

$$W_{Waste}(1 - \omega_{H_2O}) - R_{dr} - W_{out}^{S} = 0.0 \tag{3.6}$$

$$W_{out}^{S} = W_{Waste}(1 - \omega_{H2O}) * (1 - \omega_{bf})$$ (3.7)

Then the destruction rate can be expressed as:

$$R_{dr} = W_{out}^{S} * \omega_{bf} / (1 - \omega_{bf})$$ (3.8)

Then the destruction rate can be related to the solid mass hold up inside the rotary kiln as follows:

$$R_{dr} = \frac{M_{solid}}{\theta} * \omega_{bf} / (1 - \omega_{bf})$$ (3.9)

3.3 Gas Phase Mass Balance:

Taking into account possible auxiliary fuel (will be described here as CH_4) where the equation representing the rate of fuel destruction can be simply expressed as follows:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$ (3.10)

then the total gas-phase mass balance (Rovaglio, et al., 1998), which applies to the rotary kiln, becomes:

$$\frac{dM_{gas}}{dt} = W_{air}^{in} w_{N2}^{air} + W_{air}^{in} w_{O2}^{air} + (1 - \mu_{O2})R_{dr} + W_{CH4} - W_{out}^{gas} + W_{waste} w_{H2O}$$ (3.11)

while the corresponding mass balances for each component can be described by:

$$\frac{dM_i}{dt} = W_i^{in} - \frac{W_{out}^{gas}}{\sum_i PM_i y_i} y_i + V_{tot} R_i$$ (3.12)

where i represents the following reactions species CO, CO_2, H_2O, SO_2, N_2 , HCl, NO, O_2, with $y_i = \dfrac{M_i}{\sum_i M_i}$ is the gas mole fraction of species i. The flows of all the i species forming the total gas inlet flow rate and the reaction rates R_i can be determined with reference to the following simplified reaction scheme and assumptions (in addition to equation (3.2) these equations must be used to complete the model):

$$N_2 + O_2 \rightleftarrows 2NO \quad .... \text{(b)}$$

$$CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O \quad .... \text{(c)}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad .... \text{(d)} \qquad (3.13)$$

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \quad .... \text{(e)}$$

$$CH_4 + O_2 \rightleftarrows CO_2 + 2H_2O \quad .... \text{(f)}$$
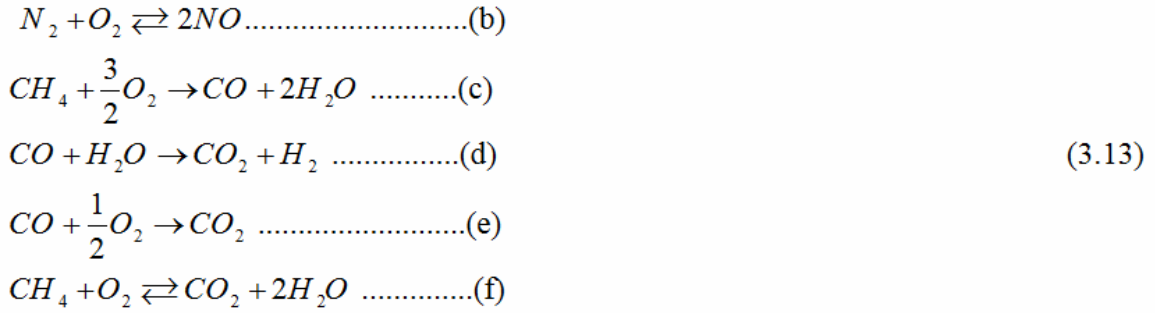
where, reaction (3.1) represents the overall waste destroying reaction producing CO_2 as result of heterogeneous combustion. CO will be converted to CO_2 (Carbon dioxide), should enough oxygen be present to accomplish reaction (3.13-e), or otherwise following reaction (3.13-f) when the oxygen amount is very small. Waste nitrogen is converted to N_2 and NO. The corresponding fractions are determined through a relationship which depends on kiln temperature and excess oxygen. The equilibrium conditions determined by reaction (3.13-d) refer to the afterburner system (homogeneous combustion). If auxiliary fuel is needed to maintain the required temperature, reactions (3.13-b) and (3.13-c) allow total or partial methane combustion as a function of the oxygen presence to be taken into account.

Reactions from (3.13-b) to (3.13-c) besides (3.13-e) are very fast and can be considered under equilibrium conditions (complete conversion for CO and CO_2) within the range of temperatures usually adopted (900 °C to 1200 °C). The extent of conversion for such reactions is in practice determined by the excess oxygen. Only reactions (3.13-d) and (3.13-f) have been considered in a kinetic regime (Rovaglio, et al., 1998), while the corresponding rate expressions have been deduced by generalizing some theoretical analysis. In particular, by considering the kiln, burner and post combustion chamber residence times separately, it is possible to evaluate the contributions to the production of NO corresponding to the different portions of the plant.

3.4 Energy Balance:

The three modes of heat transfer, convection, conduction, and radiation are present during the incineration process. Inside incinerators the heat is generally transferred to the walls or to the upper surface of the solid beds by radiation and convection and to the lower (covered) surface by the regenerative action of the rotating kiln walls. The radiating gases in the kiln (not occupied by the waste-free volume) are also present within the boundaries of the burner and/or waste flames so that they may be considered as covering the entire free volume. Thus, due to the high gas temperature, solids and exposed walls receive heat primarily by radiation from the gas volume while both convective and regenerative heat flow play only a minor role in the overall heat transfer process. On the basis of the following assumptions (Rovaglio, et al., 1998):

1. Perfectly mixed conditions (outlet temperature of both the gas and solid is the same as that temperature inside the rotary kiln)

2. Equilibrium condition between gas and solid phase (if present)

3. Complete combustion (for both waste and auxiliary fuel)

Therefore, based on the above assumptions, the following energy balance around the control volume shown in Figure 3.1 can be derived (Rovaglio, et al., 1998):

$$
\begin{aligned}
\frac{dU_{tot}}{dt} = & W_{air}^{in} H_{air}^{in} + W_{waste} Q_{waste} + W_{CH_4} Q_{CH_4} - W_{out}^{gas} H_{out} - s\overline{GS}(T_g^4 - T_{w,in}^4) \\
& - h_{in}\pi DL(T_{gas} - T_{int}) - W_{out}^S \overline{C_{PS}}(T_g - T_{ref})
\end{aligned}
\tag{3.14}
$$

where:

$$
U_{tot} = M_{solid} C_{vS}(T_{gas} - T_{ref}) + M_{gas} \sum_i \frac{M_i}{\sum_i M_i} \int_{T_{ref}}^{T_{gas}} C_{vi}(T) dT
\tag{3.15}
$$

$$
H_{air}^{in} = \int_{T_{ref}}^{T_{air}^{in}} C_{pair}(T) dT
\tag{3.16}
$$

$$H_{out} = \sum_i \frac{M_i}{\sum_i M_i} \int_{T_{ref}}^{T_{gas}} C_{pi}(T)dT \tag{3.17}$$

Equation (3.15) implies that waste and fuel are fed at the reference temperature. It can be clearly seen that U is a strong function of temperature. Equation (3.15) can be used to express U as function of temperature where the next chapter can show this in details.

$\overline{GS}$ can be evaluated by means of the well-stirred combustion chamber in which it is evaluated as (Rovaglio, et al., 1998):

$$\overline{GS} = \int_V \int_S \frac{KdVdS\cos\vartheta\tau(r)}{\pi r^2} = \frac{As}{\left(\frac{1}{C_g\varepsilon_p}\right)+\left(\frac{1}{\varepsilon_G}\right)} \tag{3.18}$$

The evaluation of the gas emissivity ε_G can be estimated graphically and/or experimentally referring to the suitable diagram concerned with radiating heat transfer, and as water and carbon dioxide are the main component in the gaseous product, the emission band that will be considered here is directly related to the combustion products: water and carbon dioxide. The emissivity of such components can be calculated through a polynomial regression of the experimental data as

a function of the sum of the single partial pressures ($P_{CW} = P_{CO2} + P_{H2O}$) and of the beam length (L_W):

$$\log_{10}(T\varepsilon_G) = \sum_{n=1}^{11} C_n x^{n-1} \tag{3.19}$$

where

$x = \log_{10}(P_{CW} * L_W)$ and the coefficients C_n which are summarized in the research by Rovaglio et al. when analyzing the effect of radiation energy as follows:

Table 3.1. Polynomial Coefficients for Gas Emisivity Evaluation, (Rovaglio, et al., 1998)

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11
2.45	0.406	0.076	0.0306	-0.223	-0.105	0.15	0.206	0.134	0.054	0.0097

This procedure will lead to an expression of emissivity as function of temperature that will be solved as independent variable with time in the dynamic modeling. The heat transfer by radiation can not be neglected in deriving the model even this will lead to a source of high nonlinearity and so to a very stiff system, however, the radiation term consists of the following parameters:

$$E_{ra} = s\overline{GS} \left(T_g^4 - T_{w,in}^4 \right) \tag{3.20}$$

which is equivalent to

$$E_{ra} = \varepsilon \sigma A \left(T_g^4 - T_{w,in}^4 \right) \tag{3.21}$$

where:

$s\overline{GS}$ accounts for the emissivity and Stefan-boltzman values, this value is temperature dependent value and can derived depending on equations 3.18 and 3.19 and the values presented in Table 3.1.

T_g^4 is the value of the effluent gas from the rotary kiln, and is assumed to be as that inside the combustion chamber

$T_{w,in}^4$ is the wall temperature where the gas volume emits its energy to.

σ is the Stefan boltzman constant

The definition of the radiation energy requires the presence of the emissivity value which should be found in a form making it possible to be inserted in the model to account for the temperature variation (John, 1997):

$P_{CW} = P_{CO2} + P_{H2O}$ is the total pressure inside the rotary kiln which shows that all of the pressure produced comes from water vapor and carbon dioxide, the beam length L_W can be found in the literature for different geometries, the next theoretical calculations is performed to derive the emissivity ε as function of temperature (Rovaglio, et al., 1998):

$$\log_{10}(T\varepsilon_G) = \sum_{n=1}^{11} C_n x^{n-1} \tag{3.22}$$

where

$x = \log_{10}(P_{CW} * L_W)$ and the Coefficients C_n are summarized in table 3.1 where the final result is an expression of the form:

$$\varepsilon = \frac{\Theta}{T} \tag{3.23}$$

where Θ is theoretical constant.

An important feature of the radiation heat transfer is the shape factor. Equation 3.21 should be multiplied by the value of the shape factor. Referring to the literature (John, 1997) Figures are presented to account for the shape factor. In the case of circular cylinder emitting to all its surfaces, the dimensions are important. In the case of the rotary kiln which is used for PCBs incineration. The ration between its length and radius is large and the ration between outer and inner radius is zero (only one cylinder is used), the value of the shape factor under these conditions is 1.0.

The second major heat transfer mode is the convection heat transfer. The convective heat transfer coefficient is computed by a Dittus-Boelter relationship (John, 1997):

$$Nu = 0.023 Re^{0.8} Pr^{1/3} \tag{3.24}$$

where:

Nu is the Nusslet number and it can be calculated as follows hD/k, and so it can be corrected to take into account the effect of entry as follows (Rovaglio, et al., 1998):

$$h_{in} = h(1 + 1.4D/L)\qquad\qquad(3.25)$$

As for the transient heat conduction within the furnace walls, the problem can be easily modeled by means of the classical equation of heat diffusion in one dimension to be solved for adjacent layers of different materials and with proper boundary conditions ensuring the continuity of heat fluxes. The real problem lies in choosing which discretization method is to be adopted and which numerical algorithm to use for integration purposes.

3.5 Energy Balance around Air Heater:

In the rotary kiln incineration plant configuration there is a heat recovery section consisting of a sequence of heat exchangers placed after the burning system. These devices have a double function:

1. air combustion pre-heating to improve the thermal yield of the plant

2. gas cooling to reduce water consumption inside the scrubbing section.
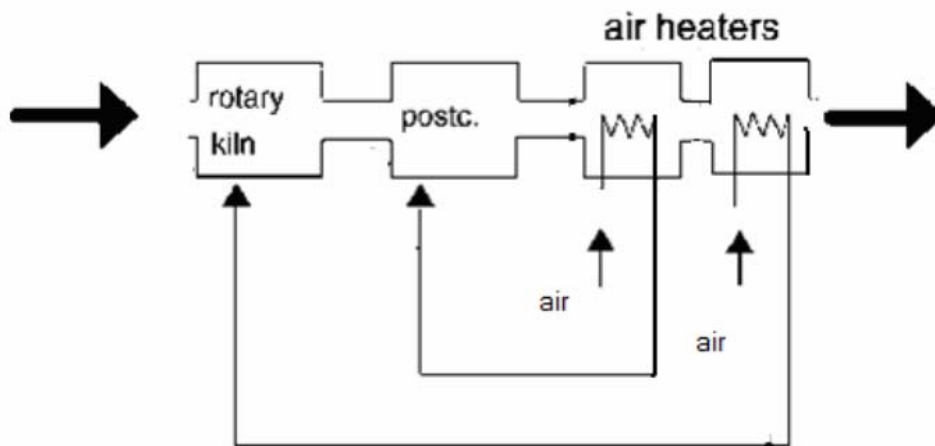
Figure 3.2. Heaters Used to Heat Air Fuel Mixture Before Entering the Rotary Kiln, (Rovaglio, et al., 1998).

These apparatuses consist of a metal shell which covers a cylinder of refractory and insulating material where, inside the enclosure, a coil of special alloy is placed. The cold air flows inside the coils while the hot gas moves along the refractory lined chamber.

A new set of equations is needed to solve this problem. Inside the heat exchangers, the hot gas temperature can be considered uniform, that is, a continuous stirred tank reactor (CSTR) scheme is assumed to be a consequence of the high turbulence due to the gas velocity and to the presence of coils and devices in the heaters (Rovaglio, et al., 1998):

$$\frac{dU_{tot}}{dt} = W_f H^{in} - W_f H_{out} - Q_{losses} - Q_{ex} \tag{3.26}$$

where H^{in} and H^{out} can be evaluated through equation (3-16 and 3-17) while W_f represents the hot gas flow rate assumed to be equal for inlet and outlet flows. The heat losses Q_{losses} through the walls can be determined as follows (Rovaglio, et al., 1998):

$$Q_{losses} = \overline{GS} * (\frac{1-k^3}{1-k^4} + A_{wall} * \frac{H_{in}}{4\sigma T_f^3}) * \sigma(T_f^4 - T_w^4) \tag{3.27}$$

$$k = \frac{T_w}{T_f} \tag{3.28}$$

where the term inside the parenthesis defines the global heat transfer coefficient which takes into account both the convective and the radiative terms. In a similar manner, the heat exchanged between smokes and coils can be determined on the basis of the following relationship (Rovaglio, et al., 1998):

$$Q_{ex} = \sum_{n=1}^{Ns}(\sigma\overline{GS} * (T_f^4 - T_{wall,n}^4) + h_e A_n(T_f - T_{wall,n})) \tag{3.29}$$

where the external convective coefficient *he* can be evaluated through the *Nu* number given by (John, 1997):

$$Nu = 0.110 Re^{0.675} Pr^{1/3} \tag{3.30}$$

which refers to a system with a cross-flow geometry.

The model will be solved for the a Geometry and characteristics that are briefly summarized in Table 3.2 which describes the pilot project designed (Rovaglio, et al.,

1998) to investigate experimentally the incineration process. The model is based only on a limited number of variables measured and available from the plant as follows:

1. Outlet gas temperature from the rotary kiln

2. Outlet gas temperature from the postcombustion chamber

3. External skin temperature for the rotary kiln

4. External skin temperature for the postcombustion chamber

5. Oxygen mole fraction in the postcombustion gas outlet

6. Air temperatures from heat exchangers.

However, the comparison is completed by the knowledge of the transient evolution of some input variables, such as:

1. Waste flow rate to the rotary kiln

2. Fuel flow rates to kiln and post combustion chamber

3. Air flow rate to the spiral heat exchangers.

Table 3.2. Rotary Kiln Description and Geometry, (Rovaglio, et al., 1998)

Property	Rotary kiln	Post combustion chamber
Internal length (m)	4.43	3.66
Internal diameter (m)	1.5	1.7
Refractory thickness (m)	0.1	0.11
Refractory conductivity (W/m k)	1.7	1.35
Refractory heat capacity (J/kg k)	700	600
Refractory density (kg/m^3)	2550	2000
Insulating thickness (m)	0.12	0.125
Insulating conductivity (W/m k)	0.29	0.198
Insulating heat capacity (J/kg k)	500	400
Insulating density (kg/m^3)	890	475

CHAPTER FOUR

Mathematical Model and Computer Simulation

4.1 Mathematical Model:

Mass and energy balances produces a set of non-linear ordinary differential equations, where time is the independent variable and mass hold up for ash and chemical species as well as the total gas hold up and temperature as the dependent variables. It should be mentioned here that the energy balance will be started using the internal energy which depends on the temperature by laws of thermodynamics, and by some manipulations, the energy balance will be expressed in terms of temperature.

The obtained set of equations can be solved by using a Matlab code composed for stiff differential equations and by using ode23s solver. The matrix (x,t) can be obtained where xprime(x) is written for the differential equations results from the conservation equations that are performed as follows:

Firstly, to the rotary kiln incinerator where heterogeneous reaction occurs, thus, material balance for the solid phase is (Rovaglio, et al., 1998):

$$\frac{dM_{Solid}}{dt} = W_{Waste}(1 - \omega_{H_2O}) - R_{dr} - W_{out}^{S} \tag{4.1}$$

Then mass balance for the gas phase is obtained by performing overall material balance and (N-1) component balance or N components balance as follows where N is the number of components:

The overall mass balance (Rovaglio, et al., 1998):

$$\frac{dM_{gas}}{dt} = W_{air}^{in} w_{N_2}^{air} + W_{air}^{in} w_{O_2}^{air} + (1 - \mu_{O_2})R_{dr} + W_{CH_4} - W_{out}^{gas} + W_{waste} w_{H_2O} \tag{4.2}$$

To perform the component balance, species that is encountered in the reaction must be determined where the following mechanism can be assumed:

$$C_{12}H_{(10-n)}Cl_n + \frac{29-n}{2}O_2 \rightarrow 12CO_2 + (5-n)H_2O + nHCl \tag{4.3}$$
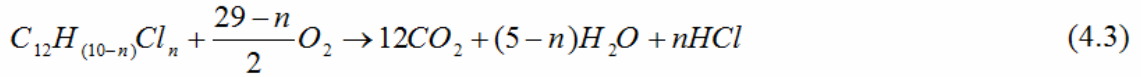
where the above reaction is the main reaction in the rotary kiln and n represents the number of chlorine atoms in the polychlorinated compounds. The number of chlorine atoms can be changed from one chlorine atom to ten atoms which represent the maximum number of chlorine atoms in the PCBs structure. During the solution of the set of equations this number is changed to study the process parameters as function of chlorine atoms. As some gases may produced, the following gas phase reactions is assumed to occur:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{4.4}$$

Thus the gas phase species are $CH_4, N_2, HCl, O_2, CO_2, H_2O$, where mass balance for each component will be written as follows:

$$\frac{dM_i}{dt} = W_i^{in} - \frac{W_{out}^{gas}}{\sum_i PM_i y_i} y_i + V_{tot} R_i \tag{4.5}$$

where the rate of material generation/consumption will be needed and will be assumed as follows:

$$\frac{dC_i}{dt} = \pm k * [c_i]^{vi} [c_j]^{vj} \tag{4.6}$$

Where the rate of consumption/generation is assumed to be elementary in the gas phase and vi and vj are the stoichiometric coefficient in the chemical reaction. The results obtained from the model solution will be compared to the available experimental results to check the validation of the previous assumptions. Referring to the literature (Yang et al 2003) diagram is generated where reaction kinetics are derived using Arrhenius equation that accounts for temperature variation, Table 4.1 summarizes the main reaction kinetics used to complete the generation of the model:

Table 4.1. Reaction Kinetics for Waste and Fuel, (Yang, et al., 2003)

Species	Pre-exponent factor	Activation energy
PCBs[*]	340	86041.7 J/mole.K
CH_4	100	8000 J/mole.K
CO[**]	1.3e11	62700

*approximated for chlorinated compounds, (Bergstrom, et al., 1987)
** very fast reaction

Finally, the energy balance is performed around the rotary kiln as follows (Rovaglio, et al., 1998):
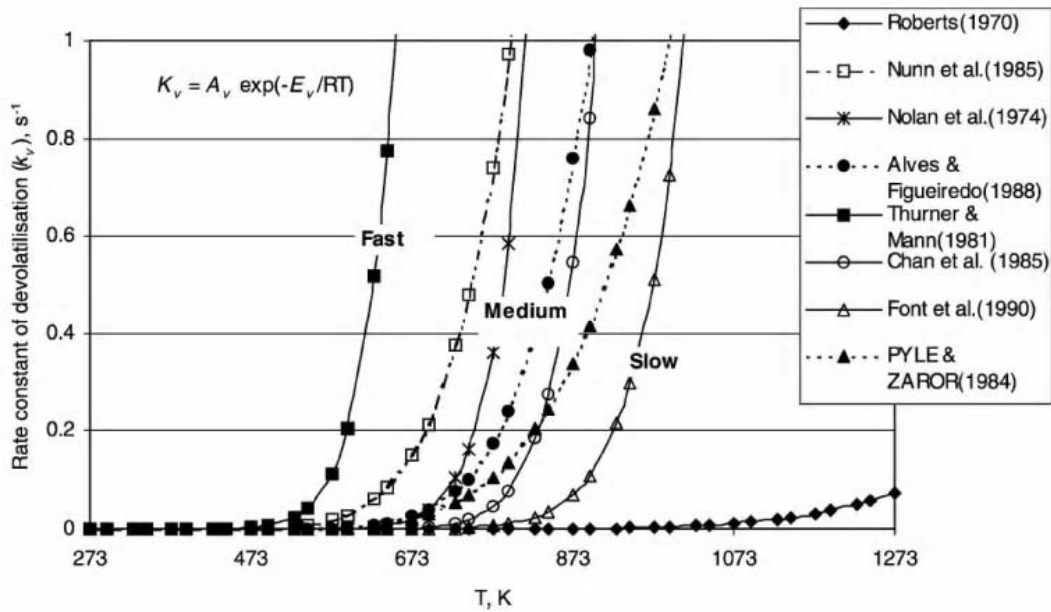
Figure 4.1. Reaction Rates Obtained by Arrhenius Equation, (Yang, et al., 2003).

$$\frac{dU_{tot}}{dt} = W_{air}^{in} H_{air}^{in} + W_{waste} Q_{waste} + W_{CH_4} Q_{CH_4} - W_{out}^{gas} H_{out} - s\overline{GS}(T_g^4 - T_{w,in}^4)$$
$$- h_{in} pDL(T_{gas} - T_{int}) - W_{out}^{S} \overline{C_{PS}}(T_g - T_{ref}) \tag{4.7}$$

where:

$$U_{tot} = M_{solid} C_{vS}(T_{gas} - T_{ref}) + M_{gas} \sum_i \frac{M_i}{\sum_i M_i} \int_{T_{ref}}^{T_{gas}} C_{vi}(T)dT \tag{4.8}$$

$$H_{air}^{in} = \int_{T_{ref}}^{T_{air}^{in}} C_{pair}(T)dT \tag{4.9}$$

$$H_{out} = \sum_i \frac{M_i}{\sum_i M_i} \int_{T_{ref}}^{T_{gas}} C_{pi}(T)dT \tag{4.10}$$

$$\overline{GS} = \int_V \int_S \frac{KdVdS \cos\vartheta\tau(r)}{\pi r^2} = \frac{As}{\left(\dfrac{1}{C_g\varepsilon_p}\right) + \left(\dfrac{1}{\varepsilon_G}\right)} \tag{4.11}$$

Equation 4.8 which relates the internal energy in the rotary kiln with temperature. And can be used to relate temperature inside the rotary kiln with model parameter that is by derivation:

$$\frac{d}{dt}U_{tot} = \frac{d}{dt}(M_{solid}C_{vS}(T_{gas} - T_{ref})) + \frac{d}{dt}\left(M_{gas}\sum_i \frac{M_i}{\sum_i M_i}\int_{T_{ref}}^{T_{gas}} Cv_i(T)dT\right)$$

$$= M_{solid}(C_{vs})\frac{dT}{dt} + TC_{vs}\frac{dM_{solid}}{dt} - T_{ref}C_{vs}\frac{dM_{solid}}{dt} + \tag{4.12}$$

$$\frac{dT}{dt}\left(\sum C_i * Cv_i\right) + (T - T_{ref})*\left(\sum Cv_i * \frac{dC_i}{dt}\right) = \Psi$$

where:

$$\Psi = \frac{dU_{tot}}{dt} = W_{air}^{in}H_{air}^{in} + W_{waste}Q_{waste} + W_{CH4}Q_{CH4} - W_{out}^{gas}H_{out} - s\overline{GS}(T_g^4 - T_{w,in}^4) \tag{4.13}$$

$$-h_{in}pDL(T_{gas} - T_{int}) - W_{out}^S\overline{C_{PS}}(T_g - T_{ref})$$

This simplifies the right hand side of the energy balance equation and

$$C_{tot} = M_{gas}\sum_i \frac{M_i}{\sum_k M_k} \tag{4.14}$$

This represents the species concentration of the gaseous effluents from the rotary kiln, which after derivation it will represent the species material balance. It should be noticed here that the elimination of the first summation symbol in equation 4.14 leads to the individual concentrations of each species in the outlet gas phase.

Insert the above equations into the energy balance equation and arranging will produce :

$$\frac{dT}{dt}(\sum_{i=1}^{i=6}(C_i * Cv_i) + M_{soild} * Cv_s) = \Psi - T * C_{vS} * \frac{dM_{solid}}{dt} + T_{ref} * C_{vs} * \frac{dM_{solid}}{dt}$$
$$-(T - T_{ref}) * \sum(Cv_i * \frac{dC_i}{dt}) \qquad (4.15)$$

Thus the final energy balance that will complete the model will be as follows:

$$\frac{dT}{dt} = (\Psi - T * C_{vS} * \frac{dM_{solid}}{dt} + T_{ref} * C_{vs} * \frac{dM_{solid}}{dt} - (T - T_{ref}) * \sum(Cv_i * \frac{dC_i}{dt}))/B \quad (4.16)$$

where:

$$B = (\sum_{i=1}^{i=6}(C_i * Cv_i) + M_{soild} * Cv_s) \qquad (4.17)$$

The above model will be able to find the temperature variation, solid ash out flow, mass hold up inside the rotary kiln, in addition to the concentration of all of gaseous species for wide variety of PCB's (number of chlorine atoms). Another feature of the this model is that the excess air that is used to ensure complete combustion can be changed to study its effect on the process parameters.

The same procedure will be repeated for the post combustion chamber (where no solid phase combustion will occur and only gas phase reaction will be considered), then the heat recovery system will be used to utilize the heat in the outlet gas flow rate. The following flowchart shows the algorithm of model solution:

4.2 Parameters needed in developing the model:

1. Heat capacities for the gaseous species and the solid waste

2. Heat of reaction of the assumed reactions

3. Model design parameter such as: length and diameter of rotary kiln, waste flow rate,…etc

4. Physical properties (reaction rate constants, molecular weight,…etc).

Some of the above parameters can be found in literature, but others can be assumed or evaluated.

Table 4.2. Heat Capacities* Coeficients for the Species Reactions, (Smith, et al., 1996)

Species	a	$b*10^2$	$c*10^5$	$d*10^9$
Carbon dioxide	36.11	4.233	-2.887	7.464
Hydrogen chloride	29.13	-0.1341	0.9715	-4.335
Nitrogen	29.0	0.2199	0.5723	-2.871
Oxygen	29.1	1.158	-0.6076	1.311
Water Vapor	33.46	0.688	0.7604	-3.593
Methane	34.31	5.469	0.3661	-11.0

*where heat capacities at constant pressure are calculated using he following formula: C_p (J/ mol. K) = a + bT+ cT^2 + dT^3 and the heat capacities at constant volume C_v are calculated using the following formula: $C_v=C_p-R$: where R=8.314 J/mol.K

4.3 Model degree of freedom:

1. Number of unknowns are 9 that is (5 gaseous species, solid waste hold up inside the rotary kiln, temperature, gas hold up inside the rotary kiln).

2. Number of equations are 8 (3 nonlinear ordinary differential equations come from mass balance for solids and gases and one energy balance in addition to 5 component balance, and the auxiliary equation of ash outlet flow rate=mass hold up/residence time).

3. Set of algebraic equations for physical properties.

As the model for rotary kiln incinerator is now well defined, the same procedure will be repeated for all incineration plant.

4.4 Simulation and model solution:

The derived model solution requires auxiliary equations such as thermodynamic relations and physical properties (constants or temperature dependent) to be inserted into the model, the solution algorithm can be shown as follows:
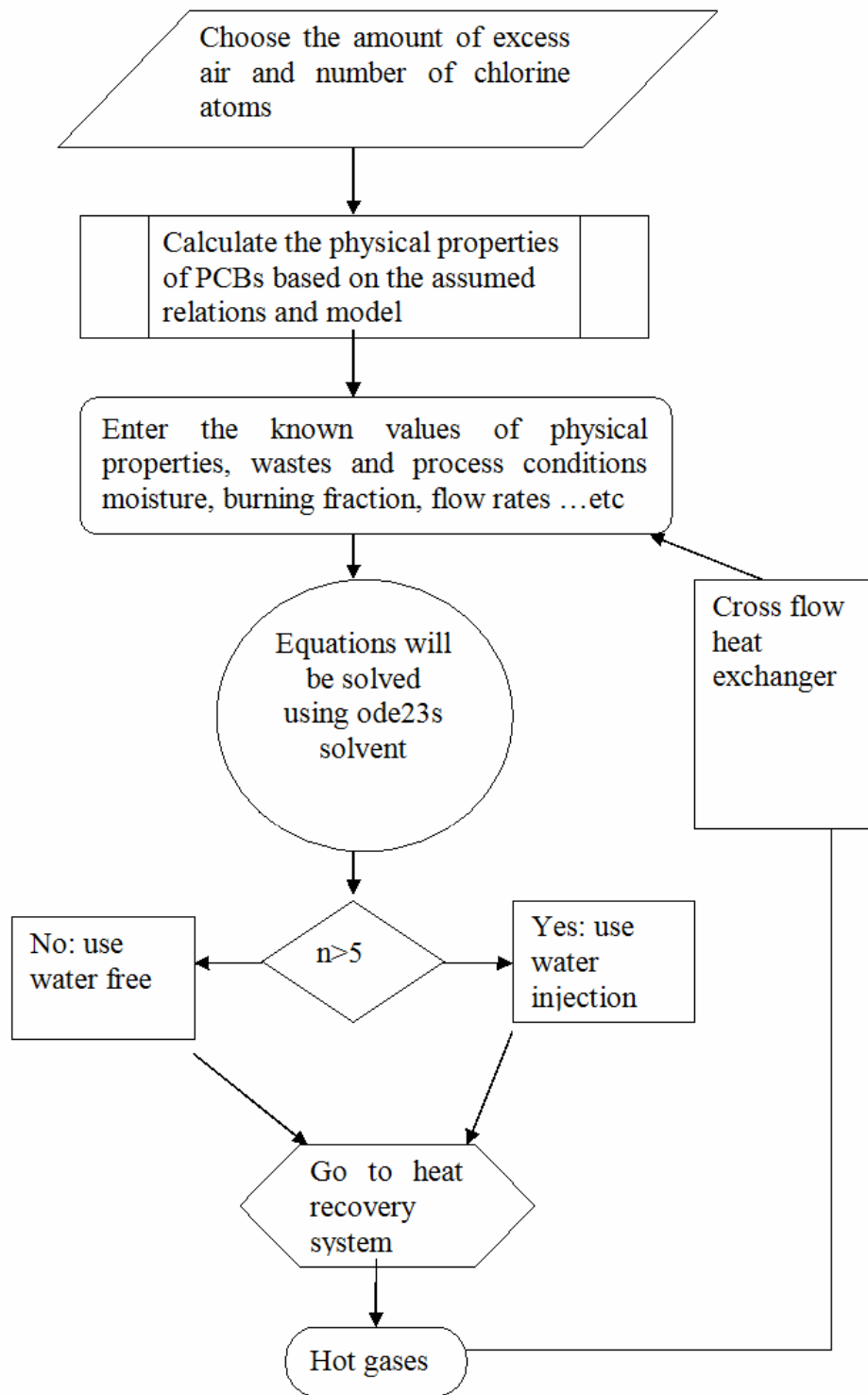
Figure 4.2. Flow Chart for the Mathematical Modeling.

CHAPTER FIVE

Energy Use and Recovery

5.1 Introduction:

This chapter deals with the units used to recover the heat stored in the effluent gases from the rotary kiln, the idea is to use this heat in one application where this heat can be useful, a steam power plant where superheated steam is needed is one of these applications. The fuel used in the boiler to generate steam can be reduced, and the resulting gases still can be used with their less energy.

To gain this heat, heat exchangers are inserted in the chosen power plant, Figure 5.1 (Smith, et al. 1996). Firstly, double pipe heat exchanger is inserted in the stream out of the last feedwater heater. This will increase the temperature of the stream fed to the boiler where less heat is added in the boiler to generate superheated steam
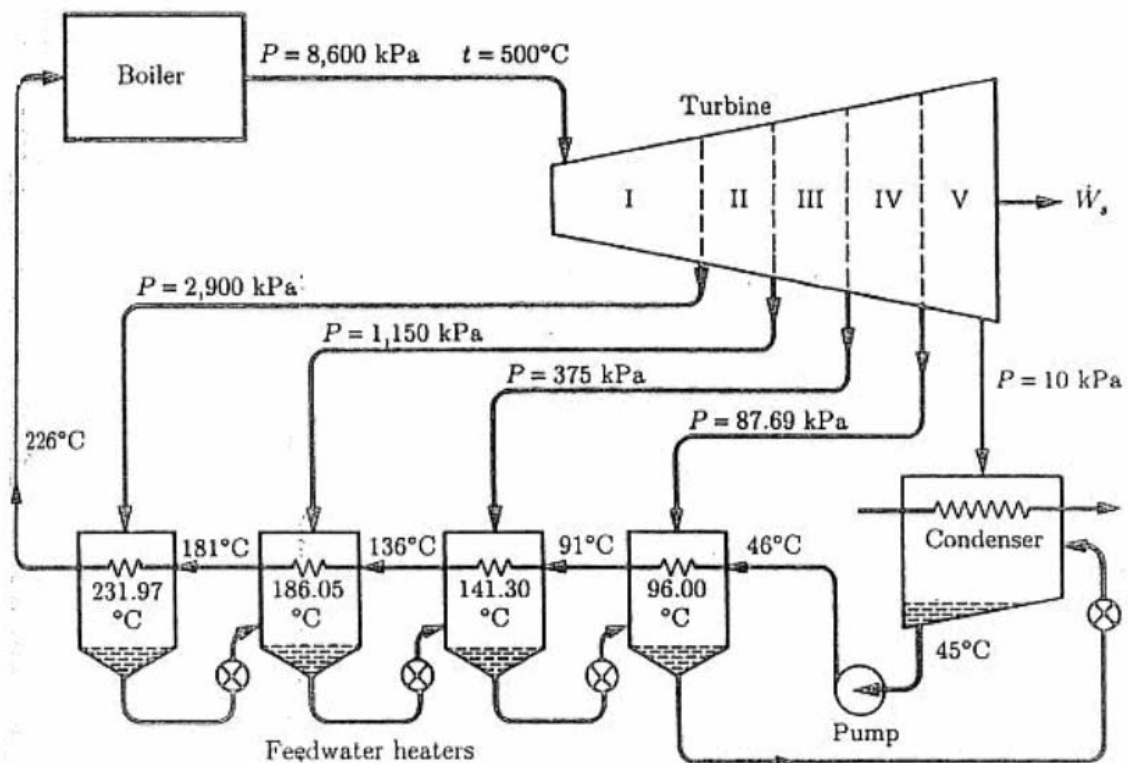
Figure 5.1. Steam Power Plant Cycle with Feedwater Heaters, (Smith et al. 1996).

Secondly, a cross flow heat exchanger is used to recover the heat that still exist in the effluent gas, thus a cross flow heat exchanger is inserted for the hot gases after it leaves the double pipe heat exchanger (enters as hot fluid) to heat the fuel-air mixture that enters the rotary kiln combustion chamber (enters as cold fluid) this will save the fuel used to heat the gaseous mixture that enters the rotary kiln and improve the combustion efficiency.
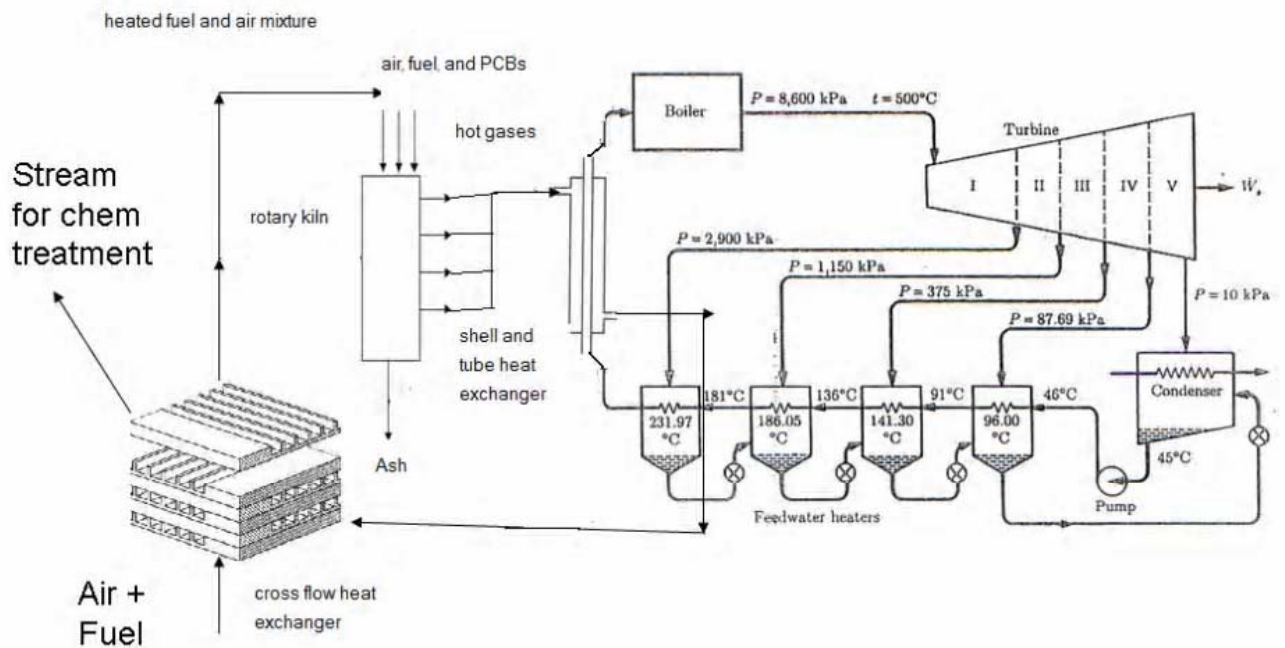
Figure 5.2. Steam Power Plant with Rotary Kiln and Heat Recovery Units.

5.2 Steam power plant:

The gas effluent from the rotary kiln incinerator will be at high temperature of 1200 K, this temperature will be reduced to less than 200 °C which is determined based on an experimental observation to prevent the formation of toxic furans and dioxins, so this work suggest a new way to gradual decrease of this temperature to around 200 °C so as to acquire the energy stored in the gases.

One way to do so is the steam power plant Figure 5.1, which will be chosen with feedwater heating, where an energy recovery unit is inserted before the boiler so as to

increase the temperature of the water that will enter the boiler to generate the superheated steam that will be introduced to the turbine which is divided into five sections to produce work. The over all efficiency of the cycle will be recalculated and compared to the value obtained without the heat exchanger incorporated.

The operating temperatures indicated on Figure 5.1 are typical values and will be used for the comparison study where different types of PCBs are incinerated with different operating conditions such as amount of excess air used, in addition to the best ways to gain the stored energy in the gas phase will studied.

The steam rate produced from such a cycle is 100 kg/sec, the conditions of steam generation in the boiler are 8600 kPa and 500 °C, the exhaust pressure of the turbine is 10 kPa and the saturation temperature of the exhaust steam is 45.83 °C. Allowing for slight sub cooling of the condensate, the temperature of the liquid water from the condenser is fixed at 45 °C, the feed water pump which operates under the conditions of 45 °C and 10 kPa with 0.75 efficiency which causes a temperature rise of about 1 °C based on the following correlation:

$$\Delta H = C_p \Delta T + V(1 - \beta T)\Delta P \tag{5.1}$$

Where β is defined as follows

$$\beta = \frac{1}{V}(\frac{\partial V}{\partial T})_p \tag{5.2}$$

Which makes the temperature of the feed water entering the series of heat exchangers equal to 46 °C.

The saturation temperature of the steam at the boiler pressure of 8600 kPa is 300.06 °C, and the temperature to which the feedwater can be raised in the heat exchangers is less than that. This temperature is a design variable which depends on the economical aspects, so this value must be chosen before doing any calculations, an arbitrary value

of 226 °C is chosen for the water stream that will enter the heat exchanger before it will enter the boiler to generate steam. Since this will increase the temperature of the stream that will enter the boiler, the calculations will be repeated and compared to that with no heat exchanger before the boiler in terms of overall efficiency and heat added in the boiler.

The four feedwater heat exchangers have the same temperature rise, thus the total temperature rise is 180 °C which will be divided into four 45 °C increments, an assumed minimum temperature difference for heat transfer of no less than 5 °C, and extraction steam pressure is chosen such that saturation temperature values in each feedwater heat exchanger are at least 5 °C greater than the exit temperature of the feed water stream. The condensate from each feed water heat exchanger is flashed through throttling valve to the heater (heat exchanger) at the next lower pressure, and the collected condensate in the final heater is flashed into the condenser. Therefore all of the condensate returns from the condenser to the boiler in the way of the feedwater heaters.

Initial calculations are made based on the traditional steam power plant cycle (Figure 5.1-modification of Rankine cycle), then the calculations will be repeated for the modified power plant cycle where heat exchanger is added, where, the effect of two parameters are investigated on the overall cycle efficiency, that is outlet exhaust temperature from the rotary kiln and the amount of excess air used.

The turbine is divided into five sections, as the steam is extracted at the end of each section, the flow rate in the turbine decreases from one section to the next. The amount of steam extracted from the first four sections are determined by energy balances through the following equation that assumes steady flow process:

$$\Delta\left[\left(H+\frac{1}{2}u^2+zg\right)\dot{m}\right]_{fs}=\dot{Q}+\dot{w}_s \qquad (5.3)$$

The stream of water at 226 °C from the fourth feedwater heater will be heated by the gas effluent form the rotary kiln (in the modified Rankine cycle this stream is passed directly to the boiler) and so its properties will be changed from:

$P^{sat}=2598.2\ kPa$

$H=971.5\ \ kJ\!/\!kg$

$V=0.001201\ \ m^3\!/\!kg$

Into new pressure and temperature (boiler temperature and pressure). This implies new enthalpy, which is expected to reduce the amount of heat and fuel in the boiler to achieve the required pressure and temperature. Figure 5.3 shows the heat gained from the heat exchanger that inserted to the cycle to increase the temperature of the water out of feedwater heaters to achieve the previously mentioned process.

The process shows that an increase the temperature of the water before it enters the boiler. Thus the calculations will be repeated for each case of the model simulated concerning the gas output properties and for different operation conditions (number of chlorine atoms and amount of excess air).
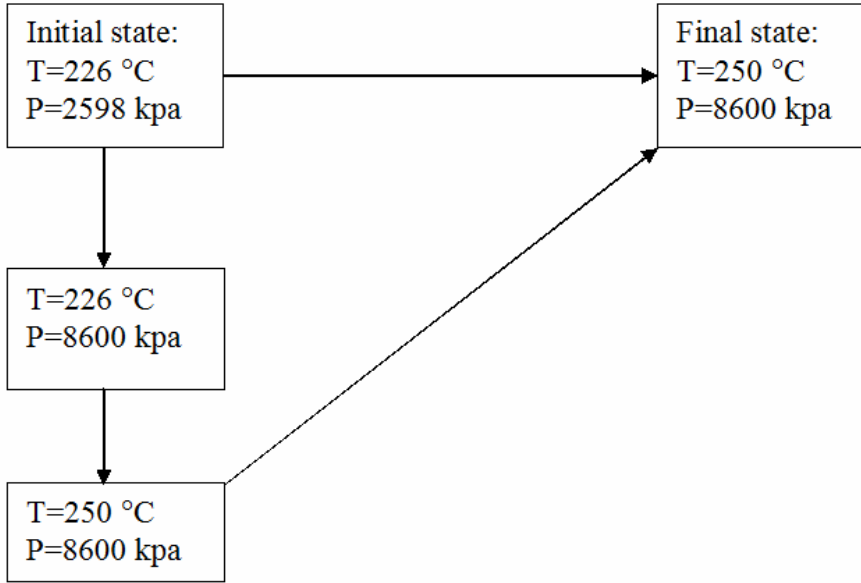
```
┌─────────────────────┐                    ┌─────────────────────┐
│ Initial state:      │───────────────────▶│ Final state:        │
│ T=226 °C            │                    │ T=250 °C            │
│ P=2598 kpa          │                    │ P=8600 kpa          │
└─────────────────────┘                    └─────────────────────┘
          │                                           ▲
          ▼                                          ╱
┌─────────────────────┐                             ╱
│ T=226 °C            │                            ╱
│ P=8600 kpa          │                           ╱
└─────────────────────┘                          ╱
          │                                      ╱
          ▼                                     ╱
┌─────────────────────┐                        ╱
│ T=250 °C            │───────────────────────╱
│ P=8600 kpa          │
└─────────────────────┘
```

Figure 5.3. The Heat Gained from the Heat Exchanger Inserted to the Cycle to Increase the Temperature of the Water out of Feedwater Heaters.

The designed heat exchanger used is chosen to be double pipe and countercurrent heat exchanger, and is modeled using NTU method as both the inlet temperature of hot and cold fluids are known. The temperature of feed water to the boiler is 226 °C and the gas effluent form the rotary kiln that is dependent on the system conditions and can be obtained from the model in the first section. The following equations are used to describe the heat exchanger:

$$C_h = \dot{m}_h C_{ph} \tag{5.4}$$

$$C_c = \dot{m}_c C_{pc} \tag{5.5}$$

$$\xi = \frac{C_{max}(T_{cout} - T_{cin})}{C_{min}(T_{hin} - T_{hout})}$$

$$\frac{C_{min}}{C_{max}} = \frac{T_{cout} - T_{cin}}{T_{hin} - T_{hout}} \tag{5.6}$$

$$NTU = \frac{UA}{C_{min}}$$

Where C_{max} is the maximum between C_h and C_c. UA is the conductance and is used for the design consideration. For shell and tube heat exchanger with one shell pass and 2, 4, 6, …etc tube passes the following equations are used (Hodge and Taylor, 1999):

$$C = \frac{C_{min}}{C_{max}}$$

$$E = \frac{\frac{2}{\xi} - (1+C)}{(1+C^2)^{\frac{1}{2}}}$$

$$NTU = -(1+C^2)^{-\frac{1}{2}} \ln(\frac{E-1}{E+1})$$

$$\xi = 2[1 + C + \frac{1 + \exp(-NTU(1+C^2)^{\frac{1}{2}})}{1 - \exp(-NTU(1+C^2)^{\frac{1}{2}})}(1+C^2)^{\frac{1}{2}}]^{-1}$$

(5.7)

After calculating the hot gas out from the rotary kiln (output form the model), this feed stream is introduced to the heat exchanger to calculate T_{cout} which will improve the performance of the boiler. Then the cycle calculations are performed for the new values by applying material and energy balances as follows:

Finding the amount of heat required in the boiler as:

$$Q_{boiler} = 3391.6 - H_{Tcout}$$

(5.8)

Where 3391.6 is the enthalpy of the steam out of the boiler at the indicated pressure and temperature in units of kJ/kg, thus the boiler efficiency is calculated as follows:

$$\eta = \frac{|W_S(net)|}{Q_{boiler}}$$

(5.9)

Where the numerator value in the previous expression is the net work obtained from the turbine. The energy balance will be performed to lead to the following table:

Table 5.1. Cycle Calculations

	Enthalpy kJ/kg	Work kJ/kg	Temperature °C
Section I	3151.2	-240.40	363.65
Section II	2987.8	-148.08	272.48
Section III	2827.4	-132.65	183.84
Section IV	2651.3	-133.32	96.0
Section V	2435.9	-149.59	45.83

The required information needed to complete the calculations are mass flow rate of the exhaust gas from the rotary kiln which depends on the operating conditions. The heat capacities for both water as cold fluid and for the exhaust gas from the rotary kiln. Which is approximately, for that of water vapor as it not only represents the maximum concentration of the gaseous species. It is also added to the rotary kiln to complete the combustion process. Following are the values of temperatures that will be used to characterize the shell and tube heat exchanger.

$$T_{h,in} = 927°C$$
$$T_{h,out} = 300°C$$
$$T_{c,in} = 226°C$$
$$T_{c,out} = 251°C$$

The above values if inserted in the Mathcad program will lead to a heat exchanger efficiency of about 0.98 this value will be combined with that of cycle and the heat recovery unit that will be discussed below to lead to an overall efficiency of the process.

5.3. Heat recovery system:

The two streams out of the shell and tube heat exchanger are water stream and hot gases. These streams are sent respectively to the boiler to complete the power cycle. And to the other heat exchanger that is cross flow heat exchanger for further heat recovery. The cross flow heat exchanger is used so as to heat the fuel-air mixture that

enters the rotary kiln. This will reduce the energy needed to heat the mixture before it enters the combustion chamber. As the two streams enter the cross flow heat exchanger are both in gas phases, the design will be for unmixed fluids. The fuel-air mixture is considered as cold fluid and the gases out of the shell and tube heat exchanger is considered as hot fluid.

To characterize the cross flow heat exchanger the surfaces will be determined. Firstly, it is suggested that $17.8-\dfrac{3}{8}$ W and 9.03 finned surfaces (Hodge and Taylor, 1999) are used. The dimensions b, β, D_h, fin thickness, and fin length are determined so as to calculate the required geometrical properties as follows (Hodge and Taylor, 1999):

$$\alpha_1 = \frac{b_1 \beta_1}{b_1 + b_2 + 2a}$$

$$\delta_1 = \frac{\alpha_1 D_{h1}}{4}$$

$$L_1 = \frac{D_{h1} A_1}{4 A_{c,1}} \tag{5.10}$$

where :

$$A_{c,1} = \frac{\dot{m}_1}{G_1}$$

Where a is the plate spacing, and G is the mass velocity and can be estimated as follows (Hodge and Taylor, 1999):

$$G = \sqrt{\frac{\Delta P_i \, 2\rho_{i,in} g_c}{(K_c + 1 - \sigma^2) + 2(\frac{\rho_{i,in}}{\rho_{i,out}} - 1) + f \frac{A_i}{A_{c,i}} \frac{\rho_{i,in}}{\rho_{i,m}} - (1 - \sigma^2 - K_e)\frac{\rho_{i,in}}{\rho_{i,out}}}} \tag{5.11}$$

Where i stands for the surface number and since there are two surfaces so i can be either 1, or 2. ΔP is the pressure drop and can be estimated as follows (Hodge and Taylor, 1999):

$$\frac{\Delta P_i}{P_i} = \frac{G^2}{2g_c} \frac{\upsilon_i}{P_i} \left[(K_c + 1 - \sigma^2) + 2(\frac{\upsilon_j}{\upsilon_i} - 1) + f_F \frac{A}{A_c} \frac{\upsilon_m}{\upsilon_i} - (1 - \sigma^2 - K_e)\frac{\upsilon_j}{\upsilon_i} \right] \tag{5.12}$$

Where:

υ_m is the mean specific volume and is defined as:

$$\upsilon_m = \frac{1}{A}\int_0^A \upsilon\, dA \tag{5.13}$$
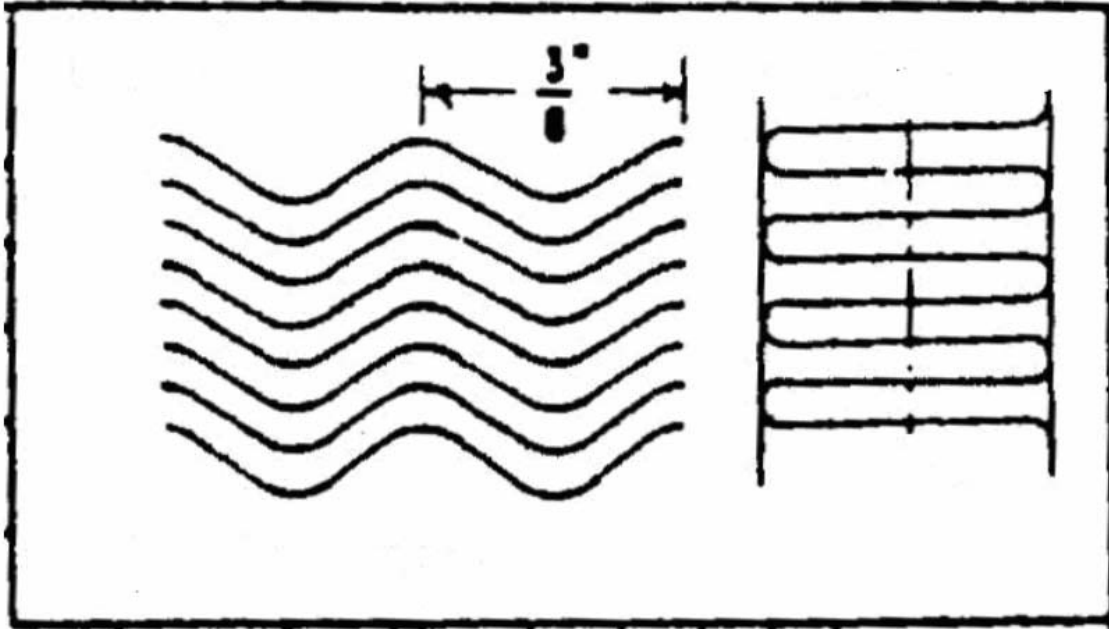

Figure 5.4. Heat Transfer Wavy-fin Plate-fin 17.8-3/8W Surface Used in Cross Flow Heat Exchanger, (Hodge and Taylor, 1999).
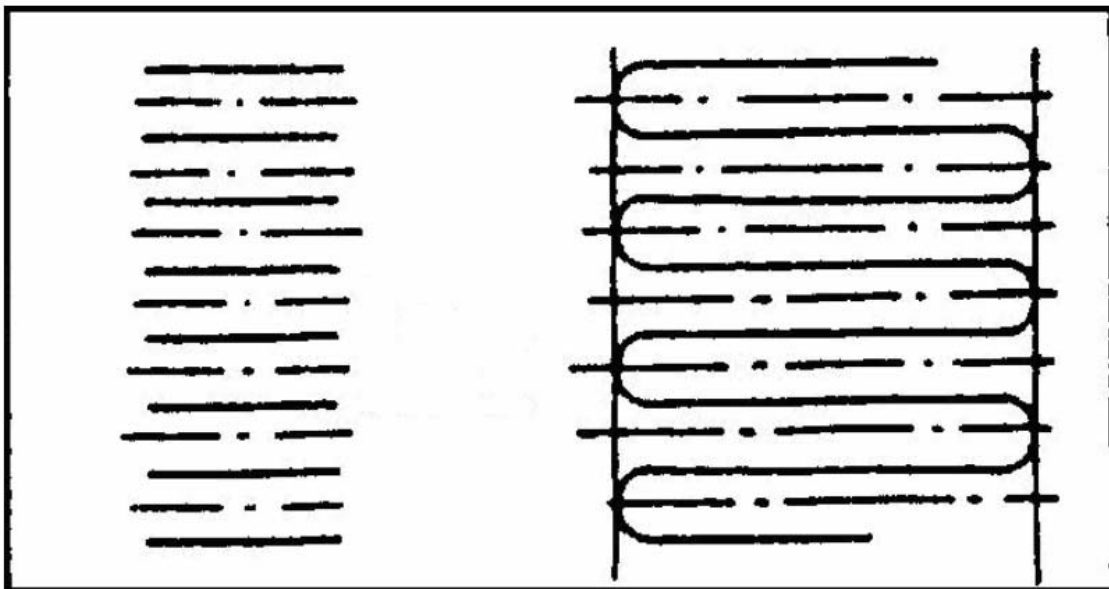

Figure 5.5. Heat Transfer Plain Plate-fin 9.03 Surface Used in Cross Flow Heat Exchanger, (Hodge and Taylor, 1999).

To solve for the cross flow heat exchanger. A Mathcad program (ShahCF.mcd) was used. Since the solution will be performed numerically where trial and error procedure is used, and iterations with complicated equations are needed. The ShahCF.mcd algorithm is used:
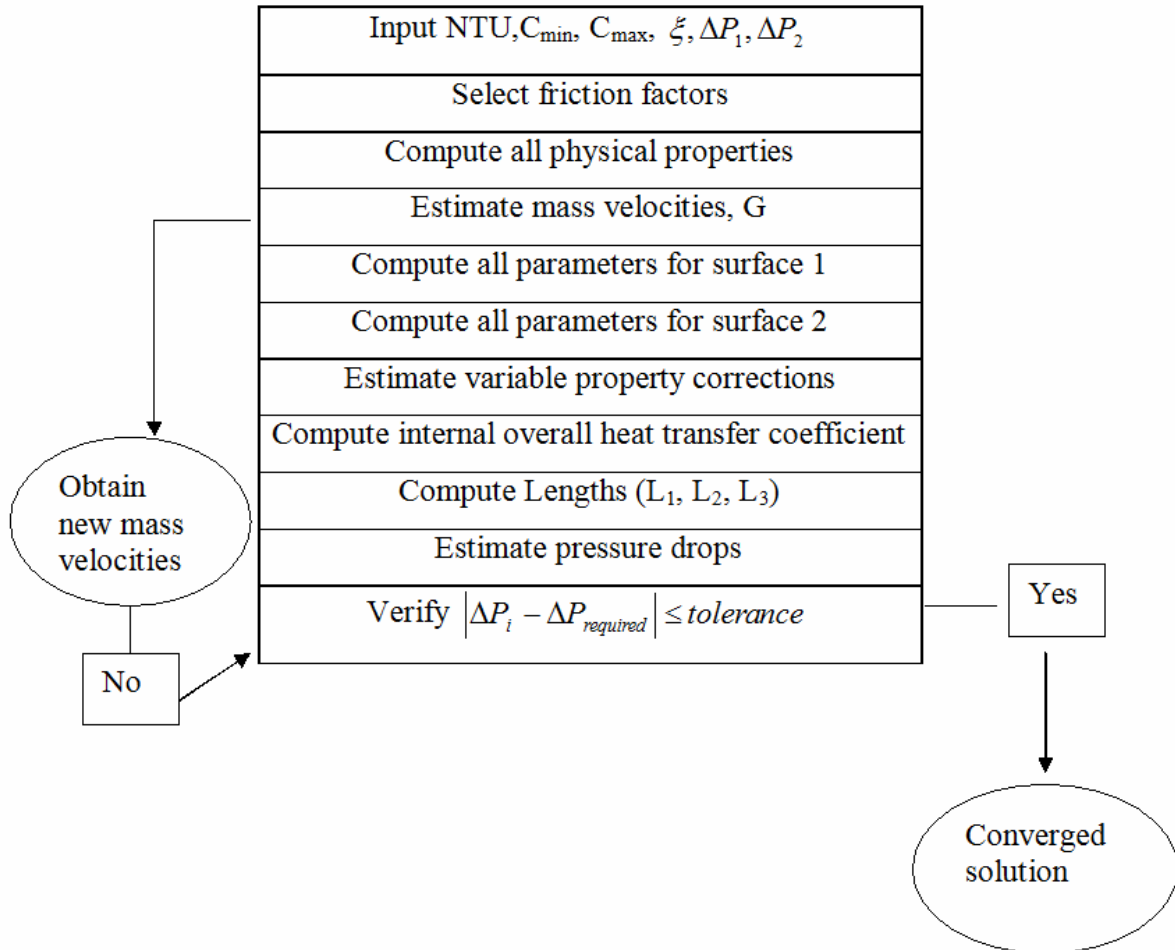

| Input NTU,C_{min}, C_{max}, ξ, ΔP_1, ΔP_2 |
| Select friction factors |
| Compute all physical properties |
| Estimate mass velocities, G |
| Compute all parameters for surface 1 |
| Compute all parameters for surface 2 |
| Estimate variable property corrections |
| Compute internal overall heat transfer coefficient |
| Compute Lengths (L_1, L_2, L_3) |
| Estimate pressure drops |
| Verify $\left| \Delta P_i - \Delta P_{required} \right| \leq tolerance$ |

Obtain new mass velocities

No

Yes

Converged solution

Figure 5.6. Block Diagram for Program ShahCF. mcd, (Hodge and Taylor, 1999).

It should be mentioned here that some of the data needed for the iterative solution will be obtained from figures (Hodge and Taylor, 1999). To obtain for example the recommended values of entrance and exit loss coefficients and data for heat transfer surfaces (Kays and London, 1964).

The final results for the heat recovery unit will be shown in the next chapter, in addition to sample of the Mathcad program.

5.4. Design of heat recovery unit:

One of the important aspects of the suggested power cycle is the insertion of heat recovery unit. That is the cross flow heat exchanger. The importance of such a unit is to recover most of the heat stored in the hot stream that exits from the shell and tube heat exchanger. This heat will be used as one of its application to heat the fuel-air mixture that will enter the rotary kiln so as to reduce the amount of energy needed to start the incineration process.
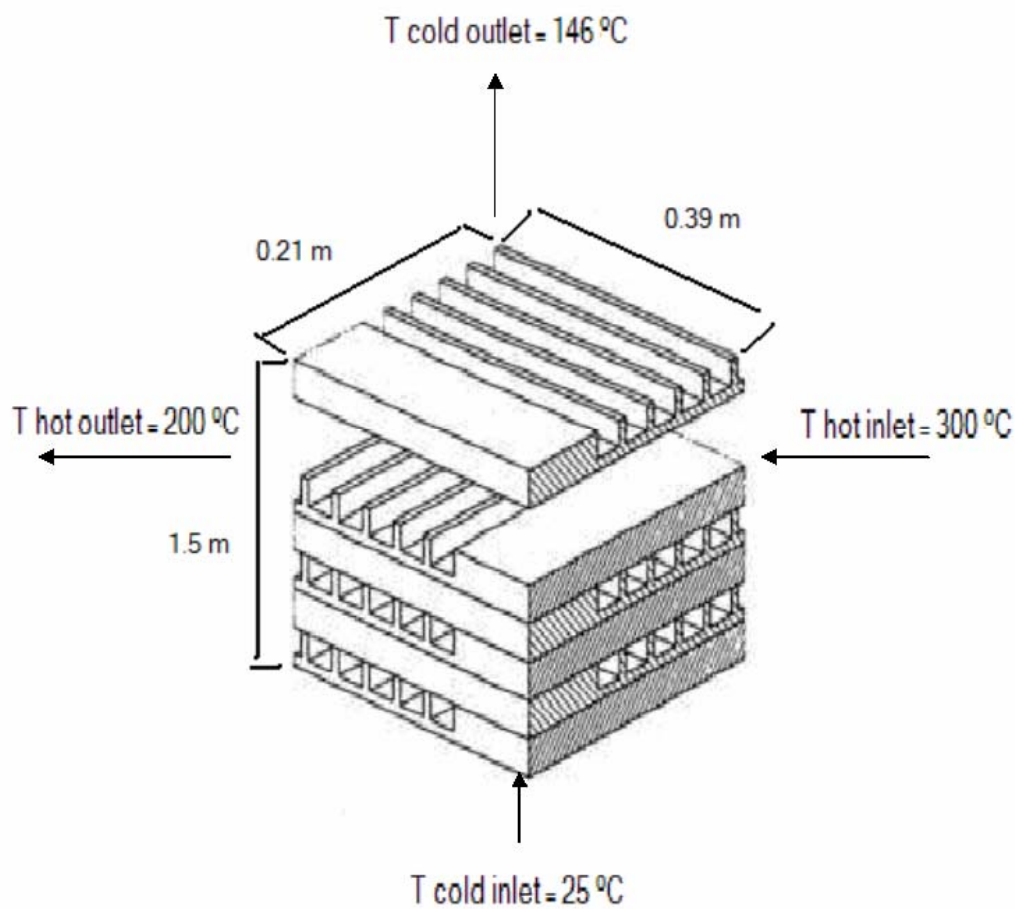

Figure 5.7. Cross Flow Heat Exchanger Used to Recover Heat, (Hodge and Taylor, 1999).

Appendix B shows the steps and the iterative solution for the above mentioned heat exchanger. Through applying the Shah method Figure 5.6 for solution, Table 5.1 summarizes the final design parameters.

It should be mentioned here that the two surfaces used here are $17.8\text{-}\dfrac{3}{8}$ W and 9.03 finned surfaces have the values of free-flow to frontal area ratios of 0.29 and 0.6 respectively. These values were calculated based on the correlations presented in chapter four. Another Mathcad program was used to find the number of transfer units (NTU). This program is shown in the appendices gives that for unmixed cross flow heat exchanger with $C = \dfrac{C_{min}}{C_{max}}$ equal to one is 0.617 which was used to determine another characteristics for the cross flow heat exchanger. The number of passes per surface of 12.0.

Table 5.2. Mathcad Solution for the Cross-flow Heat Exchanger

Property	Surface 1	Surface 2
Actual pressure drop, kPa	55.2	240.9
Mass velocity, kg/m^2.sec	5.2	18.2
Design pressure drop, kPa	55.1	241.1
L1, m	0.21	
L2, m	1.5	
L3, m	0.39	

The use of such a unit will help in heating fuel-air mixture that will react in the rotary kiln. Thus the same model developed for the incineration of PCBs will be adjusted to account for this variation.

The temperature for each stream that will be in contact with the cross flow heat exchanger will be as follows:

$$T_{h,in} = 300°C$$

$$T_{h,out} = 200°C$$

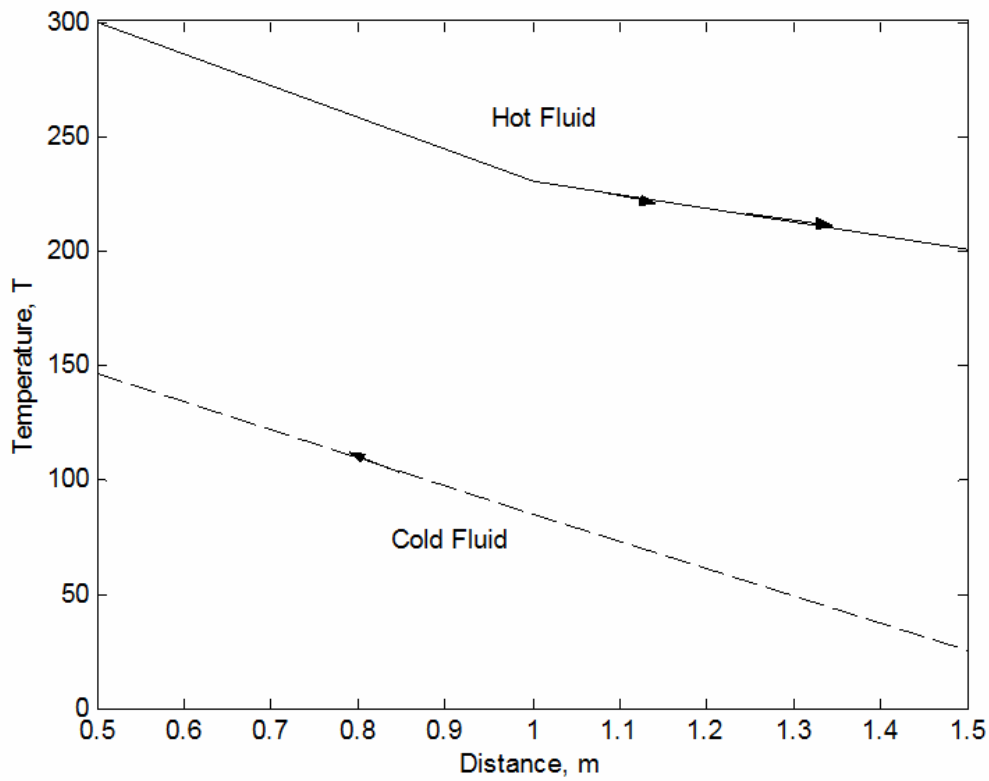$$T_{c,in} = 25°C$$

$$T_{c,out} = 146°C$$

Figure 5.8. Temperature Measured in ºC Varies with Distance (T-X Diagram) for the Cross Flow Heat Exchanger.

The outlet temperature of the cold stream was determined based on experimental observation related to toxic elements formation. Dioxin as it is noticed that no such a harmful element will be formed at this temperature. After insertion the above mentioned values to a Mathcad program and applying the following calculation to account for heat load in the cross flow heat exchanger and then:

$$q = \dot{m}_{cold} C_{p,cold} (T_{c,in} - T_{c,out}) \tag{5.14}$$

$$\xi = \frac{q}{C_{min} (T_{h,in} - T_{c,in})} \tag{5.15}$$

Where the efficiency is found to be 0.36 and NTU value is 0.617.

The outlet stream temperature for the cold fluid (fuel-air mixture) is then fed to the rotary kiln incinerator, a process that will not only improve the incineration process but will also save energy.

The above mentioned value is inserted in the previously derived model and the outlet temperature will be obtained and compared with the original value where no heat recovery system is used.

5.5 Cycle discussion and explanation:

In a conventional power plant, the molecular energy of the fuel is released by the combustion process. The wastes PCBs energy will be released by the incineration process.

In a steam power plant (usually modeled as a modified Rankine cycle). Feed water heaters allow the feed water to be brought up to the saturation temperature gradually. This minimizes the irreversibility associated with heat transfer to the process fluid (water). The gases effluents from the rotary kiln incinerator are used to heat water (similar to the economizer) from the feed water heaters before it enters the boiler. This will also minimize the heat duty in the boiler and is expected to increase the efficiency of the process and the cost of operation.

CHAPTER SIX

Results and Discussion

6.1 Rotary kiln incineration:

One of the important features in the incineration of hazardous wastes is the volume reduction of the incinerable wastes. The inlet waste is converted into ash that consists of combustion products and non-burning fractions. Because of the rotational movement of the combustion chamber and its rotating angle, the ash continuously comes out of the combustion chamber. Thus, it is important to determine the amount of solids formed during the incineration process (solid mass holdup). This amount will come out from the process where it is then simply land filled. The model simulation can get the mass holdup inside the rotary kiln, Figure 6.1 predicts this parameter for number of chlorine atoms of 1.0.
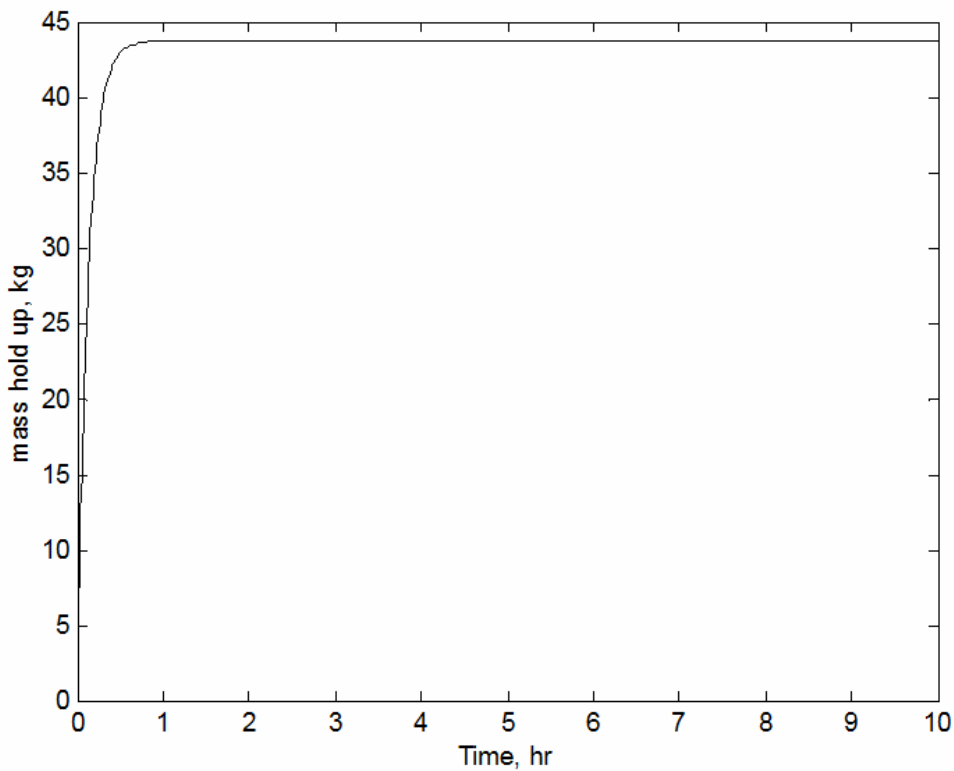

Figure.6.1. Ash Holdup Inside the Rotary Kiln During Incineration for One Chlorine Atom and 0.1 Excess Air.

It can be clearly seen from the Figure 6.1 that the incineration is fast. The value of ash formed reaches steady state value rapidly. This behavior is expected as the operating temperature is very high. To study the effect of increasing the number of chlorine atoms on the solid holdup inside the combustion chamber Figure 6.1 is repeated for different chlorine atoms number. However, since the operating temperature is very high the number of chorine atoms has no effect on ash formation inside the combustion chamber. And because the waste fed into the rotary kiln is homogeneous and has identical behavior, however if the feed properties is changed that is incinerating different types of waste or changing the burning fraction ω_{bf} the solid might be changed depending on the value of burning fraction.

The use of excess air in the incineration is important to ensure the complete combustion of the waste. Thus, the gas phase elements will be affected by changing the excess air. This aspect is important to anticipate the concentration of gaseous pollutants and concentration in the effluent gas. However, the presence of nitrogen in the air stream will affect the combustion temperature and efficiency. So the hold up of gas phase components will be evaluated.

Figure 6.2 shows that the oxygen amount is high at the first hour of the process. This means that the reaction is not immediate and need approximately 7.0 minutes to start. After the reaction proceeds the oxygen holdup as expected starts to drop to reach its steady state value after approximately 3 hours. This means the end of reaction, this behavior is attributed to the fact that the reaction rate is fast.
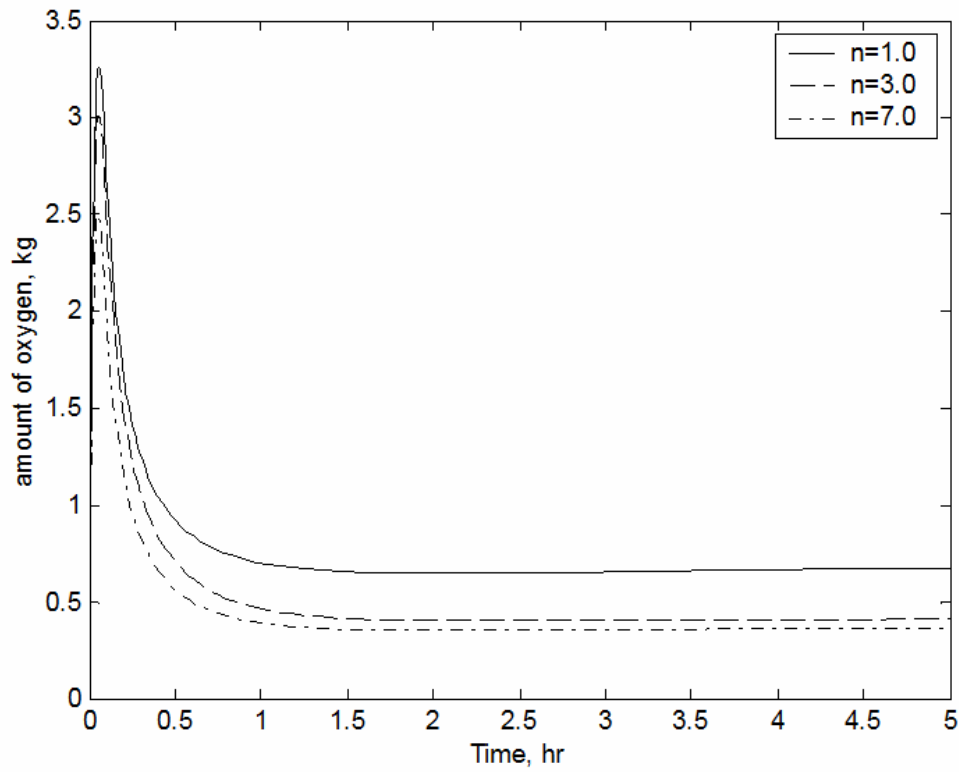
Figure.6.2.a. Oxygen Hold up Inside Rotary Kiln for 0.1 Excess Air and at Different Number of Chlorine Atoms.
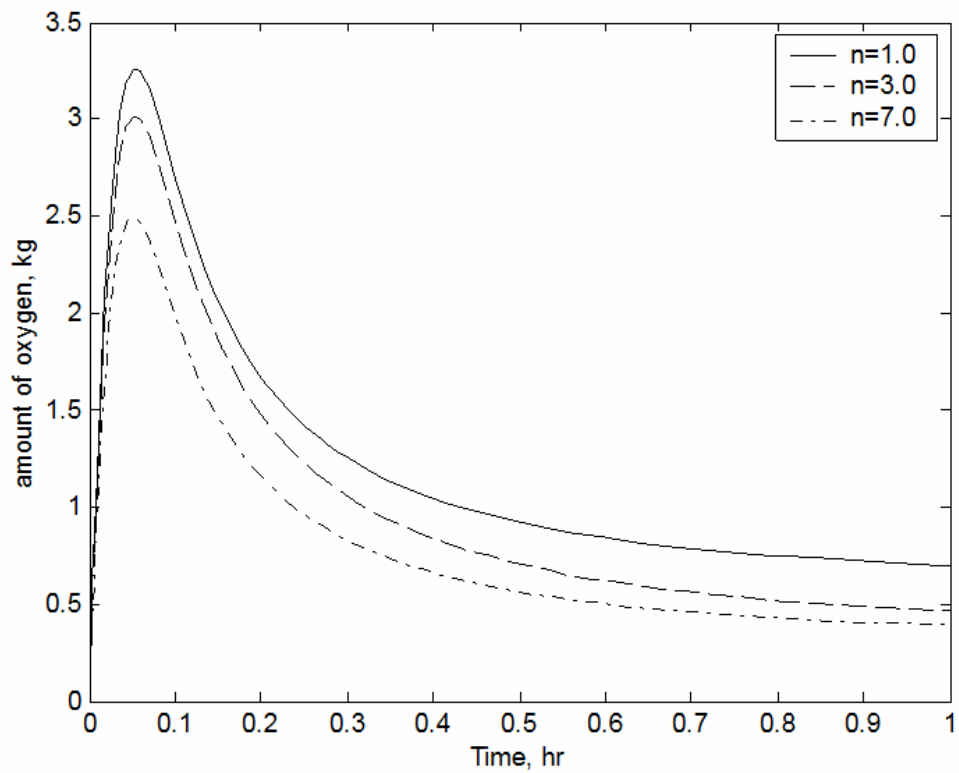

Figure.6.2.b. Oxygen Hold up Inside Rotary Kiln for 0.1 Excess Air and at Different Number of Chlorine Atoms.

To study the effect of increasing chlorine atoms in the waste stream. Figure 6.2.b.shows that as the number of chlorine atoms increases the oxygen hold up inside the rotary kiln decreases. This means that larger amount of oxygen is needed for the destruction of chlorine atoms replaces the hydrogen ones. Thus, more oxygen is needed for increasing chlorine atoms in the waste.

It is clearly seen that the increase in chlorine toms requires more oxygen. The model can simply account for that by increasing the amount of excess air for the same number of chorine atoms (number of chlorine atoms can be changed simply form 0-10).

Figure 6.3 shows that as the amount of excess air increases the oxygen hold up inside the rotary kiln increases. The three curves have the same beak for oxygen demand because they are for the same waste stream that is one chlorine atom.
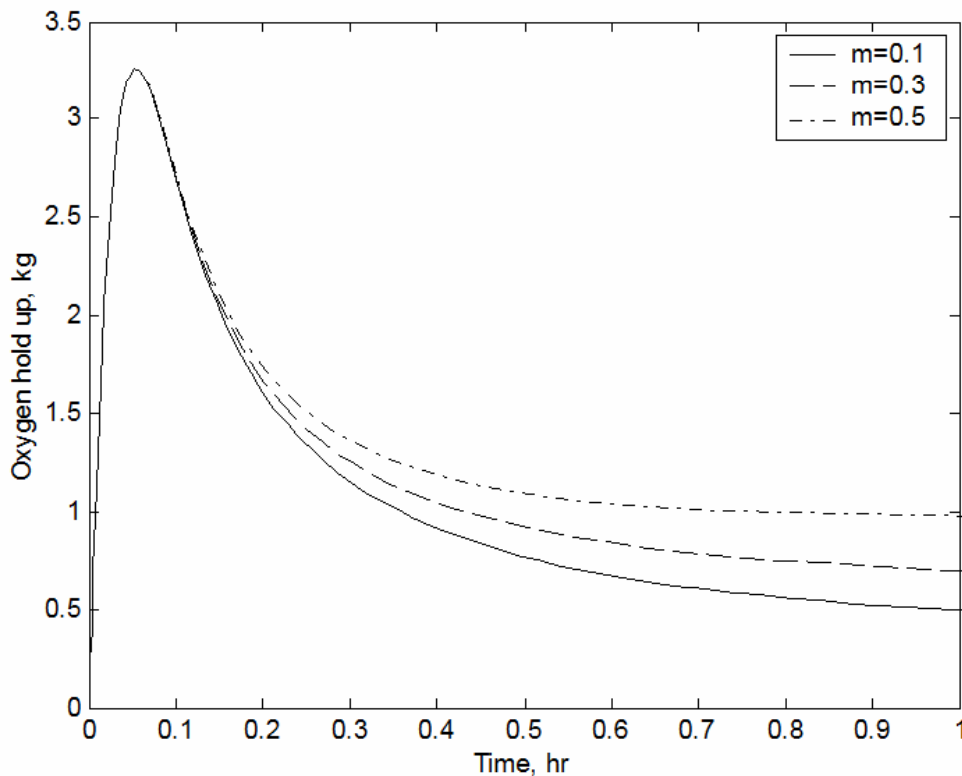

Figure 6.3. Oxygen Hold up Inside Rotary Kiln for one Chlorine Atom at Different Amount of Excess Air.

However, if the number of chlorine atoms is changed, and the amount of excess air is fixed at a value greater than 0.1. The same behavior of Figure 6.2.a-b, that is more oxygen is needed for the chemical destruction (incineration) process. Which is reflected by decreasing in the amount of oxygen holdup inside combustion chamber (3.5 for n=1.0 but 2.5 for n=7.0). as it can be clearly seen from. Figure 6.4.
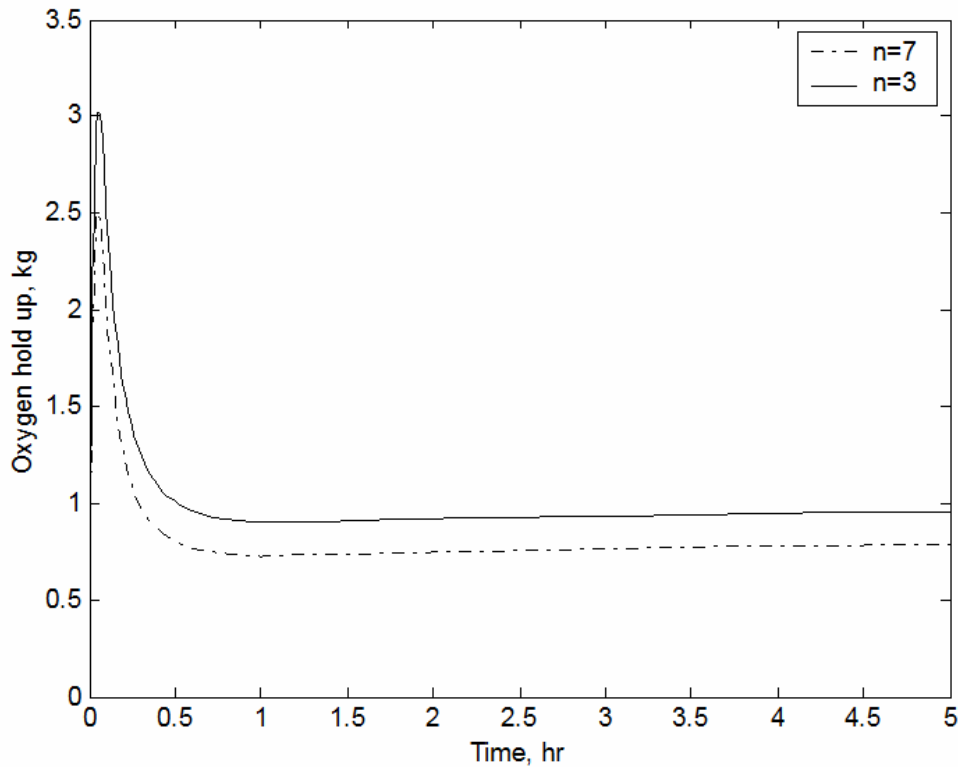
Figure 6.4. Oxygen Hold up Inside Rotary Kiln for 0.5 Amount of Excess Air Different Number of Chlorine Atoms.

Furthermore, at steady state conditions the amount of oxygen holdup inside the rotary kiln for greater amount of excess air is greater. That is it is about 1.5 kg for excess air of 0.5 but it is only 0.5 for chlorine atom number of 7.0.

The amount of carbon dioxide hold up is very important in the incineration process. Because the presence of hydrocarbons will enhance the production of carbon dioxide. Figure 6.5 anticipates the carbon dioxide hold up as a result of incineration process.
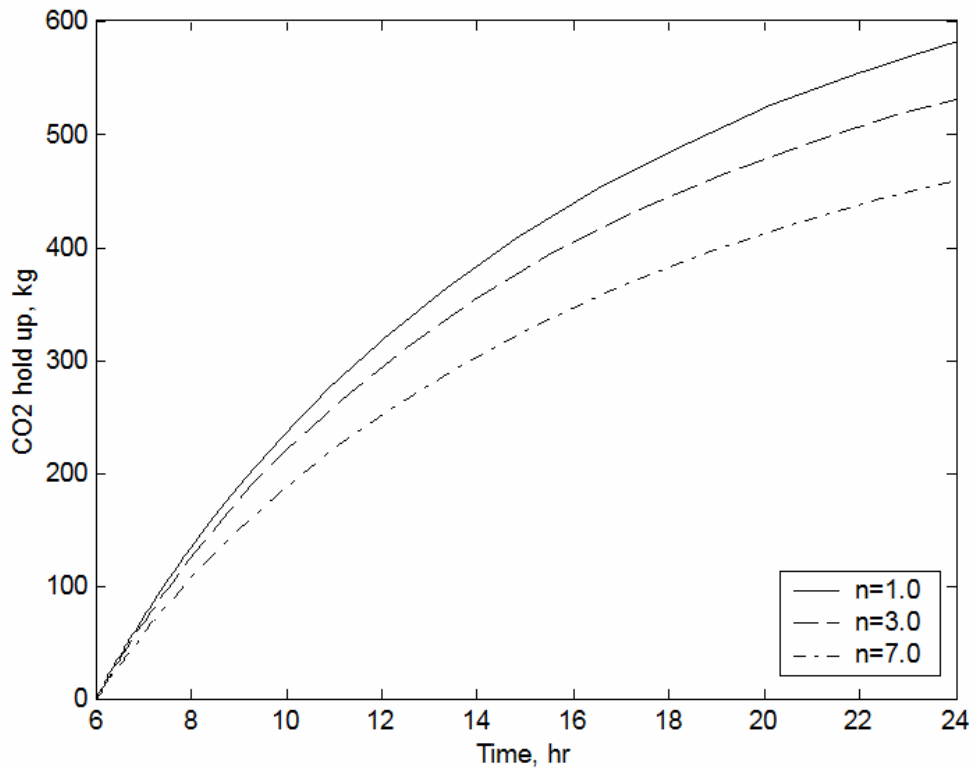
Figure.6.5. Carbon Dioxide Hold up Inside Rotary Kiln for 0.1 Amount of Excess Air and Different Number of Chlorine Atoms.

It can be clearly seen that the amount of carbon dioxide is continuously increased as large number of carbon atoms exist. However, it is noticed that the amount of carbon dioxide decreased as number of chlorine atoms increased. Which is expected as the number of hydrogen atoms bonded to the carbon atoms decrease. Thus, the number of carbon-hydrogen bonds participated in the reaction to produce the carbon dioxide decreased.

To study the effect of increasing the amount of excess air on carbon dioxide hold up inside the rotary kiln, the number of chlorine atoms is kept constant at one chlorine atom and the amount of air excess is increased. Figure 6.6 shows that the same trend of decreasing carbon dioxide as increasing the amount of excess air (600 kg of carbon dioxide for $n=1.0$ and $m=0.1$ but 400 for $n=1.0$ and $m=0.5$).
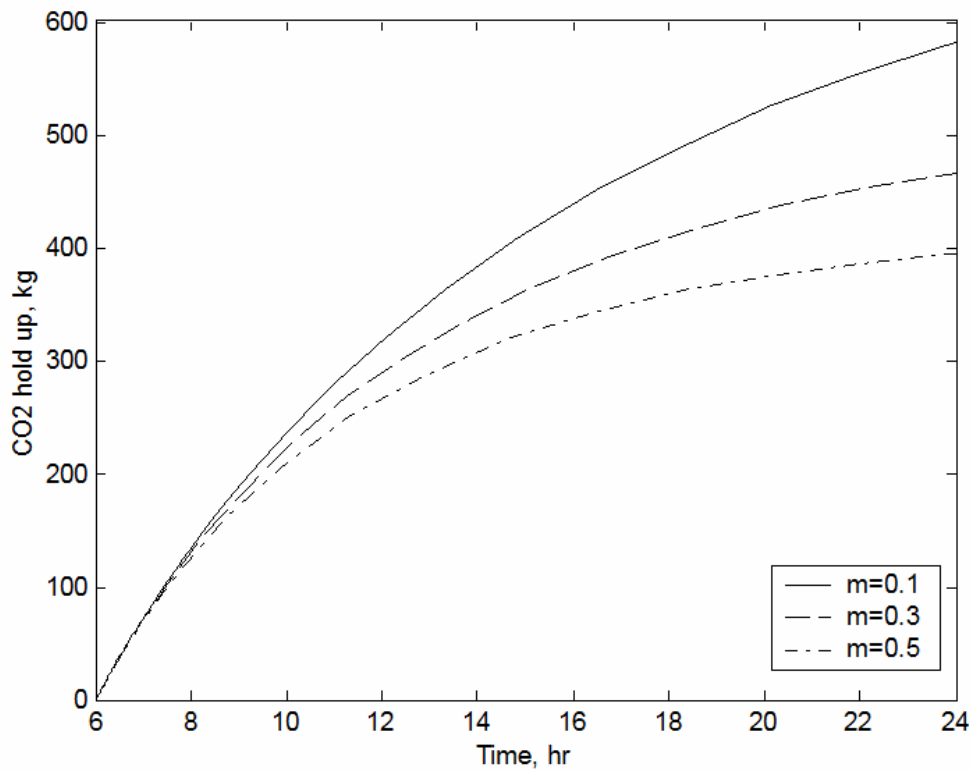
Figure 6.6. Carbon Dioxide Hold up Inside Rotary Kiln at Different Amount of Excess Air and for One Chlorine Atom.

The above discussion leads to the idea of controlling carbon dioxide emissions which depends on number of chlorine atoms. As the number of chlorine atoms increases the carbon dioxide emissions decreases. Which is out of control that depends on feed waste characteristics. And increasing the amount of excess air (as the amount of excess air increases the carbon dioxide emissions decreases) which is controlled step. Therefore, Figure 6.7 shows that, the amount of carbon dioxide emitted can be controlled if the number of chlorine atoms increased. This can be achieved by changing the amount of excess air it is only about 300 kg of carbon dioxide for 7.0 chlorine atoms and 0.5 amount of excess air but it is around 400 kg for one chlorine atoms at 0.5 amount of excess air.

It should be mentioned here that the increase in the amount of excess air will affect the temperature inside the rotary kiln. Thus affecting the combustion process (will be seen later), thus it must be under careful study.
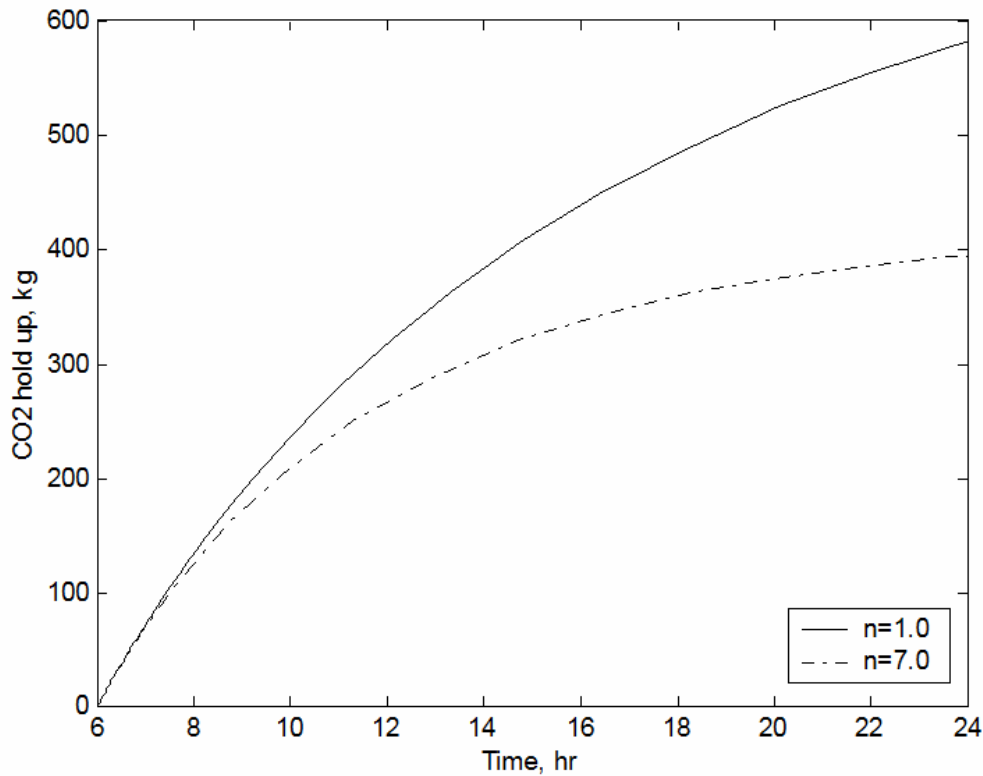
Figure 6.7. Carbon Dioxide Hold up Inside Rotary Kiln at Different Number of Chlorine Atoms and Constant Amount of Excess Air Greater than 0.1.

The presence of water vapor inside the rotary kiln results from the humidity in the waste fed and from the reaction. Thus it is expected to have an increase in the water vapor hold up similar to that of carbon dioxide. However, it expected to be more. The model derived can predict the water hold up inside the rotary kiln. This value is affected by the presence of chlorine atoms. Figure 6.8 shows approximately the above mentioned trend of increasing the water vapor hold up as a result of incineration process. Because water vapor and carbon dioxide is the default product of any hydrocarbon combustion process.

It is also noted that decreasing the amount of water vapor hold up as increasing the number of chlorine atoms. This behavior can be explained as that of carbon dioxide holdup. However, as the number of chlorine atoms exceeds 5.0, the trend is reversed,
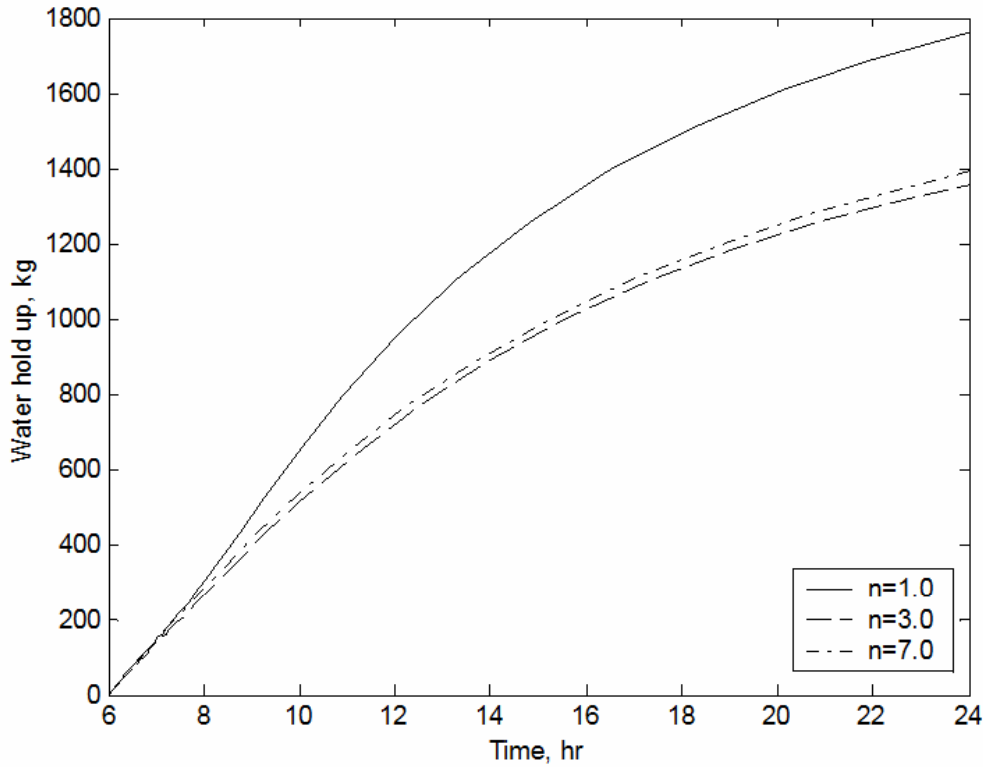
Figure 6.8: Water Vapor Hold up Inside Rotary Kiln at Different Number of Chlorine Atoms and 0.1 Amount of Excess Air.

that is an increase in the amount of water vapor hold up as incineration process proceeds, but it is still less than that of one chlorine atom.

This behavior can be explained by returning back to proposed mechanism of PCBs incineration process (equation 3.2) that is:

$$C_{12}H_{(10-n)}Cl_n + \frac{29-n}{2}O_2 \rightarrow 12CO_2 + (5-n)H_2O + nHCl$$
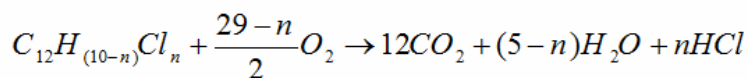
It can be easily verified that as the number of chlorine atoms (n) increase to a value greater than 5 the stoichiometric coefficient of water is negative. Theoretically, the

water vapor is a reactant rather than a product. Thus, the stoichiometric value will be added to the material balance of water. Because of that the value of water vapor hold up is larger when chlorine atoms increases.

Physically, the above trend and discussion explain the addition of water droplets to the waste fed to the incinerators in real practices. The model derived here is adjusted to account for this variation.

To study the effect of increasing the amount of excess air on the amount of water vapor hold up. Figure 6.9 shows that as the amount of excess air increases the amount of water vapor decreases. This trend is attributed that the air is used to destruct the chlorine bonds rather than forming water vapor

Studying the same aspect but for larger number of chlorine atoms. Figure 6.10 shows that, the same trend of decreasing the amount of water vapor as increasing the amount of excess air. However, it should be emphasized here that the amount of water vapor hold up inside rotary kiln is some how greater for number of chlorine atoms greater than 5. This is attributed to the fact that water is added during incineration process.
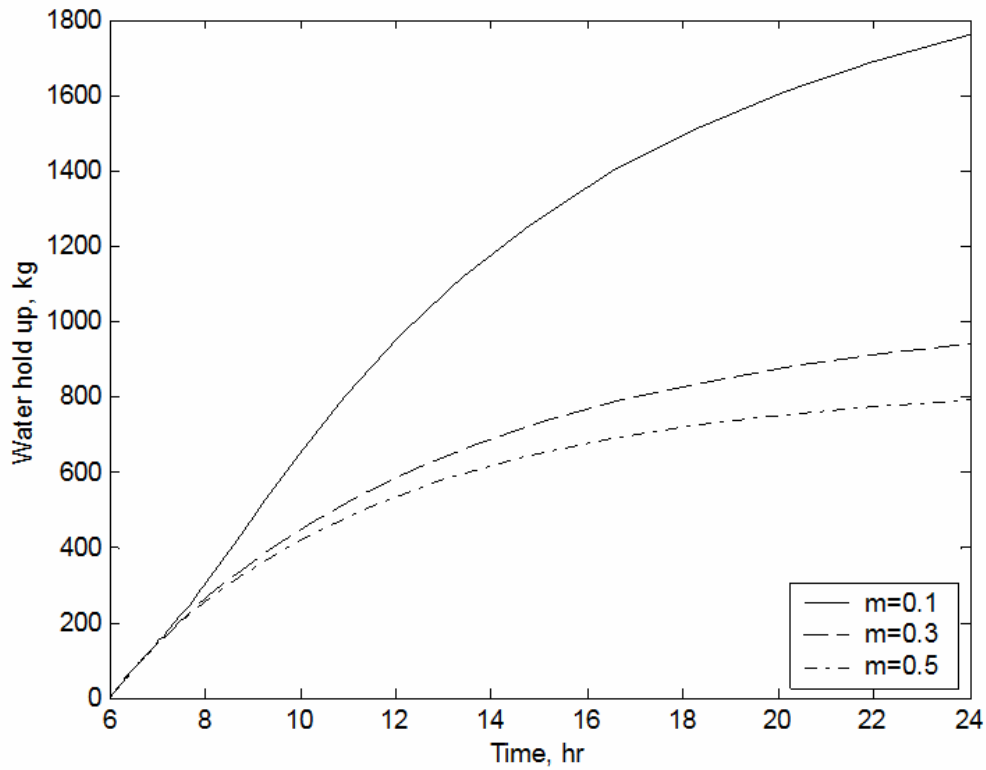
Figure 6.9. Water Vapor Hold up Inside Rotary Kiln at Different Amount of Excess Air and for One Chlorine Atom.

One of the most important pollutant or (reaction product) anticipated to exist as predicted from the theoretical model of PCBs incineration is the hydrochloric acid. Which results from the presence of chlorine atoms. Thus, it is expected to have an increase in the amount of hydrochloric acid as the number of chlorine atoms increases. Then the method to control the amount of it is by studying the effect of excess air used.
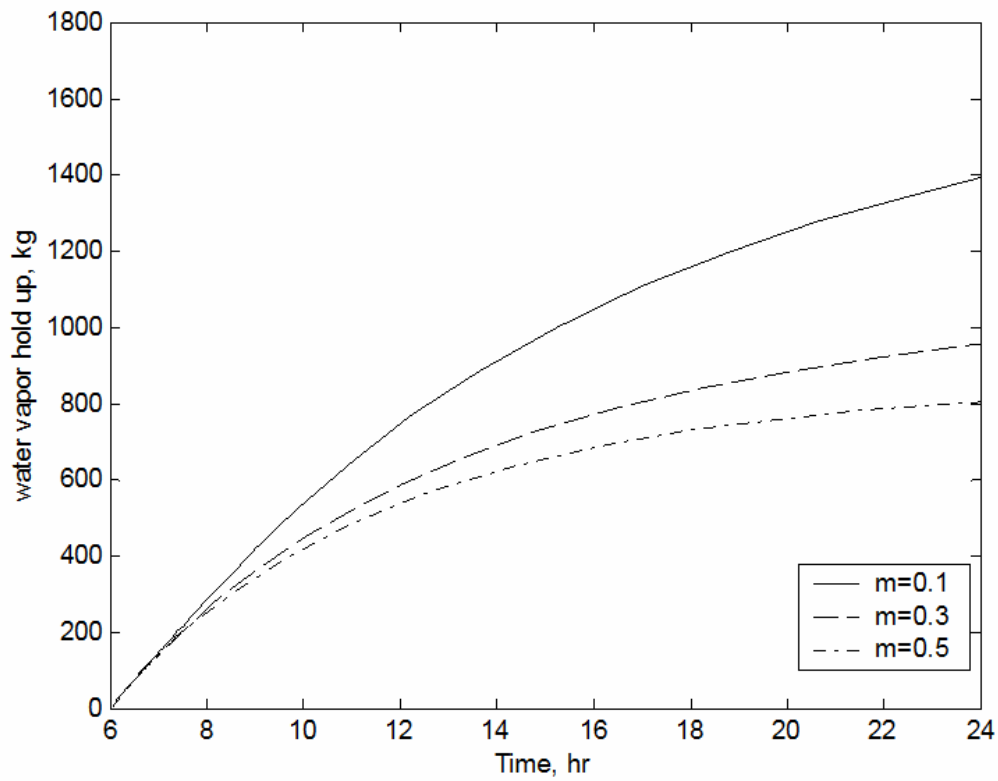
Figure 6.10. Water Vapor Hold up Inside Rotary Kiln at Different Amount of Excess Air and for Seven Chlorine Atoms.

Figure 6.11 shows the results of increasing the amount of hydrochloric acid produced inside the rotary kiln as the number of chlorine atoms increases. The chlorine atoms will bond with the hydrogen atoms to form the structure of the hydrochloric acid. The experimental results show that, and refers to it to the source of corrosion in the rotary kiln. Its concentration must be reduced and treated before emitted to atmosphere.

Figure 6.11. Hydrochloric Acid Hold up Inside Rotary Kiln at Different Number of Chlorine Atoms and 0.1 Amount of Excess Air.

To study the effect of excess air on the formation of hydrochloric. The chlorine atoms number will kept constant for two values (less than five and greater than five). Where the amount formed can be expected and the necessary action to treat the effluent gas is prepared. Figures 6.12 and 6.13 show the above mentioned behavior.

It can be clearly seen from the above mentioned Figures that the excess air is efficient in decreasing the amount of hydrochloric acid. This behavior is attributed to the dilution effect of the excess air. The same behavior is noticed in the incineration of PCBs containing higher number of chlorine atoms. However, the large drop of hydrochloric acid concentration needs to be verified with experimental results.
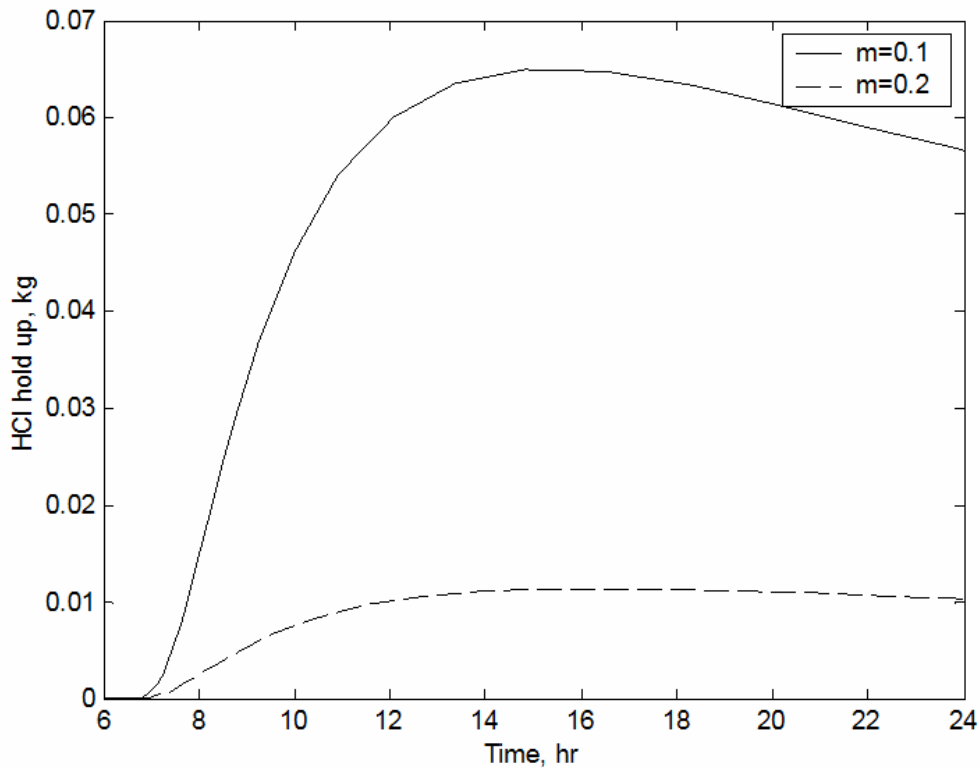
Figure 6.12. Hydrochloric Acid Hold up Inside Rotary Kiln at Different Amount of Excess Air and for Seven Chlorine Atoms for one Chlorine Atom.

The use of fuels in first operating is necessary for start up (ignition) step. Thus hydrocarbon fuel as methane will be used as a fuel. It should be mentioned here that if number of chlorine atoms inserted in this model equal to zero the system will solve for pure hydrocarbon incineration.
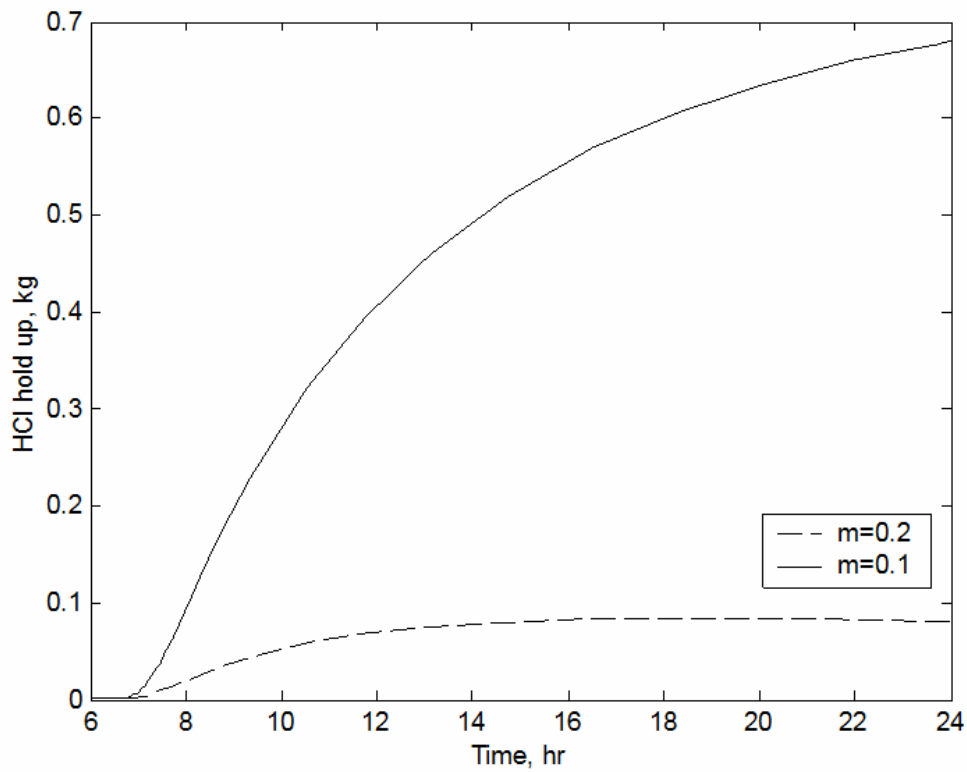
Figure 6.13. Hydrochloric Acid Hold up Inside Rotary Kiln at Different Amount of Excess Air and for Seven Chlorine Atoms.

Figure 6.14 shows that the amount of methane gas inside the combustion chamber that decreases as time proceeds. This behavior is due to the continuous consumption of methane gas. However, at the beginning of the reaction the amount of methane is increased before the combustion and so (reaction) begins. No matter what is the number of chlorine atoms are there, the methane combustion or consumption rate is independent because it is only a start up element.

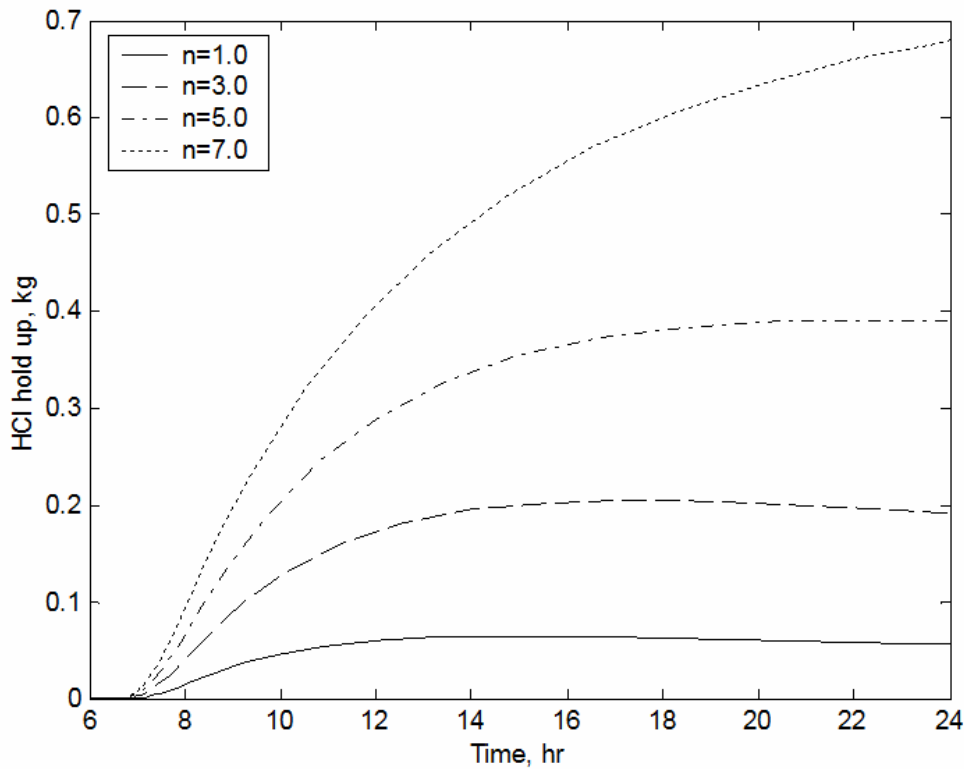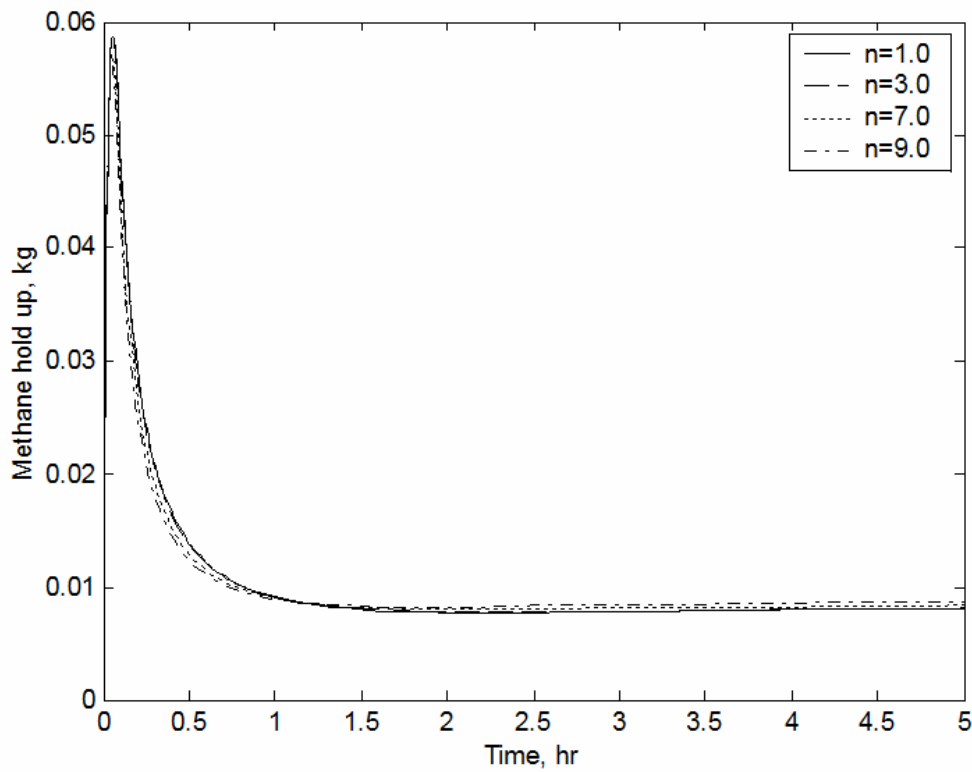**Figure 6.14. Methane Hold up Inside Rotary Kiln at Different Number of Chlorine atoms and 0.1 Amount of Excess Air.**

The use of excess air may cause faster drop in the methane consumption. As it can be seen from the Figure 6.15. However, approximately the same concentration (hold up) of methane can be noticed. This is again attributed to the fact that methane is only a startup element. The same trend is expected if the number of chlorine atoms increases.

One of most important element in the combustion chamber is the total gas hold up. That results form the combustion process and it is some how similar to the solid mass hold up in the rotary kiln Figure 6.1. Figure 6.16 shows the gas hold up inside the rotary kiln.

Figure 6.15. Methane Hold up Inside Rotary Kiln at Different Number of Chlorine Atoms and 0.1 Amount of Excess Air.

Figure 6.16 shows that there is an increase of gas hold up in the combustion chamber. However, it starts to decrease and then reach constant value that is the steady state value. The drop in the values of gas hold up may be attributed to the reaction that might happen in the gas phase or to the decrease in the total volume after mixing the gases from reaction products.

If the number of chlorine atoms increases, the total gas volume produced decreases. This is attributed to fact that the amount of gases produced is decreased as reaction products.

If the amount of excess air increases the amount of gas hold up inside rotary kiln increases. As it can be shown from Figure 6.17. Where the drop in gas mass is neglected if compared to the amount of excess air used. Meanwhile the general trend is repeated.

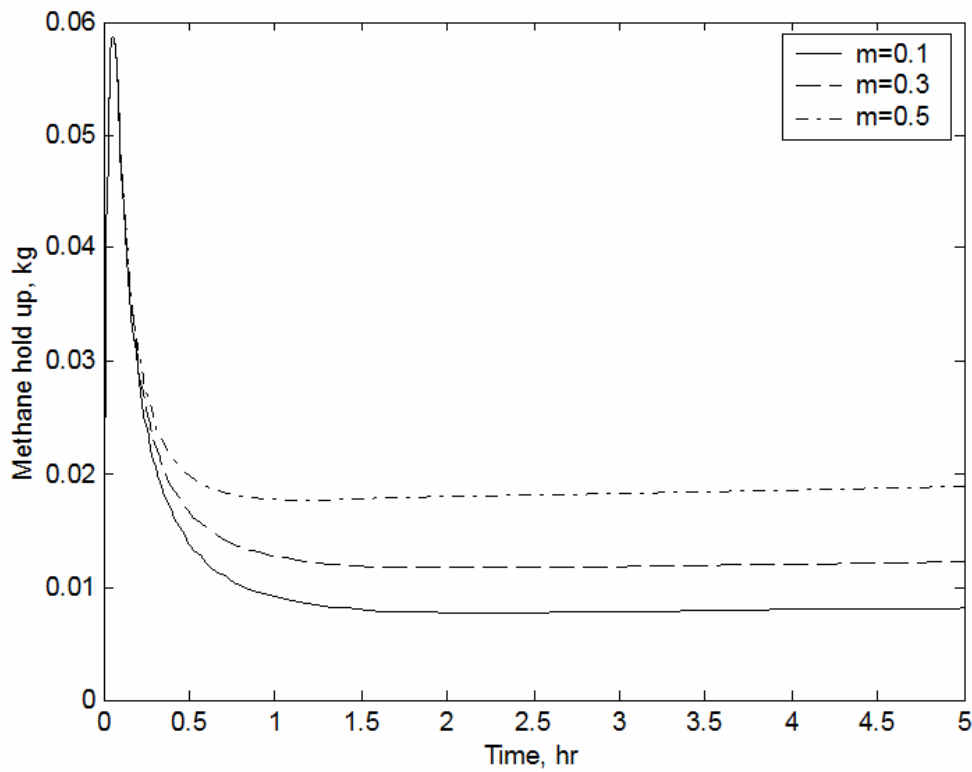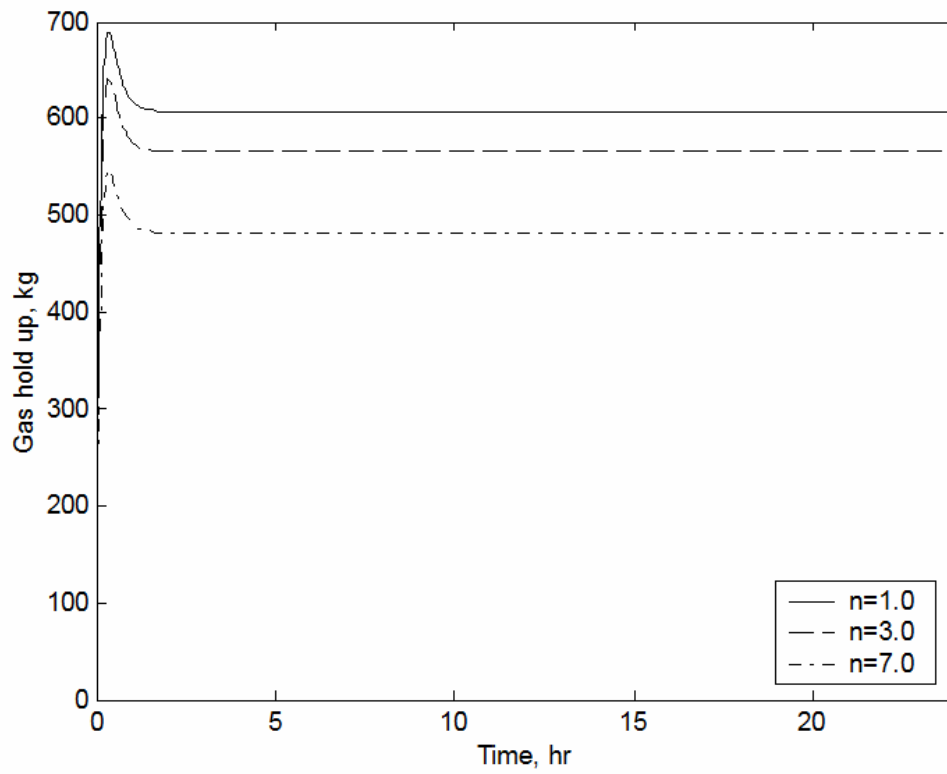**Figure 6.16. Gas Hold up Inside Rotary Kiln at Different Number of Chlorine Atoms and 0.1 Amount of Excess Air.**
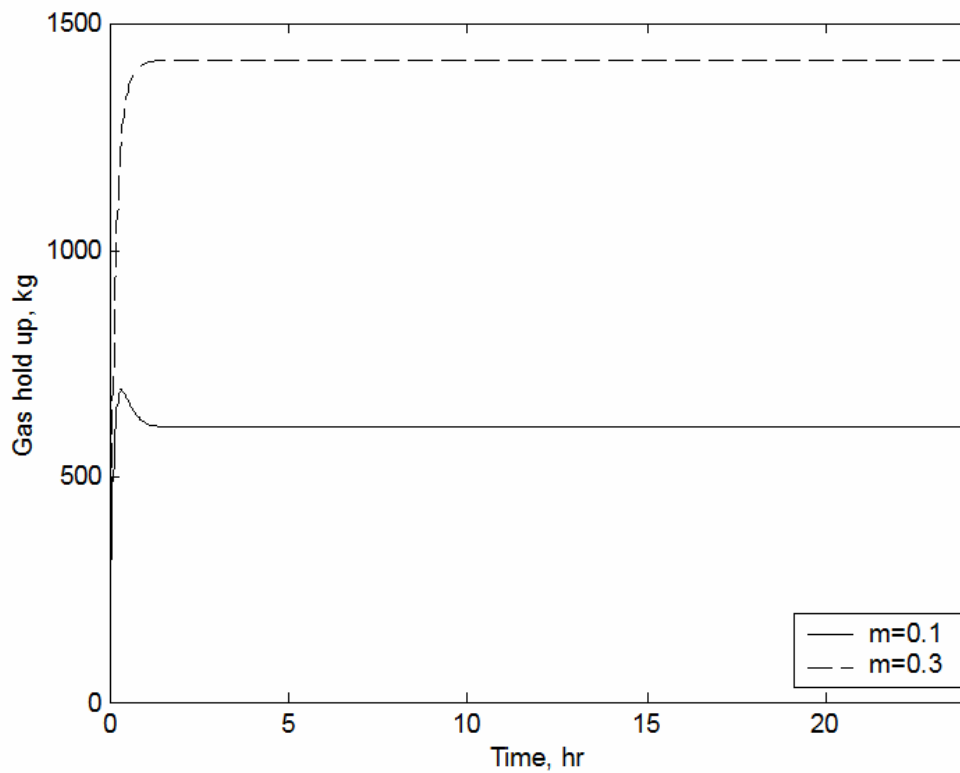
Figure 6.17. Gas Hold up Inside Rotary Kiln at Different Amount of Excess Air and One Chlorine Atom.

Finally, and most important parameter in the incineration process is the energy that can be utilized. Energy can be reflected by temperature results from the incineration. Figure 6.18 shows the temperature increase as a result from the incineration process.
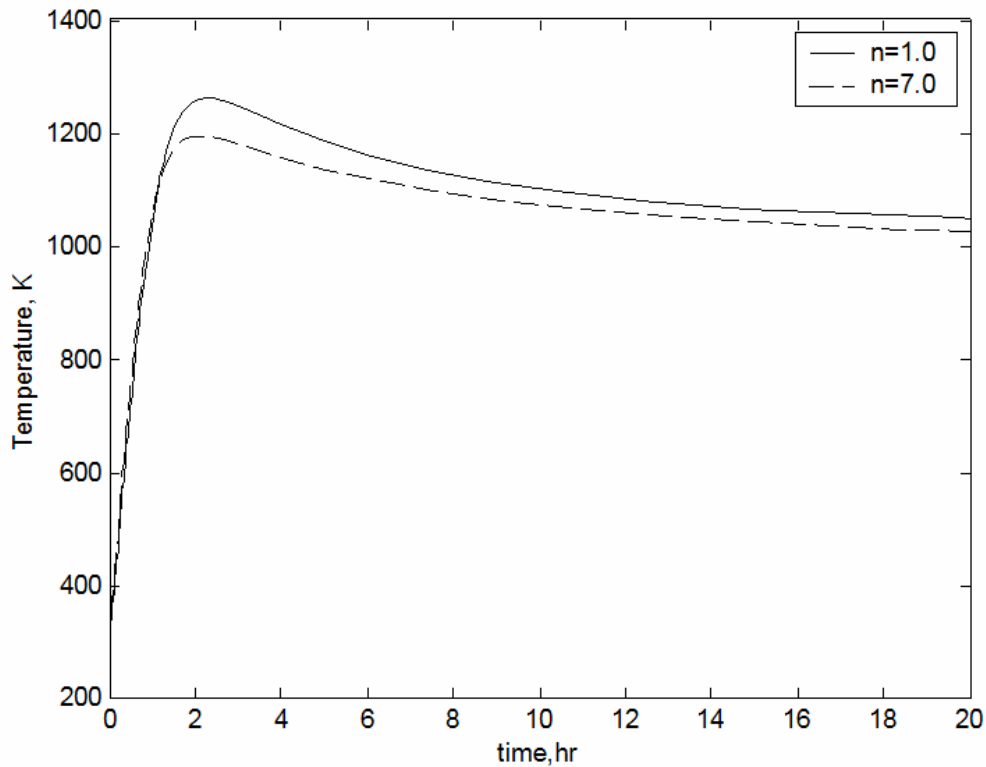
Figure 6.18. Temperature Inside Rotary Kiln at Different Number of Chlorine Atoms and 0.1 Amount of Excess Air.

It can be clearly seen from Figure 6.18 that as the number of chlorine atoms increases the temprature decraeses. This is attributed to the fact that the heat of combustion of the feed waste is less when more chlorine atoms present.

The effect of excess air on the temperature distribution inside the rotary kiln can be seen in Figure 6.19. Which shows a drop in temperature for the incraese in the excess air. This trend may be attributed to the presence of nitrogen element in the air fed which act as energy scavenger that steels the heat from the combustion cahamber. Thus, the idea is to recover this heat and more from the exhust gases.

The same behavior is noticed when the number of chlorine atoms exceeds 5. Figure 6.20 shows the general trend is the decraese in temperature for the increase in the number of chlorine atoms.

If the number of chlorine atoms exceeds five atoms, and the amount of excess air remains at 0.1 then again the same trend will be repated in Figure 5.21 and Figure 5.22.
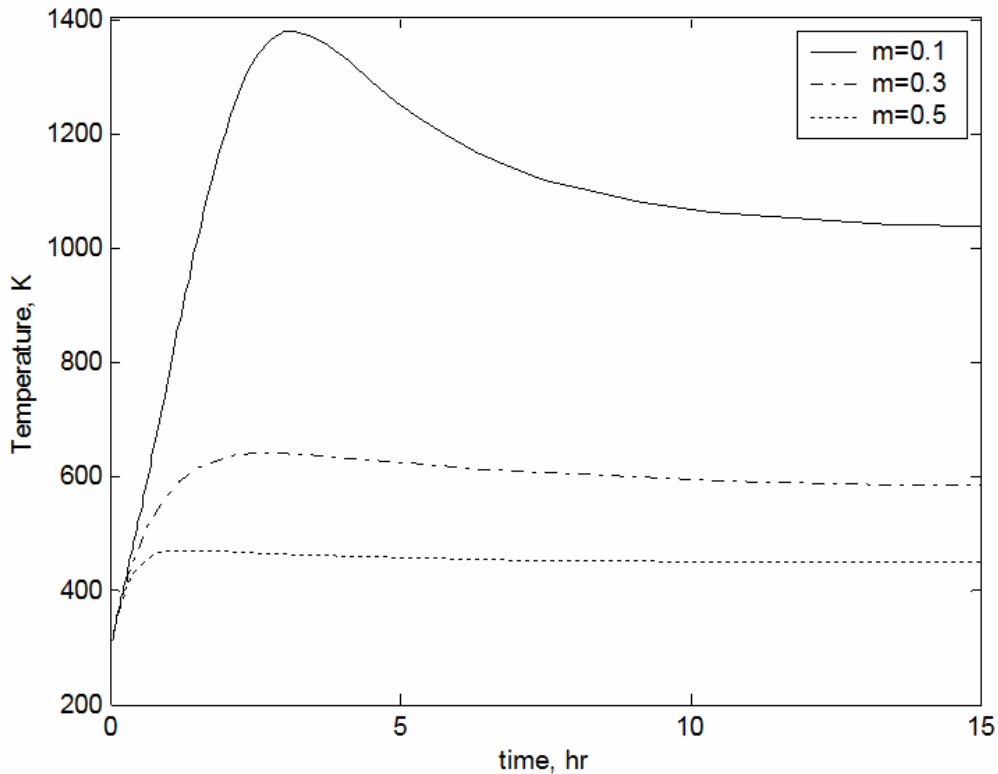
Figure 6.19. Temperature Inside Rotary Kiln at Different Amount of Excess Air and for One Chlorine Atom.

The results obtained will be compared with the published experimental data. As the modeling of the incineration of PCBs is based mainly on experiemntal studies and pilot plants, where the modeling and simulation procedure is still new and depends some how on performing some experiments. Figure 6.23 shows a comparison for some of chlorinated wastes incinerated in rotary kilns.
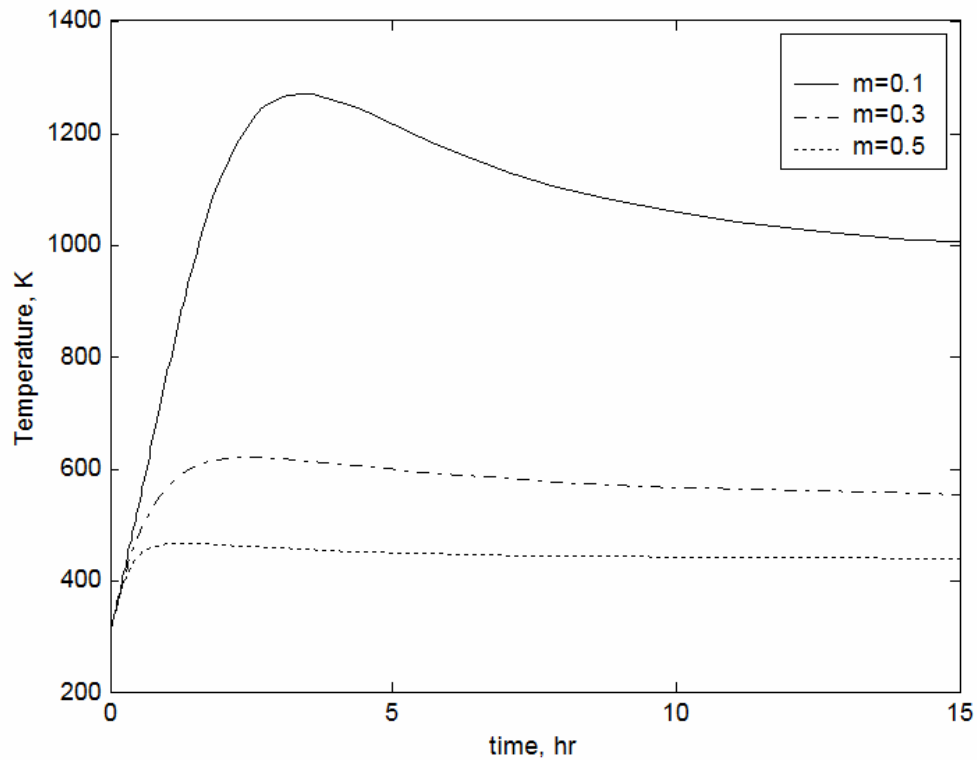
Figure 6.20: Temperature Inside Rotary Kiln at Different Amount of Excess Air and for Seven Chlorine Atoms.
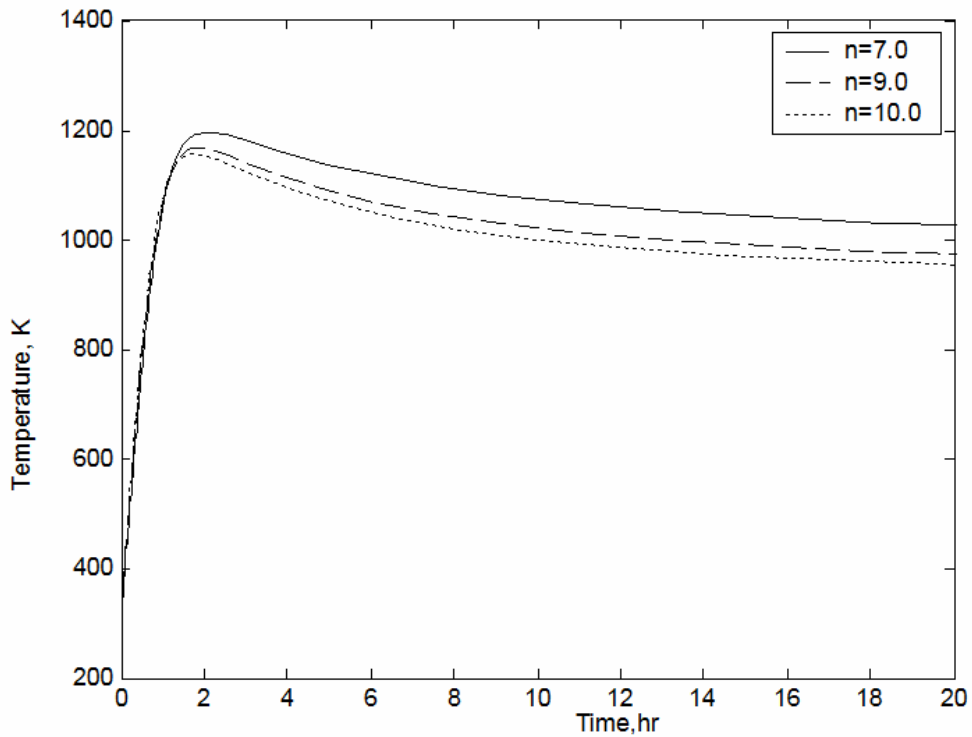
Figure 6.21. Temperature Inside Rotary Kiln at Different Number of Chlorine Atoms Greater than 5 and for 0.1 Amount of Excess Air.
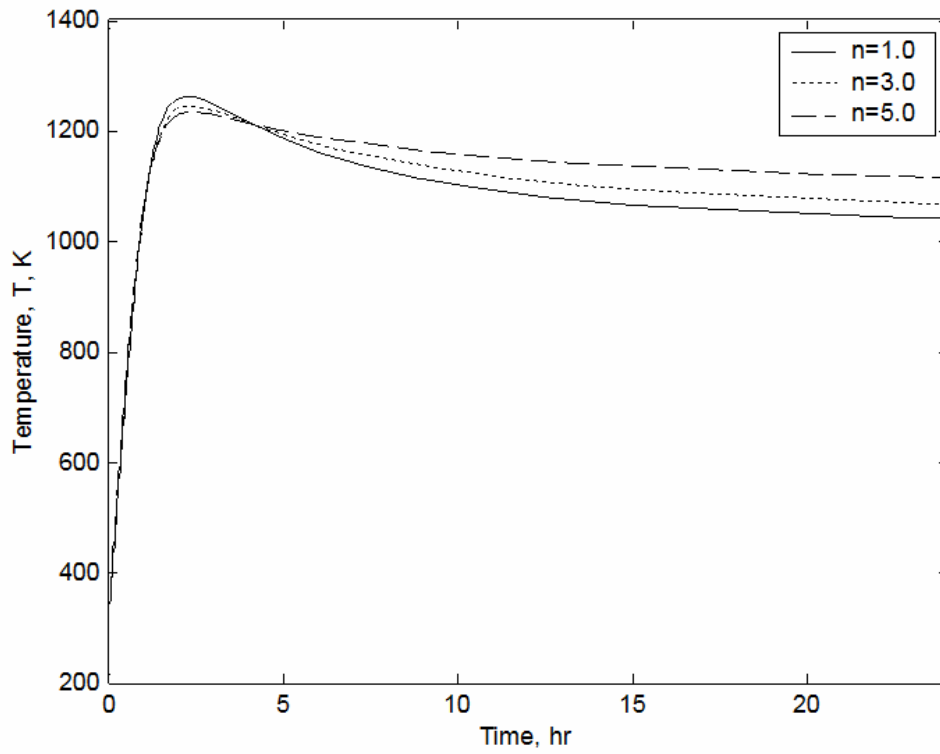
Figure 6.22. Temperature Inside Rotary Kiln at Different Number of Chlorine Atoms Less than 5 and for 0.1 Amount of Excess Air.
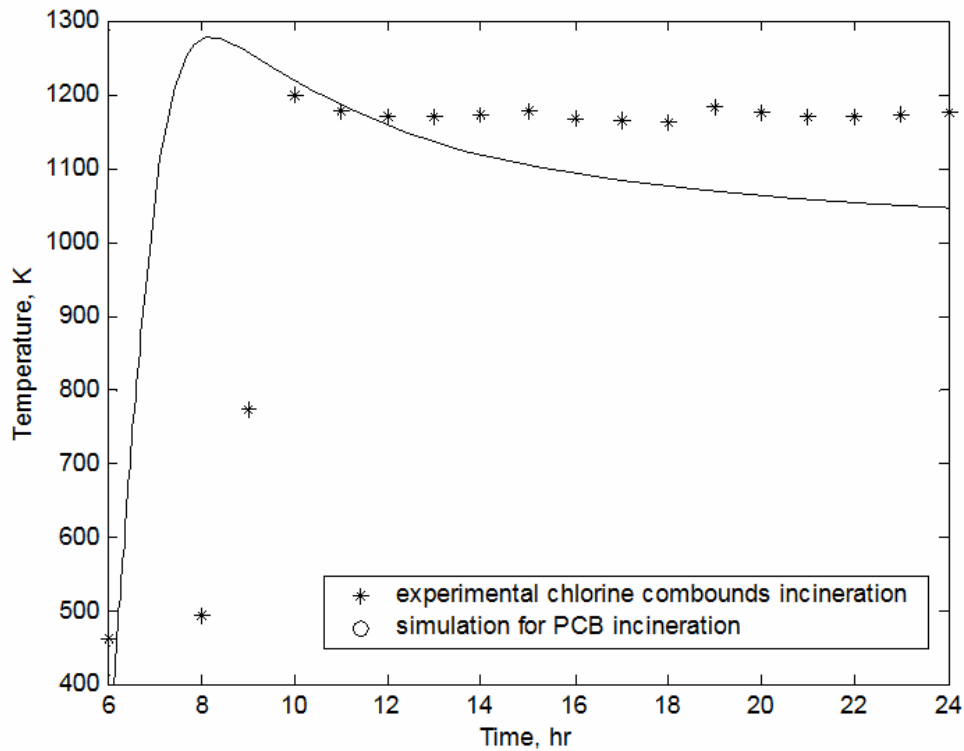
Figure 6.23. Temperature Inside Rotary Kiln Obtained Experimentally and Compared to the Results Obtained by the Current Model, (Rovaglio, et al., 1998).

The temperature represents the amount of energy generated during the incineration process. Figure 6.24 shows the energy generated from the incineration of PCBs in rotary kilns.
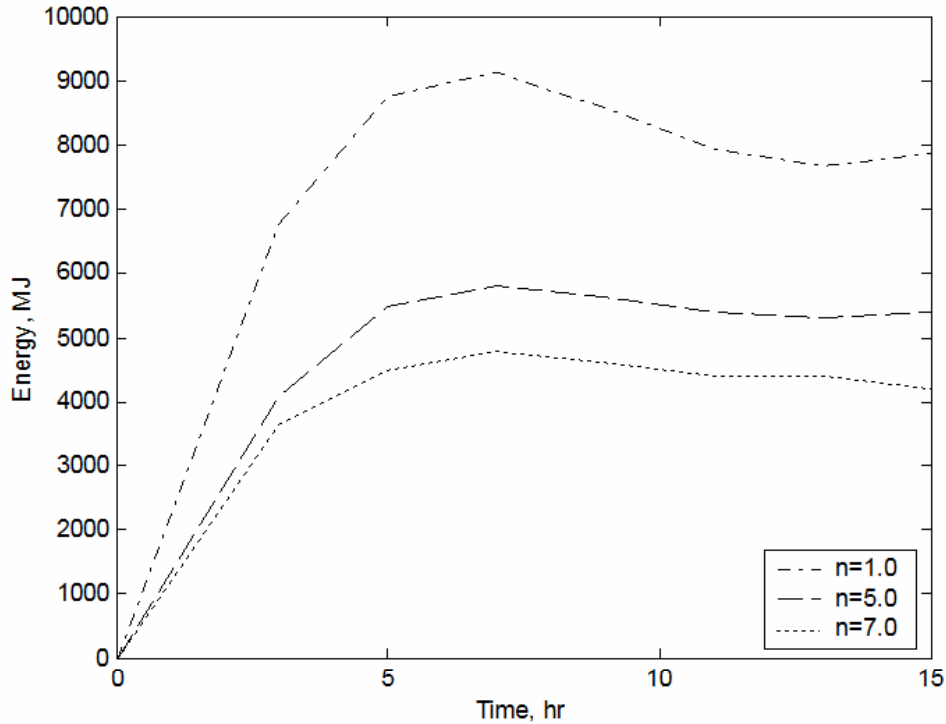
Figure 6.24. Energy Generated During the Incineration Process of PCBs for Different Number of Chlorine Atoms and 0.1 amount of Excess Air.

This energy can be calculated by using equation 3.15 that relates the energy with temperature as follows:

$$U_{tot} = M_{solid} C_{vS} (T_{gas} - T_{ref}) + M_{gas} \sum_i \frac{M_i}{\sum_i M_i} \int_{T_{ref}}^{T_{gas}} C_{vi}(T) dT \qquad (3.15)$$

Where the model results for temperature and mass hold up are inserted in equation (3.15) to obtain the energy produced during incineration.

Figure 6.24 shows an increase in the energy generated as time proceeds. The maximum energy generated is for one chlorine atom. Energy produced tends to decrease as the number of chlorine atoms increases. This is attributed to the fact that part of the energy is consumed in destruction of new bonds result from the presesnce of chlorine

atoms. This behavior is similar to that of temeparture variation with number of chlorine atoms Figure 6.18.

The effect of excess air on the energy generaton is shown in Figure 6.25. The trend of decreasing the energy generated as increasing the amount of excess air is repeated. This behavior supports what is presented in Figure 6.19 of decreasing the temperature as a result of increasing the amount of excess air.
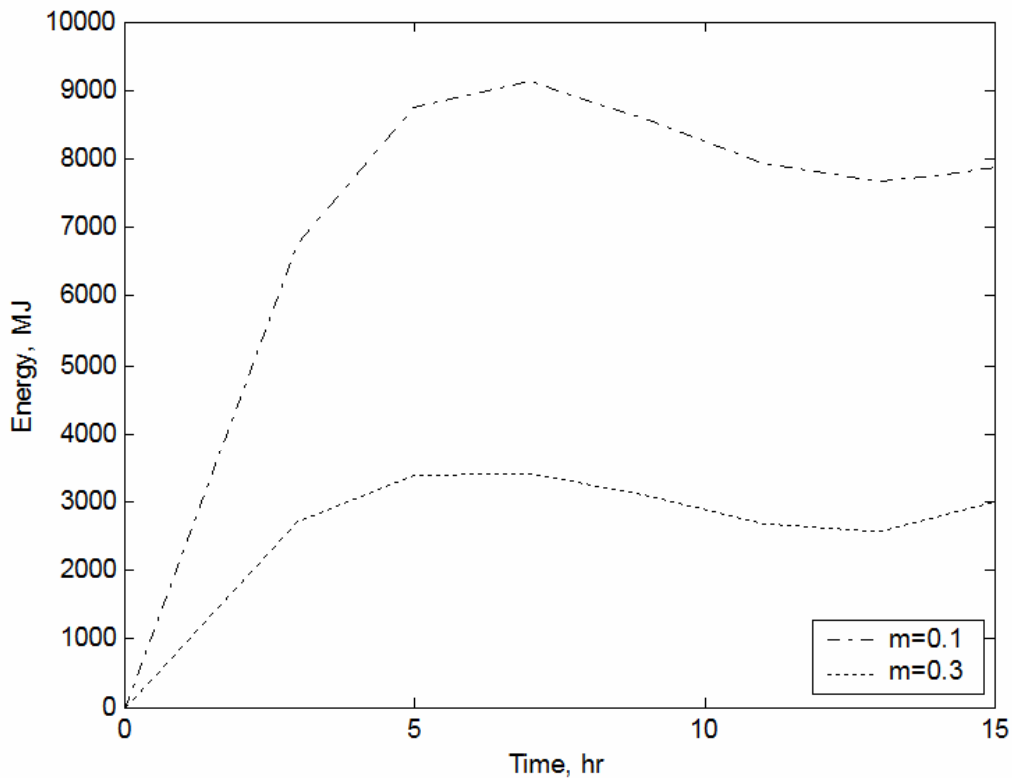
Figure 6.25. Energy Generated During the Incineration Process of PCBs for One Chlorine Atom and Different Amount of Excess Air.

Referring to the literature (Rovaglio, et al., 1999), similar commercial units for the incineration of chlorinated compounds has 0.9-1.2 MW burning capacity (waste and auxiliary fuel). The value obtained from the unit simulated for PCBs incineration in this work shows a burning capacity of 2.1 MW. This value is comparable to that presented in the literature.

The model validation will be examined by not only comparing the results obtained by PCBs incineration but also for the pure methane (auxilliary fule) combustion. The model can account for this by replacing the values that related to the waste by zero (for example the soild waste inserted into the rotary kiln i.e msin=0.0) and comparing the results by that in the published literature.

Figure 6.26 shows that the temperature obtained by the combustion of pure methane. The value of the temeprature is around 1050 K, and the profile comparison for the combustion of methane in the presence of the waste. It can be shown that the temperature increase in the the case of PCBs presence is greater than that for pure methan. This is attributed to the fact that PCBs have some inetrnal energy stored and released by incineration which can be used as energy source. However, the trend in the temperature profile is little bit differrent this is due to the fact of combustion mechanism is different by the presence of different reactions and components.
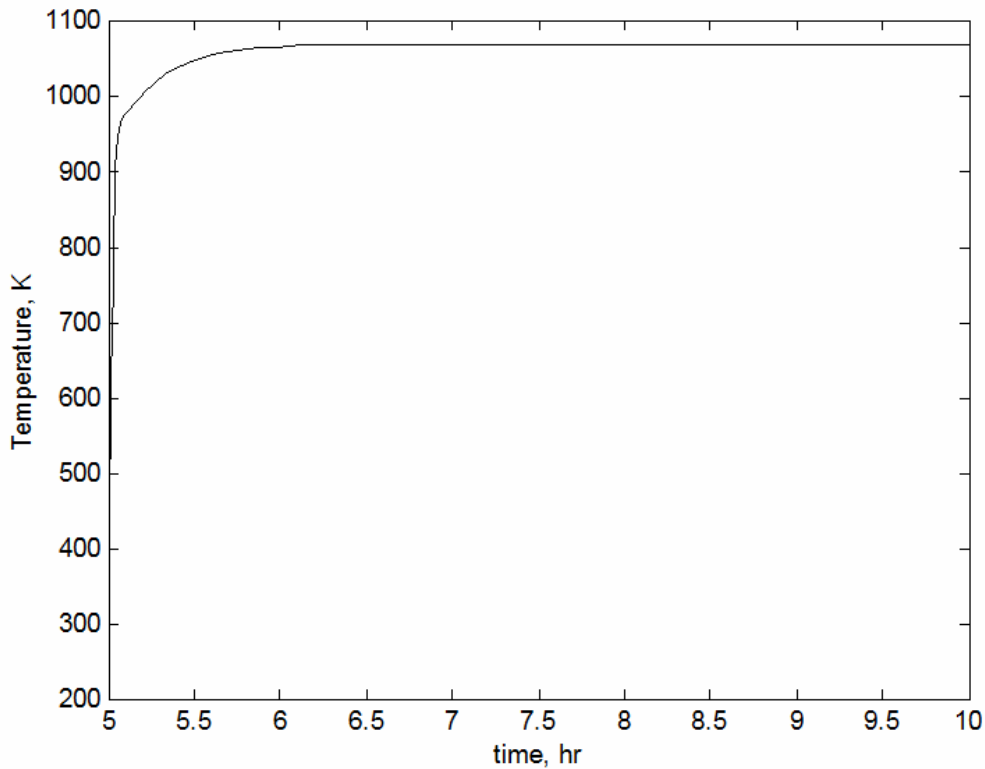
Figure 6.26-a. Temperature Profile for Pure Methane Combustion.
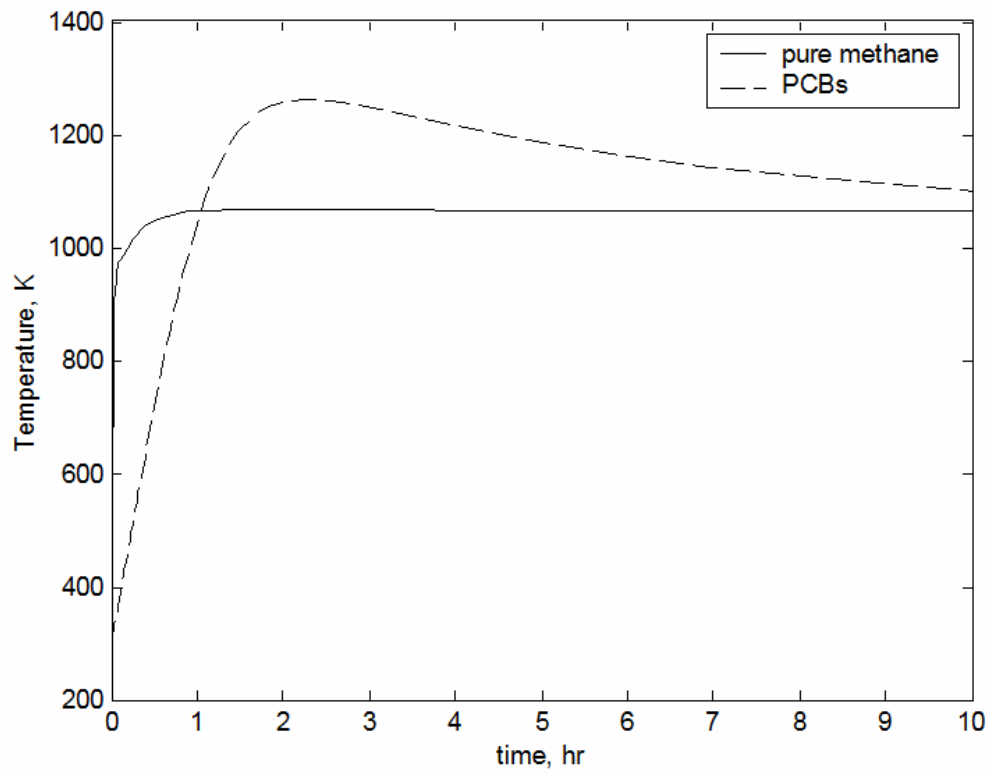
Figure 6.26-b. Comparison Between Temperature Profile for Methane Combustion Alone and Methane as Auxilliary Fule for PCBs Combustion.

The results comparison for pure methane combustion by presenting the temperature profile with oxygen mole fraction on Figure 6.27. Shows a comparable behavior between values obtained experimentally and that obtained by the model presented in this study.
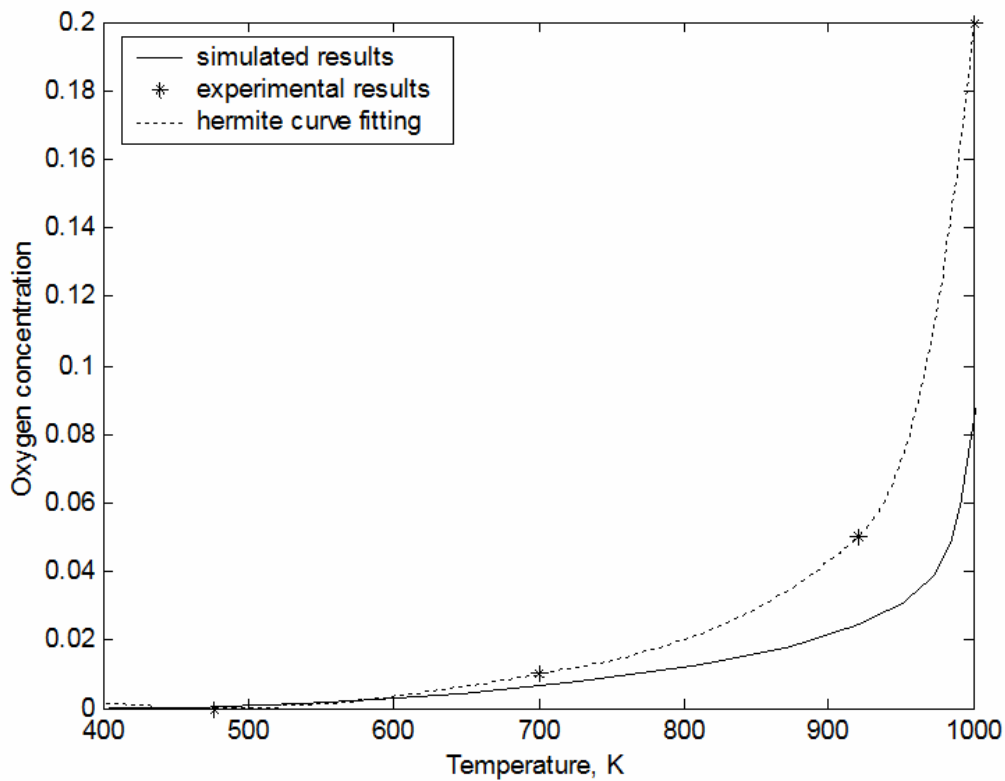
Figure 6.27. Comparison Between the Temperature Profile Related with Oxygen Concentration Simulated and Obtained Experimentally, (Baukal, 2000).

Figure 6.27 shows that same trend can be obtained by the model developed in this study and the experimental work obtained and presented in the literature (Baukal, 2000). It should be mentioned here that the oxygen concentration will decrease as time proceed and its concentration can be kept high by adjusting the excess air. Thus, Figure 6.27 shows the real behavior obtained experimentally. Once the real procedure and exact concentrations of methane gas and oxygen flow rates are known, a curve fit is shown. This curve fit is to give the exact trend of the data points which show an increase in temperature as the oxygen concentration increases.

Certain types of pollutants are expected in almost all types and conditions of incineration furan and dioxin. One of the advantages of the assumed incineration model is that traces of such pollutants are produced. The assumed plant for incineration that

includes a cooling tower will guarantee that neither furan nor dioxin is formed. That is

the cooling for 150 °C which is used as design criterion for the heat recovery units.

6.2 Steam Power Plant:

The most important parameters that affect the cycle efficiency are the temperature of

the exhaust gas and the amount of excess air. Thus the cycle calculations repeated for

different operating conditions lead to Figure 6.28 that represents the increase in the

overall efficiency of the cycle. It should be mentioned here that the calculations for the

traditional Rankine cycle lead to an efficiency of 0.29 (Smith, et al. 1996). However, the

efficiency of the modified Rankine cycle with feedwater heaters is 0.32.
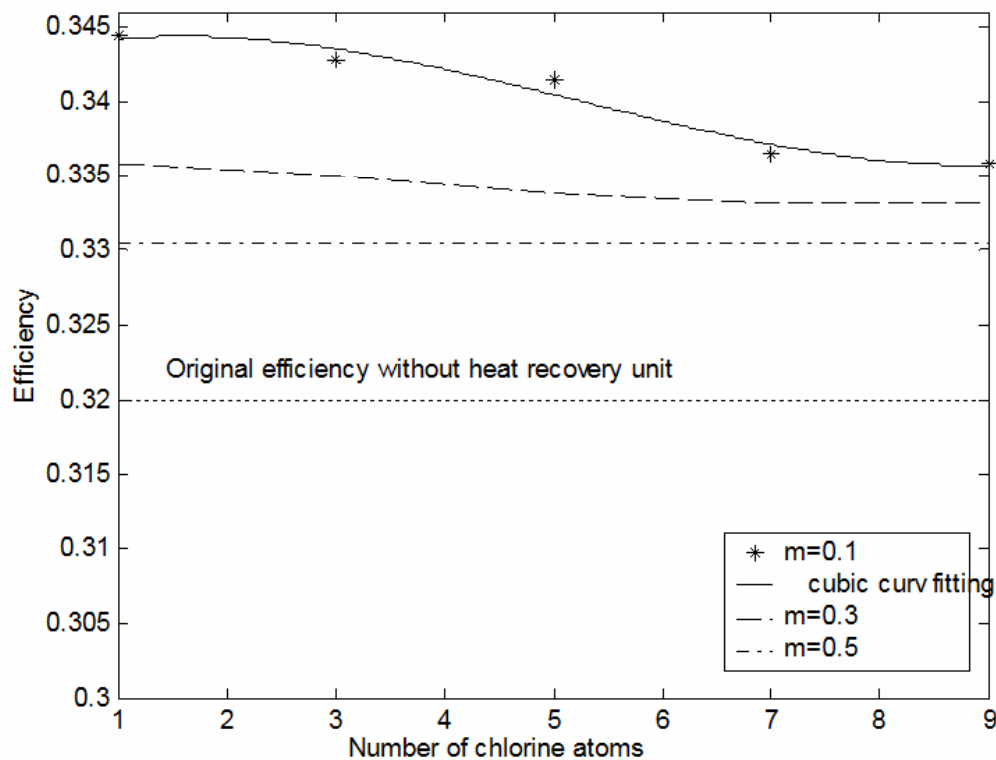
Figure 6.28: Overall Efficiency of the Cycle for one Chlorine Atom and Different Amount of Excess Air.

However, it can be clearly seen from Figure 6.28 that there is an increase in the

overall cycle efficiency to 0.34 as maximum and to 0.33 as minimum. This is attributed

to the fact that the inserted heat exchanger increases the temperature of the stream that enters the boiler which saves energy addition to the boiler and so decreases the amount of Q_{boiler} thus increases the overall efficiency.

In addition to the two factors affecting the increase in the overall efficiency. That are amount of excess air and the temperature of the exhaust gas. Figure 6.28 proves this but shows that the only parameter significantly and unconditionally affecting the overall efficiency is the temperature of the exhaust gas. The efficiency increases as the temperature of the exhaust gas increases (this is can be anticipated and indirectly noticed). It is shown in Figures 6.18-6.22 where increasing the number of chlorine atoms decreases the temperature of the exhaust gas. Thus, increasing the temperature of the exhaust gas which will enter the heat exchanger will consequently increase the temperature of the cold fluid out let temperature. Thus increasing the temperature of the stream entering the boiler makes larger saving and decreasing the heat added in the boiler and so increasing the overall efficiency.

However, increasing the amount of the excess air increasing the overall efficiency to a value greater than that with the feedwater heaters. But less than that if the exhaust gas temperature increases. This is attributed to the fact the temperature of the exhaust gas decreases as amount of excess air increases. Figure 6.20 in addition to the increase in the amount of excess air not always increases the overall efficiency. As the value of the excess air reaches value of 0.5 the overall efficiency remains the same.

Since the purpose of heating the feedwater in the manner shown in Figure 5.1 is to raise the temperature at which heat is added in the boiler. Which raises the thermal efficiency of the plant that is said to operate on a regenerative cycle. The inserted heat exchanger will also do the same job of further increase in the temperature at which heat is added to the boiler. Thus, the thermal efficiency of a steam power cycle is increased

when the pressure and hence the temperature in the boiler is raised. It is also increased by increasing the superheating in the boiler and so high pressure and temperature at the boiler results in higher efficiency.

Finally, as the amount (the feed rate of the waste is 350 kg/hr) and the type of waste incinerated determine the exhaust temperature. Different types of wastes and/or different amount of feed rate can be incinerated to calculate the new temperature of the rotary kiln. Which may affect the increase of the cold fluid enters the boiler. Since the amount of cold fluid used is larger than that of the exhaust gas (high capacity power plant 80 mega watt) the effect of the temperature increase will be limited.

Further more the size of the incinerator used will affect the increase in the temperature. Because it will affect the feed rate of the waste, a relatively small size rotary kiln is used and inserted in the cycle. The following dimensions characterize the incinerator, length of 4.43 m, diameter of 1.5 m which form a cylindrical rotary kiln that produces 96.7 kJ/kg of wastes incinerated, and this is equivalent to 3.5 kg wastes/kg of steam produced (194 kg gas/kg steam in heat recovery unit).

6.3 Energy recovery unit:

Figure 6.29 shows that there is a slight increase in the temperature of the rotary kiln as a result of the insertion of the heat recovery system. Which extracts the heat from the exhaust gas and supplies it to the fuel-air mixture. The increase in the temperature is not significant and this is due to the fact that small amount of waste is incinerated and the large amount of steam produced. This means that increasing or/and changing the amount of the waste will lead to better incineration behavior.
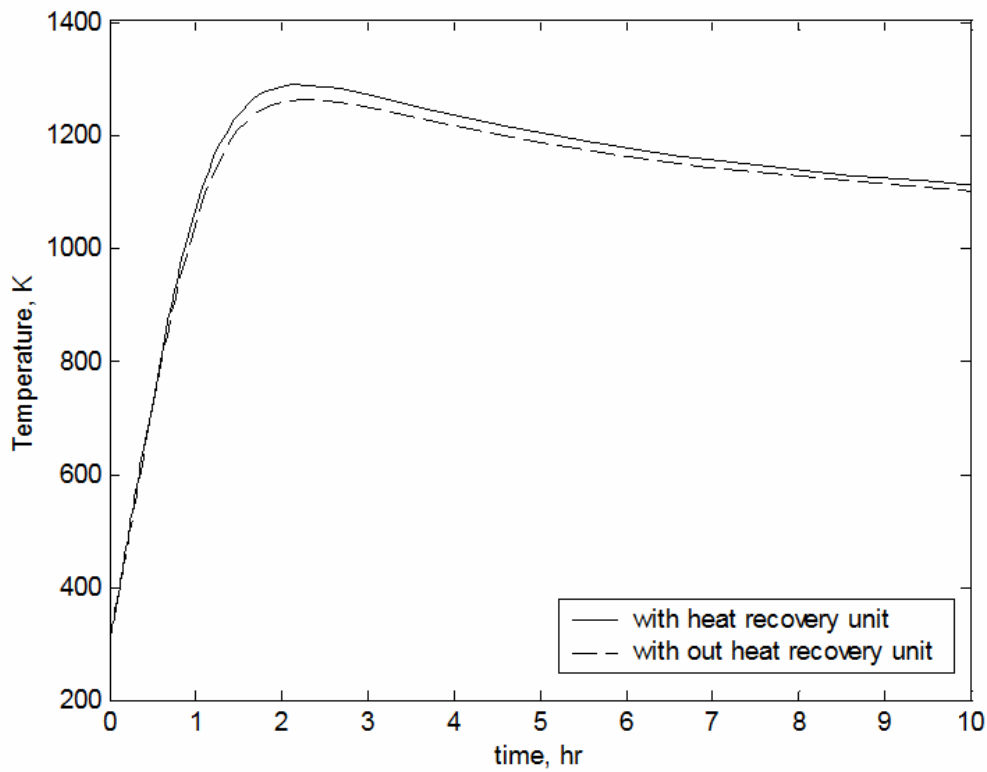
Figure.6.29 Temperature Profile for Rotary Kiln where Heat Recovery System is Added to the Process Compared to the Traditional One.

6.4 Economical analysis:

One of the aspects to show the advantages of the heat recovery unit of the rotary kiln incineration, is the economical study. Which will account for the annual savings. The idea is to save fuel consumption in the boiler that produces superheated steam.

Through the calculations it is found that 2418.6 kJ is needed to produce 100 kg/sec of steam in the traditional power plant. However, 2329.4 kJ is needed if the heat recovered from the rotary kiln by heat recovery unit, which means 89.2 kJ of energy saved. Based on real situation through field inspection to such power plants and cement factories, fuel oil 175000 tons annually rated is used to produce superheated steam with a price fluctuations ranging from (500 to 397) J.D/ton.

To calculate the expected savings, certain information is needed such as physical properties of the fuel oil (heating value, API gravity, …etc), to mak use of the above information, a simple mathematics lead to:

$$annual \text{ fuel oil savings} = (89.2\frac{kJ}{kg}*100\frac{kg}{sec})/4.7e+7\frac{kJ}{ton}$$

$$= 6000 \frac{ton}{year}$$

$annual$ savings=annual fuel saving*fuel oil price

$$=6000\frac{ton}{year}*449\frac{J.D}{ton}$$

$$= 2694000 \frac{J.D}{year}$$

This calculated value is subtracted from the annual paying for the raw material (fuel oil).

To complete the Economical study and express it in meaningful results. The minimum length of time theoretically necessary to recover the original capital investment in the form of cash flow to the project based on total income minus all costs except depreciation. Which is the payback period (Peters and Timmerhaus, 1991). The expenses can be summarized as operating costs consist of operating and maintenance (O&M) expenses. And capital charges (Department of energy United States of America , 2001), which is estimated to be around 5% from the capital investment at maximum. where the capital investment is estimated to be 12 million JD including the heat recovery units and waste disposal fees.

The graphical solution for the payback period can be performed by using an excel sheet. Where the formulas are inserted and mathematical calculations are performed. Figure 6.30 shows that
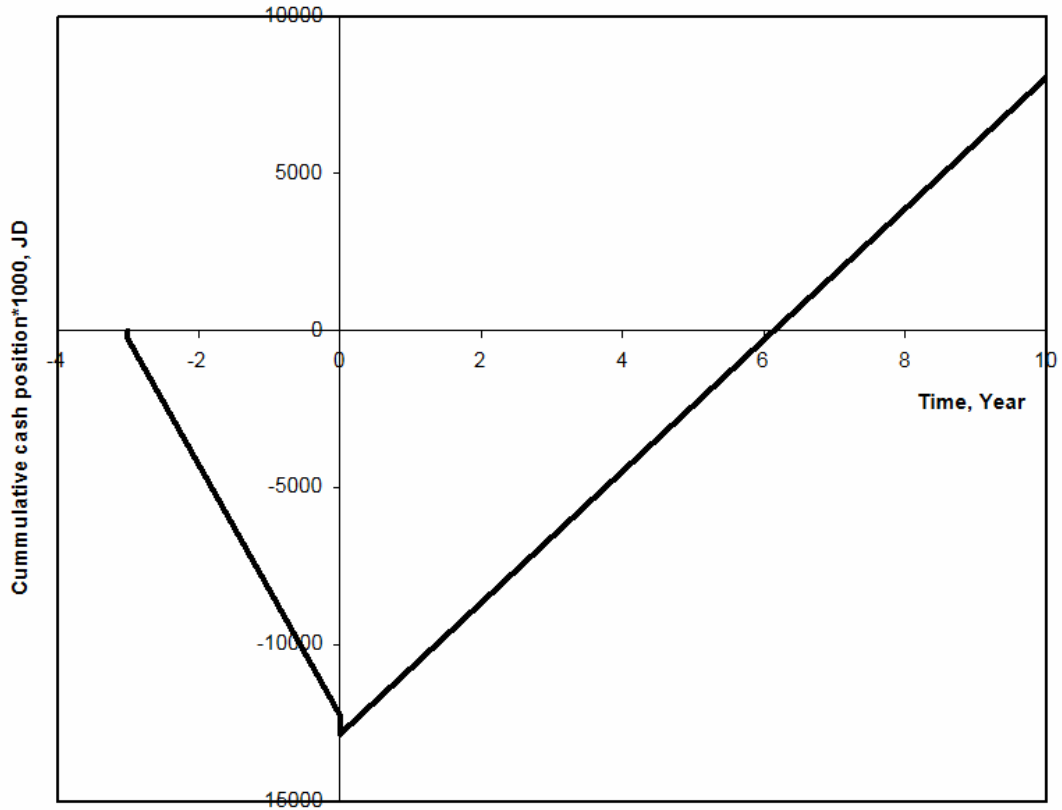
Figure 6.30: Economical Study and Payback Period for the Rotary Kiln Incinerator with Heat Recovery Unit.

It can be clearly seen that the project will return its original capital investment within about 6 years which is acceptable value.

7. Conclusions and Recommendations:

7.1 Conclusions:

A generalized model for the dynamic simulation of PCBs incineration in rotary kilns was developed. This model is able to verify the variations in operating conditions, chemical structure of the material being incinerated, and waste-feeding operations.

A heat recovery unit is used to utilize the energy produced form the incineration. The recovered heat is used to improve the efficiency of high capacity steam power plant with typical operating conditions.

The analysis of the results obtained form the model proves that the model is able to produce comparable results with soft wares designed for rotary kiln incinerators and

with the experimental results. A generalized formula for a certain type of wastes can be assumed. In addition to assumed chemical reaction, mass and energy balances are written to derive the mathematical model.

For PCBs a temperature of 1200 K is reached. The value of temperature varies depending on the number of chlorine atoms and amount of excess air. As the number of chlorine atoms and amount of excess air increases the temperature decreases. The major incineration products are carbon dioxide, water vapor, and hydrochloric acid. Their concentration in the outlet gas stream depends on the temperature, chlorine atoms in PCBs, and amount of excess air. The incineration capacity for the units simulated is 2.1 MW compared to 0.9-1.2 MW incineration capacity of similar commercial units.

The recovered heat acquired from the heat recovery unit is efficient to significantly improve the efficiency for steam power plants. The efficiency is improved to 0.34 for 80MW steam power plant when the rotary kiln and heat recovery units are used. This value is improved if compared to 0.29 for traditional steam power plant.

Brief economical analysis shows that the recovered heat provides a significant annual savings in fuel and money. The results show that the investment in establishing the rotary kiln incinerator and heat recovery unit with a payback period around 6 years. The annula saving are estimated to be 2.7 million J.D.

7.2 Recommendations:

The assumed chemical reaction is limited in its component because of the lack in available data for waste characterization. Assumptions are made throughout the model solution. Thus, for better understanding of the incineration of hazardous wastes and making use of the energy generated during the incineration process, the following are recommended:

1. Studying the variations in the composition and amount of wastes incinerated theoretically and experimentally. This combination will minimize assumptions and errors and provides more practical model.

2. Studying the changing of the type of the incinerator.

3. Trying to find further application for the heat recovered in a manner to improve the incineration process.

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Appendix A

Computer Programs

Appendix A.1: Matlab Code for incineration unit

```
function xprime=inc(t,x)
m=0.1;
n=9.0;
r=8.314;
l=4.43;
d=1.5;
v=pi*0.25*l*(d^2);
wwater=0.02;
wbf=0.5;
cppcbs=186+(17*n);
cppcbl=324+(15*n);
mwpcbl=154+(34*n);
msin=900; %kg/hr
theta=0.25; %residence time hr
mch4=45;
wo2in=((29-n)*0.5*msin)+(2*mch4);
wairin=wo2in/0.21;
wn2=wairin-wo2in;
k1=3.4e2*exp(-86041.7/(8.314*x(8)));
k2=1e2*exp(-8000.0/(8.314*x(8)));
cp2=38.9/32;
cp3=34.3/44;
cp4=29/18;
cp5=29/36;
cp6=29/16;
cv2=(39-r)/32;
cv3=(34.3-r)/44;
cv4=(29-r)/18;
cv5=(29-r)/36;
cv6=(29-r)/16;
qpcb=297600+((186+(16*n))*(x(8)-298));
qch4=802600+(34.3*(x(8)-298));
Tref=298;
Tw=(x(8)+298)/2;
% mass balance
xprime(1)=msin-(x(1)/theta)-(x(1)*wbf/(theta*(1-wbf)));
sum=x(2)+x(3)+x(4)+x(5)+x(6)+(wn2*theta);
wout=wn2+(x(7)/theta);
y2=x(2)/sum;
y3=x(3)/sum;
y4=x(4)/sum;
y5=x(5)/sum;
y6=x(6)/sum;
y7=wn2*theta/sum;
```

```
z1=(y2*32)+(y3*44)+(y4*18)+(y5*36)+(y6*16)+(y7*28);
z2=(y2*cp2)+(y3*cp3)+(y4*cp4)+(y5*cp5)+(y6*cp6)+y7;
z3=(x(2)*cv2)+(x(3)*cv3)+(x(4)*cv4)+(x(5)*cv5)+(x(6)*cv6)+(
wn2*theta*20/28);
xprime(2)=(wo2in/32)-(wout*y2/z1)-(k1*v*x(2))-(k2*v*x(2));
xprime(3)=(k1*v*x(2)*24/(29-n))-
(wout*y3/z1)+(k2*v*x(2)*0.5);
if n<5
xprime(4)=(wwater*msin/18)-(wout*y4/z1)+(k1*v*x(4)*(2*(5-
n)/(29-n)))+(k2*v*x(2));
else
xprime(4)=((n-5)*msin*18/mwpcbl)+(wwater*msin/18)-
(wout*y4/z1)+(k1*v*x(4)*(2*(n-5)/(29-n)))+(k2*v*x(2));
end
xprime(5)=(k1*v*x(2)*2*n/(29-n))-(wout*y5/z1);
xprime(6)=(mch4/16)-(wout*y6/z1)-(k2*v*x(6));
z4=(xprime(2)*cv2)+(xprime(3)*cv3)+(xprime(4)*cv4)+(xprime(
5)*cv5)+(xprime(6)*cv6);
xprime(7)=(wairin*(1+m))-
((wo2in/(wbf*msin))*x(1)*wbf/(theta*(1-
wbf)))+mch4+(wwater*msin)-wout;
%energy balance
h=0.22*3.6;
xprime(8)=(((wairin/29)*28*(x(8)-
Tref))+(qpcb*msin/mwpcbl)+(qch4*mch4/16)-(wout*z2*(x(8)-
Tref))-((518/x(8))*3.6*5.7e-8*3.14*l*d*((x(8)^4)-
((Tw)^4)))-(3.14*d*l*h*(x(8)-Tw))-
(x(1)*cppcbs*(1/mwpcbl)*(x(8)-298)/theta)-
(cppcbs*xprime(1)*(x(8)-298)/mwpcbl)-(z4*(x(8)-
298)))/((x(1)*cppcbl/mwpcbl)+z3);
w2=(y2*x(7))/z1;
w3=(y3*x(3))/z1;
w4=(y4*x(4))/z1;
w5=(y5*x(5))/z1;
w6=(y6*x(6))/z1;
xprime=xprime';
% main program cod
clc
clear

t_start=0;
t_final=10;
tspan=[t_start t_final];
xinitial=[0.0;0.008;0.0;0.0;0.0;0.0;0.04;298];
[t,x]=ode23s('incinerator2',tspan,xinitial);

% for Gases incineration only:
function xprime=inc(t,x)
m=0.0;
n=0.0;
r=8.314;
```

```
l=4.43;
d=1.5;
v=pi*0.25*l*(d^2);
wwater=0.0;
wbf=0.0;
cppcbs=186+(17*n);
cppcbl=324+(15*n);
mwpcbl=154+(34*n);
msin=0; %kg/hr
theta=0.25; %residence time hr
mch4=45;
wo2in=(2*mch4);
wairin=wo2in/0.21;
wn2=wairin-wo2in;
k1=3.4e2*0*exp(-86041.7/(8.314*x(5)));
k2=1e2*exp(-8000.0/(8.314*x(5)));
cp1=38.9/32;
cp2=34.3/44;
cp3=29/18;
cp4=29/16;
cv1=(39-r)/32;
cv2=(34.3-r)/44;
cv3=(29-r)/18;
cv4=(29-r)/16;
qpcb=(297600+((186+(16*n))*(x(5)-298)))*0;
qch4=802600+(34.3*(x(6)-298));
Tref=298;
Tw=(x(6)+298)/2;
sum=x(1)+x(2)+x(3)+x(4)+(theta*wn2);
% mass balance
y1=x(1)/sum;
y2=x(2)/sum;
y3=x(3)/sum;
y4=x(4)/sum;
y7=wn2*theta/sum;
wout=wn2+(x(5)/theta);
z1=(y1*32)+(y2*y2)+(y3*18)+(y4*16)+(y7*28);
z2=(y2*cp2)+(y1*cp1)+(y3*cp3)+y7+(y4*cp4);
z3=(x(2)*cv2)+(x(3)*cv3)+(x(1)*cv1)+(wn2*theta*20/28)+(x(4)
*cv4);
xprime(1)=(wo2in/32)-(wout*y1/z1)-(k2*v*x(1));
xprime(2)=-(wout*y2/z1)+(k2*v*x(1)/2);
xprime(3)=-(wout*y3/z1)+(k2*v*(x(1)));
xprime(4)=(mch4/16)-(wout*y4/z1)-(k2*v*x(4)/2);
z4=(xprime(2)*cv2)+(xprime(3)*cv3)+(xprime(1)*cv1)+(xprime(
4)*cv4);
xprime(5)=(wairin*(1+m))+mch4-wout;
%energy balance
h=0.22*3.6;
xprime(6)=(((wairin/29)*28*(x(6)-
Tref))+(qpcb*msin/mwpcbl)+(qch4*mch4/16)-(wout*z2*(x(6)-
```

```
Tref))-((518/x(6))*3.6*5.7e-8*3.14*l*d*((x(6)^4)-
((Tw)^4)))-(3.14*d*l*h*(x(6)-Tw))-(z4*(x(6)-298)))/(z3);
xprime=xprime';
% main program cod
clc
clear

t_start=0;
t_final=10;
tspan=[t_start t_final];
xinitial=[0;0.0;0.0;45;90*.79/.21;400];
[t,x]=ode23s('me2',tspan,xinit
```

Appendix A.2: Mathcad Program for Heat Recovery System

```
EFFECTIVENESS-NTU RELATIONSHIPS FOR HEAT EXCHANGERS

HEAT EXCHANGER CONFIGURATION                 CODE
  PARALLEL FLOW, SINGLE PASS                 SP
  COUNTERFLOW, SINGLE PASS                   SC
  1 SHELL PASS, 2N TUBE PASSES               ST
  CROSS-FLOW, STREAMS UNMIXED                CFU
  CROSS-FLOW, STREAMS MIXED                  CFM
  CROSS-FLOW, CMIN UNMIXED                   CFMIN
  CROSS-FLOW, CMAX UNMIXED                   CFMAX
  N SHELL PASSES, 2N TUBE PASSES             STN
  FINISHED WITH PROGRAM                      FI


ENTER THE HEAT EXCHANGER CONFIGURATION CODE? CFU
ENTER THE UNKNOWN (XI OR NTU)? NTU
ENTER THE VALUE OF C AND XI? 1.0,.36


HEAT EXCHANGER FUNCTION EVALUATION PROGRAM


CROSS-FLOW, BOTH STREAMS UNMIXED


C               XI                NTU
 1              .36               .6166895


IS ANOTHER CROSS-FLOW, BOTH STREAMS UNMIXED  COMPUTATION
NEEDED
?
NO


CROSS-FLOW HEAT EXCHANGER DESIGN PROGRAM USING SHAH'S
METHOD


SURFACE 1 IS KAYS AND LONDON'S 17.8-3/8W WAVY FIN SURFACE

SURFACE 2 IS KAYS AND LONDON'S 9.03 PLAIN PLATE-FIN SURFACE

LENGTH 1        LENGTH 2        LENGTH 3
 0               0               0
NUMBER OF PASSAGES FOR EACH SURFACE =   0

                SURFACE 1       SURFACE 2
ALPHA           166.9045        157.8634
SIGMA           .2904139        .6006703
CAPACITY        .48             .48


  * * * * * * * * * * * * * * *
ITERATION =    1
  * * * * * * * * * * * * * * * *
```

```
FOR SURFACE 1 (17.8-3/8W) RE1 =    627.
ENTER STPR^.667 AND FRICTION FACTOR? 0.015,0.07

FOR SURFACE 2 (9.03)       RE2 =   3436.
ENTER STPR^.667 AND FRICTION FACTOR? 0.003,0.009
FF              7.029355E-02               8.960778E-03
FIN EFF.         .9367666        .9158969
SUR. EFF.        .9435958        .9253164
AREA            824.1744        779.5293
AC              1.619621         .6899377
LENGTH           .8854318        4.299097
L3              1.297235        1.297235

FOR SURFACE 1:  SIGMA =  .2904139  AND RE1 =    627.
ENTER THE VALUE OF KC AND KE? 0.4,0.47
FOR SURFACE 2:  SIGMA =  .6006703  AND RE2 =  3436.
ENTER THE VALUE OF KC AND KE? 0.1,0.28

                SIDE 1          SIDE 2
DELP ACT        12.12278        18.37382
G               1.234857        2.898812
DELP REQ'D      8               35

  * * * * * * * * * * * * * * *
ITERATION =    2
  * * * * * * * * * * * * * * *

FOR SURFACE 1 (17.8-3/8W) RE1 =    510.
ENTER STPR^.667 AND FRICTION FACTOR?0.015,0.08
FF              8.025542E-02               8.951848E-03
FIN EFF.         .9448578        .8953721
SUR. EFF.        .9508132        .9070905
AREA            744.1211        703.8126
AC              1.876752         .5367671
LENGTH           .6899          4.989142
L3              1.29528         1.29528

FOR SURFACE 1:  SIGMA =  .2904139  AND RE1 =    541.
ENTER THE VALUE OF KC AND KE? .4,.47
FOR SURFACE 2:  SIGMA =  .6006703  AND RE2 =  4417.
ENTER THE VALUE OF KC AND KE? .1,.28

                SIDE 1          SIDE 2
DELP ACT        8.048713        34.86504
G               1.065671        3.726011
DELP REQ'D      8               35

  * * * * * * * * * * * * * * *
ITERATION =    8
  * * * * * * * * * * * * * * *
```

```
FOR SURFACE 1 (17.8-3/8W) RE1 =    540.
ENTER STPR^.667 AND FRICTION FACTOR?0.015, 0.08
LENGTH          .68884          4.994298
L3              1.295976        1.295975


FOR SURFACE 1:  SIGMA =  .2904139  AND RE1 =    541.
ENTER THE VALUE OF KC AND KE? .4,.47
FOR SURFACE 2:  SIGMA =  .6006703  AND RE2 =  4421.
ENTER THE VALUE OF KC AND KE? .1,.28


              SIDE 1          SIDE 2
DELP ACT        8.011316        34.96856
G               1.064           3.729742
DELP REQ'D      8               35


CROSS-FLOW HEAT EXCHANGER DESIGN PROGRAM USING SHAH'S
METHOD

SURFACE 1 IS KAYS AND LONDON'S 17.8-3/8W WAVY FIN SURFACE

SURFACE 2 IS KAYS AND LONDON'S 9.03 PLAIN PLATE-FIN SURFACE

LENGTH 1        LENGTH 2        LENGTH 3
 .68884          4.994298        1.295976
NUMBER OF PASSAGES FOR EACH SURFACE =  12.22618
Ok
```

Appendix B

Fact Sheet for PCBs Incineration

Appendix B1: Destruction Methods for PCBs:

Table B1-1: Methods Approved for PCBs Disposal (Rahuman, et al. 2000)

Type of PCB material	Methods
Liquid PCBs >500 ppm 50-500 ppm	PCB incinerator PCB incinerator, PCB boiler or PCB landfill
Non-liquid PCBs> 50 ppm	PCB incinerator or PCB landfill
Dredged materials and municipal sewage treatment sludge >50 ppm	PCB incinerator or PCB landfill
PCB transformers >500 ppm 50-500 ppm	PCB incinerator or PCB landfill Drain and dispose as solid waste
Other PCB-contaminated electrical equipment (except capacitors) containing 50-500 ppm	Drain and dispose as solid waste
PCB capacitors > 500 ppm 50-500 ppm	PCB incinerator PCB incinerator or PCB landfill
PCB hydraulics machine containing > 500 ppm	Drain and dispose as solid waste
Other PCB articles >500 ppm 50-500 ppm	PCB incinerator or PCB landfill Drain and dispose as solid waste
All other PCBs >50 ppm	PCB incinerator

Appendix B. 2: Experimental Results for PCBs Incineration

Table B.2-1: General Information about PCBs, (Rahuman, et al. 2000)

Basic information	Name in Chinese:	Duo Lv Lian Ben
	Name in English:	Polychlorinated biphenyls, Polychlorodiphenyls
	Molecular formula:	$C_{12}H_{10-x}Cl_x$
	Molecular weight:	PCB_3: 266.5 PCB_4: 299.5 PCB_5: 328.4 PCB_6: 375.7
	CAS code:	1336-36-3
	RTECS code:	TQ1350000
	UN code:	2315
	Hazardous goods code:	61062
	IMDG codex page No.:	9034
Physical and chemical characters	Appearance and property:	Oily fluid or white crystalline solid or non-crystalline resin
	Main application:	Used as lubricant, plasticizer, bactericide, heat carrier, transformer oil, etc.
	Melting point:	PCB_3: -19 ~ -15℃ PCB_4: -8 ~ -5℃ PCB_5: 8 ~ 12℃ PCB_6: 29 ~ 33℃
	Boiling point:	340 ~ 375℃
	Relative density（ H_2O=1）	1.44（30℃）
	Steam pressure:	PCB_3: $0.133×10^{-3}$ kPa PCB_4: $0.493×10^{-4}$ kPa PCB_5: $0.799×10^{-4}$ kPa
	Solubility:	Not soluble in water, but soluble in most organic solvents
Risks for burning or explosion	Combustibility:	Combustible
	fire rating in *the Fire Protection Standard for Building Design*	Level C
	Flash point:	195 ^{o}C/open cup
	Hazardous characters:	It will burn if contacting open fire or high heat. It can react with oxidizer. It is decomposed at high temperature to release toxic gas. Its flammability (red) is 1 and its reactivity (yellow) is 0.
	Combustion product:	CO, CO_2, HCl
	Stability:	Stable
	Polymerization hazard:	Non
	Incompatible substance:	Strong oxidant
	Method for fire control:	Foam, CO_2, dry powder, sand are used for fire control. The fire-control tools (including SCBA)

		can not provide sufficient effective protection. If carelessly contacting such substance, the victim shall evacuate from the site. The tools shall be separated. The victim shall be thoroughly decontaminated. The storage container and its parts may be shot far and near. If such substance or any fluid contaminated by such substance enters into water, the users at the down stream with potential water pollution must be informed. Notice shall be also given to local health and fire control officials and pollution control authorities. Without the distance of safety and explosion prevention, the exposed container shall be cooled by water mist.
Packaging, storage and transportation	Hazard category:	Category No. 6.1 - toxic article
	Packaging mark for hazardous goods:	14
	Packaging category:	II
	Points of attention to storage and transportation:	It shall be stored in shady and cool storehouse with good ventilation and kept far away from fire and heat source. Special personnel shall be appointed to safely keep it. The container shall be kept sealed. It shall be stored separately from oxidizer and edible chemical materials. It can not be mixed-loaded or mixed-transported with foodstuff, seed, feedstuff and various commodities. At the operation site, smoking, water drinking or eating are forbidden. During the transportation, it shall be loaded and unloaded in a light manner so as to prevent the packaging and container from damage. During the separate-loading and transportation, attention shall be paid to personal protection.
Toxic hazard	Exposure limit:	ACGIH(1)(2): (TWA)1 mg/m^3 (42% chlorine); 0.5 mg/m^3 (54% chlorine) NIOSH(1): (TWA) 0.00 mg/m^3 (applicable to all PCBs) OSHA(1): (TWA)1 mg/m^3 (42% chlorine); 0.5 mg/m^3 (54% chlorine)
	Invasion pathway:	Inhalation, ingestion, skin absorption
	Toxicity:	LD50: 1900 mg/kg (mouse oral)
	Health hazard:	It is high toxic compound as carcinogen. Long-term contact can cause liver damage and acne dermatitis. When it is used and CCl$_4$ is contacted simultaneously, the liver damage will be increased. The toxic symptom includes nausea, vomit, body weight reduction, bellyache, dropsy, icterus, etc.. IARC evaluation: 2A groups, suspicious carcinogen; the evidences for human beings are

		limited, but the evidences for animals are sufficient. NTP: suspicious carcinogen. IDLH: 5 mg/m^3; potential carcinogen NIOSH standard document: No.77-225 PCBs Health hazard (blue): 2
First-aid	Skin contact:	Soapsuds and clean water shall be used for thorough rinse. The victim shall go to hospital. The contaminated clothes and shoes shall be taken off and separated. The medical personnel shall be guaranteed for understanding of the personal protection related to such substance and pay attention to self protection.
	Eye contact:	The eyelid shall be uncovered and rinsed for 15 minutes with flowing clean water. Then, the victim shall go to hospital.
	Inhalation:	The victim shall be removed from the site to the place with fresh air. Then, the victim shall go to hospital. If the respiration of the victim is stopped, artificial respiration shall be given to the victim. If it is difficult for the victim to respire, oxygen inhalation shall be provided.
	Ingestion:	If anyone ingests such substance by accident, he/she shall drink a proper amount of warm water for vomit. The victim shall have gastric lavage and then go to hospital.
Protection measures	Engineering control:	The site shall be strictly sealed and provided with sufficient local ventilation.
	Protection of the respiratory system:	Wear gas defence respirator. If the concentration of such substance is comparatively higher in the air, self-supported respirator shall be worn. If the concentration is above that of NIOSH REL or REL is not established yet, under the condition with any detectable concentration: self-contained open-circuit compressed air full-mask respirator and positive pressure air full-mask respirator assisted by self-contained positive pressure respirator. Escape for life: Air purification full-mask respirator (gas mask) with organic steam filtrate box, self-contained escape breathing apparatus.
	Eye protection:	Wear protection glasses for chemical safety.
	Protection clothes:	Wear corresponding protection clothes.
	Hand protection:	Wear antichemical gloves
	Others:	At the working site, smoking, eating and water drinking are forbidden. After work, the working staff shall take bath and change clothes. The working staff shall keep good sanitation habit. Physical examination shall be taken before employment and afterwards regularly. Long-

		term repeated contact shall be avoided.
Leakage disposal		The contaminated area with leakage shall be segregated with warning marks around. It is suggested that the personnel for emergency treatment shall wear self-supported respirator and chemical protection clothes. The leaking substance shall not be contacted directly but be absorbed by sand or be shoveled to barrels and then dumped in open location for deep landfill. Soap and detergent shall be used to rinse the polluted ground. The wastewater from rinse shall be first diluted and then discharged into wastewater system. If there is a large amount of leakage, such substance shall be reclaimed. Environmental information: Clean Air Act: hazardous air pollutant (chapter 1, section A, article 112) Clean Water Act: article 307 - the main pollutants, article 313 - the main chemicals or article 401.15 - toxic substances Clean Water Act: with regard to the hazardous substances in article 311, the quantity of the main chemicals shall be reported (the same as CERCLA). Resource Conservation and Recovery Act: it is forbidden to store the wastes on the ground. Resource Conservation and Recovery Act: the general treatment standard of wastewater is 0.1 mg/L and that of non-liquid waste is 10 mg/kg. Resource Conservation and Recovery Act: the suggested method for groundwater monitoring list (PQL µg/L) 8080(5); 8250(100) The Safe Drinking Water Act: the maximal contamination level is 0.0005 mg/L. The Safe Drinking Water Act: the maximal contamination goal is 0. Emergency Planning and Community right-to-know Act: As for article 304, the quantity of 0.454 kg shall be reported. Emergency Planning and Community right-to-know Act: As for article 313, minimal concentration of 0.1% shall be reported in table R. Ocean pollutants: FCR 49, Subpart 172.101, index B, serious pollutants. California suggestion 65: carcinogen substance and reproductive toxic substance.

النمذجة والمحاكاة لعمليات إنتاج الطاقة من حرق النفايات ثنائية الفينيل متعددة الكلور في الأفران الدوارة

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ملخـــــــــــص

تهدف هذه الدراسة إلى تصميم نموذج رياضي ديناميكي يصف عملية احتراق واحدة مــن الملوثات الخطرة وهي مركبات ثنائية الفينيل متعددة الكلور في الأفران الدوارة. حيث تمت كتابة النموذج الرياضي باستخدام لغة (Matlab). وهذا النموذج يقوم بدراسة العوامل المـؤثرة فـي عملية الاحتراق كمكونات النفايات وظروف التشغيل. تمت دراسة تأثير التغيــر فـي الكميـات الإضافية للهواء المستخدم في الاحتراق وأثر عدد ذرات الكلورين. أظهـرت النتـائج أن عـدد ذرات الكلورين هو العامل الأكثر تأثيراً في درجة حرارة الاحتراق والطاقة الناتجة عنه والتـي يمكن الاستفادة منها.

تم استخدام نماذج رياضية مكتوبة بلغة البرمجة (Mathcad) لتصميم أجهزة اسـترجاع الطاقة وتم دراسة تأثير هذه الأجهزة على كفاءة إحدى العمليات. حيث تم استخدامها في محطـة توليد طاقة بخارية ذات قدرة كبيرة وأظهرت النتائج زيادة مهمة في الكفاءة الكلية للمحطة عـن طريق توفير في الطاقة اللازمة لتوليد البخار.

أظهرت هذه الدراسة أن عملية احتراق مركبات ثنائية الفينيل متعددة الكلور تتم على درجة حرارة ١٢٠٠ كيلفن وتعتمد درجة الحرارة هذه على عدد ذرات الكلــورين وكميـات الهـواء الإضافية زيادة عن القيمة النظرية للهواء الداخل في الاحتـراق. وأن الحـرارة الناتجــة عــن الاحتراق يمكن أن تحسن في كفاءة محطات توليد الطاقة البخارية. وأن تحسين عملية الاحتراق

يتم بتسخين خليط الهواء والوقود الداخل إلى حجرة الاحتراق بالحرارة المخزنة فـي الغـازات الناتجة عن الفرن الدوار.

وأخيراً تم التأكد من صحة نتائج النموذج الرياضي بمقارنتها مع نتائج عملية تم الحـصول عليها من وحدات حقيقية تعمل بظروف تشغيل معتادة. حيث كانت النتائج متقاربة. بالإضافة إلى ذلك تم إجراء تحليل اقتصادي لمحطة توليد الطاقة بعـد إضـافة وحـدات الاسـترجاع إليهـا. وأظهرت النتائج توفيراً مالياً سنويا يقدر بحوالي ٢،٧ مليون دينار أردني عن طريـق التـوفير بالوقود المستخدم وبفترة تقدر بحوالي ٦ سنوات لاسترجاع التكاليف.