

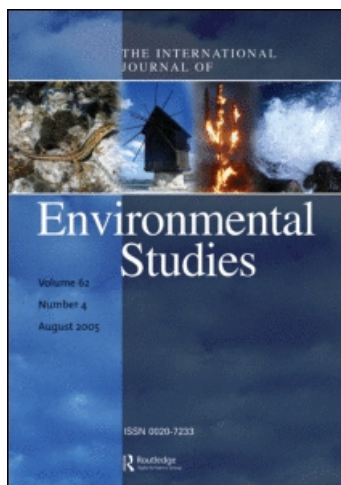
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Combustion modelling of an industrial municipal waste combustor in Malaysia

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Disposal of Municipal Solid Waste (MSW) in Malaysia by open incineration is increasingly becoming a problem. There is public concern about any pollutant emissions. Design requirements of high-performance incinerators are sometimes summarized as the achievement of 3Ts (time, temperature, and turbulence). An adequate retention time in a hot environment is crucial to destroy the products of incomplete combustion and organic pollutants. Turbulent mixing enhances uniform distributions of temperature and oxygen availability. Computational fluid dynamics (CFD) modelling is now in the development phase of becoming a useful tool for 3D modelling of the complex geometry and flow conditions in incinerators. CFD flow simulations can already permit detailed parametric variations of design variables. CFD modelling of an industrial scale MSW incinerator was done using FLUENT. The 3D modelling was based on conservation equations for mass, momentum and energy. The differential equations were discretized by the Finite Volume Method and were solved by the SIMPLE algorithm. The k- ϵ turbulence model was employed. The meshing was done using Gambit 2.0. The cold flow simulations were performed to develop the flow and velocity field. Numerical simulations of the flow field inside the primary and secondary combustion chambers have provided the temperature profiles and the concentration data at the nodal points of computational grids. Parametric study was also done to minimize the NO_x emissions.

Keywords: CFD; combustion; flow simulations; MSW; turbulent mixing; temperature profile

Introduction

The average amount of municipal solid waste (MSW) generated in Malaysia is 0.5–0.8 kg/person/day and has increased to 1.7 kg/person/day in major cities. Because of rapid development and lack of space for new landfills, big cities in Malaysia are now switching to incineration as the best disposal option for waste that cannot be economically reused or recycled. The major advantage is the marked reduction of the waste volume, typically by 90%, as well as the recovery of energy from burnable waste. But a major public concern over this technology is the question of the emission of pollutants in any form [1].

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The scarcity of dumping sites for MSW and the increasing environmental problems with landfill have led to more stringent regulations and increasing cost of waste disposal in many countries. Many alternative methods have been proposed, and among them, waste incineration has been gaining in popularity by significantly reducing the volume of collected material into an inert residue and at the same time producing a combination of heat and electricity.

The main components of Malaysian MSW are food, paper and plastics, which make up almost 80% of the waste by weight. The average moisture content of the MSW is about 55%, making incineration a challenging task [2].

The recent focus on incineration has been on environmental consequences, not on performance. In particular, the limitations, as well as the advantages, of incineration are being increasingly recognized [3]. Incineration is not a waste disposal method but rather a waste processing technology. Modern incinerators, though simple in concept, are highly complex machines. The heart of any incinerator is the combustion chamber where waste is burned. The overall unit includes usually various types of systems. Many forms of waste including medical, hazardous and radioactive may have to be burned. Therefore, design and operation of incinerators is a difficult task which needs effective supporting tools.

The combustion process in municipal waste incinerators is a two-step process taking place in two separate zones: the waste layer on the grate and the gas phase in the freeboard. Design requirements of high-performance incinerators are sometimes summarized as the achievement of 3Ts (time, temperature, and turbulence). An adequate retention time in a hot environment is crucial to destroy the products of incomplete combustion and organic pollutants. Turbulent mixing enhances uniform distributions of temperature and oxygen availability. In this context, the design of a combustion chamber, in which air and combustion gases pass through while participating in strong radiative heat transfer, must be analysed and evaluated [4].

CFD modelling of MSW combustion

The rising popularity of incineration of municipal solid waste (MSW) calls for detailed mathematical modelling and understanding of the incineration process. In this paper, governing equations for mass, momentum and heat transfer for both solid and gaseous phases in a MSW solid-waste incineration furnace are described and relevant sub-models are presented. The burning rates of volatile hydrocarbons in a MSW combustor of solids are limited not only by the reaction kinetics but also by the mixing of the volatile fuels with air. The mixing rate is controlled by the computer program.

Over the years, various chamber designs and air/gas flow arrangements have been tested in actual field applications. Comparative evaluation of furnace chamber designs have often relied on cold flow experiments using two-dimensional water tables and/or three-dimensional cold airflow models. Yet even these scale model experiments are expensive and are limited in their applicability. On the other hand, numerical computation has rapidly become available. This adequately accommodates the complex geometry and flow conditions in incinerators. CFD flow simulations now permit detailed parametric variations of design variables to be assessed. Many researchers have performed numerical simulation of mixing inside the combustion chamber. The maximum destruction of pollutants inside the furnace is the main objective; therefore, mixing of the cold air and hot gases and subsequent pyrolysis reaction of hypothetical organic pollutants need to be investigated. Numerical simulations of the flow field inside the combustion chamber provide velocity, temperature and concentration data at the nodal points of computational grids [5].

Nevertheless, because waste is very heterogeneous, research in this area has produced only limited knowledge about the process. The combustion process itself, with its strong interaction between gas and solid phase, is difficult to understand and subsequent pollutants cannot easily be traced back to their source. Therefore, there is a great need for deeper investigation into different aspects of the process and especially into the matter of controlling pollution at source.

MSW combustor design

The existing industrial MSW combustors consist of a Primary and Secondary Combustor. The given arrangement of the combustor is shown in figure 1. The specific features of the MSW combustor which have been used for modelling purpose are as follows:

- i) The MSW inlet is placed at the bottom of the primary combustor.
- ii) The primary air supply is from the sides of the primary combustor, as shown in figure 2.
- iii) The primary burners are introduced for heat supply.
- iv) Similarly, the two secondary burners are placed for complete combustion of organic compounds in secondary combustors.
- v) The MSW and wood wastes inlet is simulated from the bottom of the primary combustor, as shown in figure 3.

The MSW characteristics are given in tables 1 and 2.

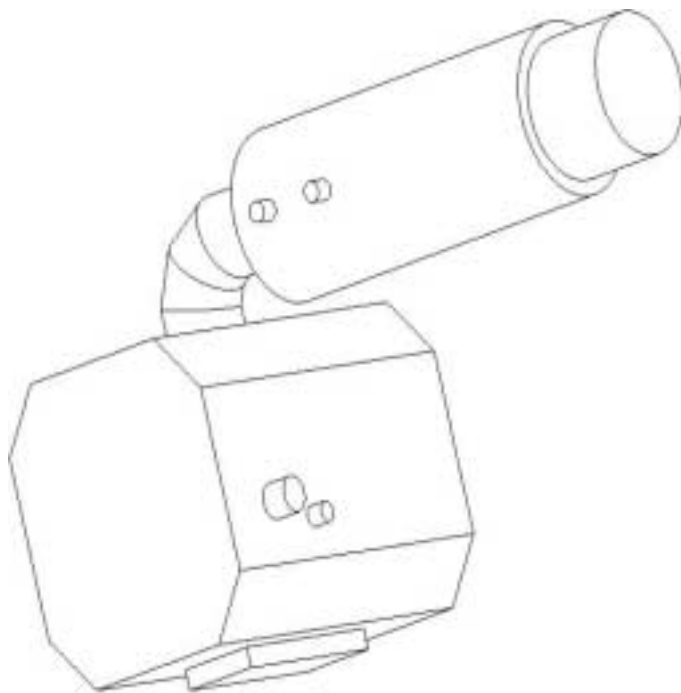


Figure 1. Basic design of combustor used for simulation.

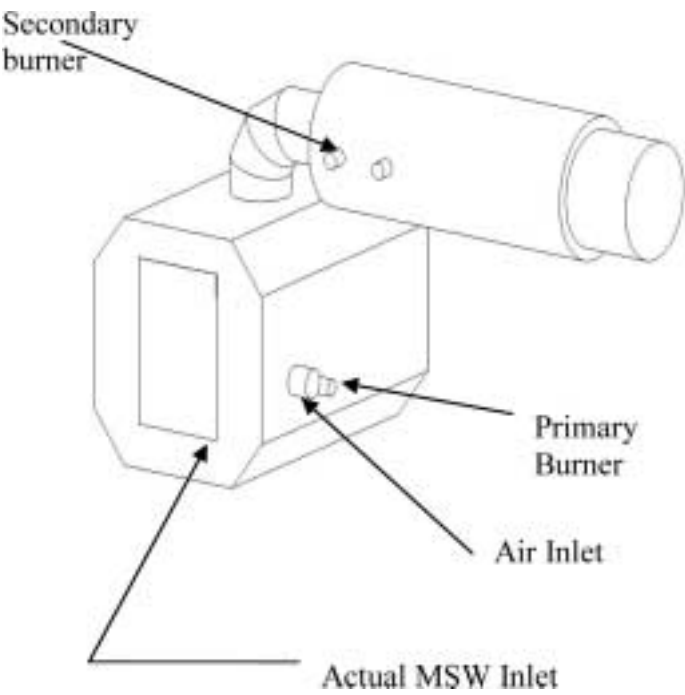


Figure 2. Locations of fuels and air inlet ports.

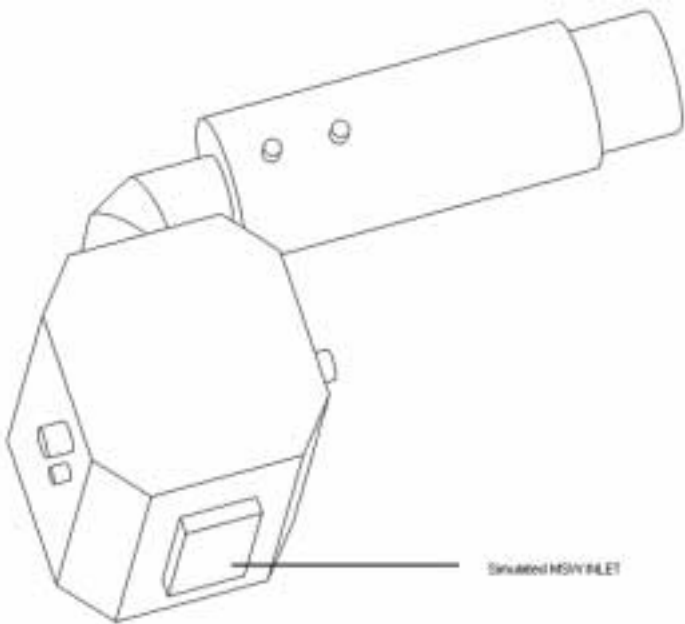


Figure 3. Simulated inlet for MSW and wood wastes.

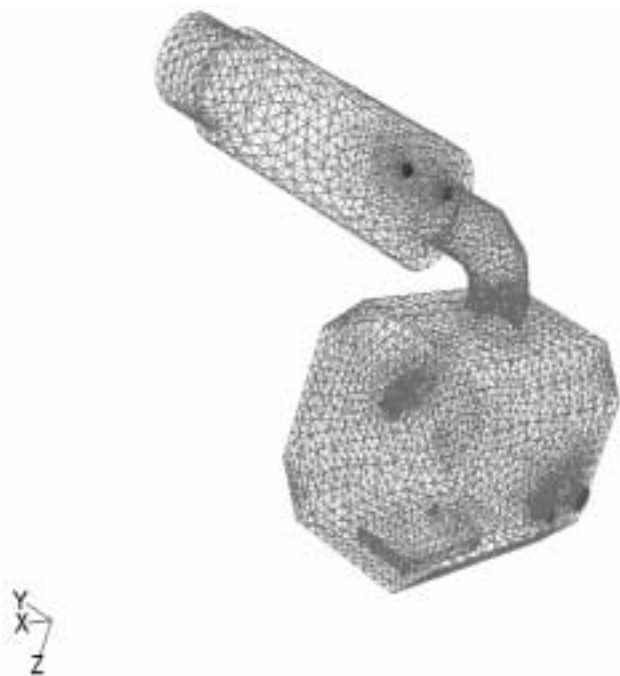


Figure 4. Meshing of combustor using Gambit 2.0.

The meshing was done using Gambit 2.0. In order to have a smooth meshing, fine meshing was done but care was also given to computational time. Currently work is being done for simulation of MSW flow in primary and secondary combustors. A typical computational grid is shown in figure 4.

Fluent modelling

Accurate modelling of the sophisticated thermal and chemical processes in packed-bed incineration of waste is a challenge to scientists, because of the wide variations in waste composition and the many different pollutants they may generate. Nevertheless, mathematical modelling is a necessity, and a comprehensive and advanced computer program needs to be

Table 1. Fuel quality of MSW

Type	Quantity (tonnes/day)				Calorific value (MJ/kg)		
	5.13				6.0		
Municipal Solid Waste	Dry basis (%)						
(MSW)	C	H	N	S	O	Ash	Moisture
	46.2	6.9	1.3	0.2	28.2	17.2	55

Table 2. Fuel quality of mixture of MSW and wood wastes (off-cuts)

Type	Quantity (tonnes/day)				Calorific value (MJ/kg)		
MSW	4.070				6.0		
Wood wastes (off-cuts)	1.580				15.3		
	Dry basis (%)						
	C	H	N	S	O	Ash	Moisture
MSW	46.2	6.9	1.3	0.2	28.2	17.2	55
Wood wastes (off-cuts)	51.8	6.4	1.4	0.1	32.6	7.7	37.2

developed which can predict not only the burn-out of various wastes but also the formation of major pollutants and toxic materials [6].

Most work, however, has been more on the empirical side. These studies usually have not given the spatial details of the incineration processes within the packed-beds. This paper concerns, on a more detailed scale, the issue of modelling. The whole bed and the freeboard area above are divided into many small volumes. The transport equations concerning the flow, heat transfer and combustion of the solid and gas phases are then discretized over these volumes or cells, and solved iteratively over the whole computation domain. The computation gives the results on the distributions of temperature, waste components, gas species and other properties both within the bed and in the freeboard space. Other features of the work include visualization of the channelling effect and analysis of the transient effects of changing the waste input or other bed operating conditions [7].

The FLUENT modelling is based on the three-dimensional conservation equations for mass, momentum and energy. The differential equations are discretized by the Finite Volume Method and are solved by the SIMPLE algorithm. As a turbulence model, the $k-\epsilon$ was employed. This comprises two transport equations for the turbulent kinetic energy and its dissipation rate. The FLUENT code uses an unstructured non-uniform mesh, on which the conservation equations for mass, momentum and energy are discretized. The $k-\epsilon$ model describes the turbulent kinetic energy and its dissipation rate and thus compromises between resolution of turbulent quantities and computational time [8]. In order to simulate combustion of MSW, the models used in FLUENT are shown in table 3.

Table 3. List of FLUENT models used in simulation

Model	Settings
Space	3D
Time	Steady
Viscous model	Standard k-epsilon turbulence model
Wall treatment	Standard Wall Functions
Heat transfer	Enabled
Radiation model	P1 Model
Species transport	PDF ((species)
Combustion model	Non Premixed Combustion

The heterogeneity of the MSW and lack of information about the physical properties of MSW makes it difficult to do combustion modelling. The simulations were done for both MSW and mixture of MSW and wood. A long time passed before a solution could be obtained. To achieve a converged solution, the code had to run for 18,000 iterations.

Results and discussions

A 3-D combustor was modelled using FLUENT Version 6.1, which incorporates the various sub-process models and solves the governing equations for both gases and solids. Thermal and chemical processes are mainly confined within the burning bed. The combustion simulation was done for both MSW only and the mixture of MSW and wood wastes. From the simulation results it was evident that for a large part of the burning process, the total mass loss rate was constant until the solid waste was totally dried out and a period of highly rising carbon monoxide (CO) emission followed. The maximum temperatures in the primary combustors for MSW and mix fuel combustion were around 1600 K and 1900 K respectively.

Temperature profiles for both the combustors region are shown in Figures 5 and 6. According to simulations, the temperature is low near the primary air inlet, but as the flow of MSW moves towards the primary combustor's exit the combustion process starts and temperature rises. A gradual increase in temperature follows until the flow reaches the connector between primary and secondary combustor, where roughly it has a constant temperature of about 1300 K.

The fuel-mixing region in the primary combustor of mixed fuel is smaller than in the MSW primary combustor. This is caused by the higher temperature and more turbulent mixing in that region. This may be also attributed to the channelling effect. Channelling causes the feed air to bypass the normal void portions between the MSW particles and escape through

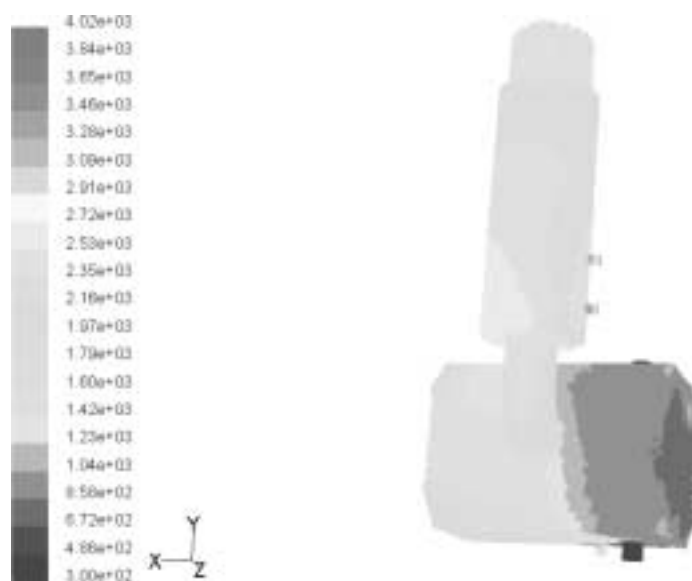


Figure 5. Contours for static temperature for MSW combustion.

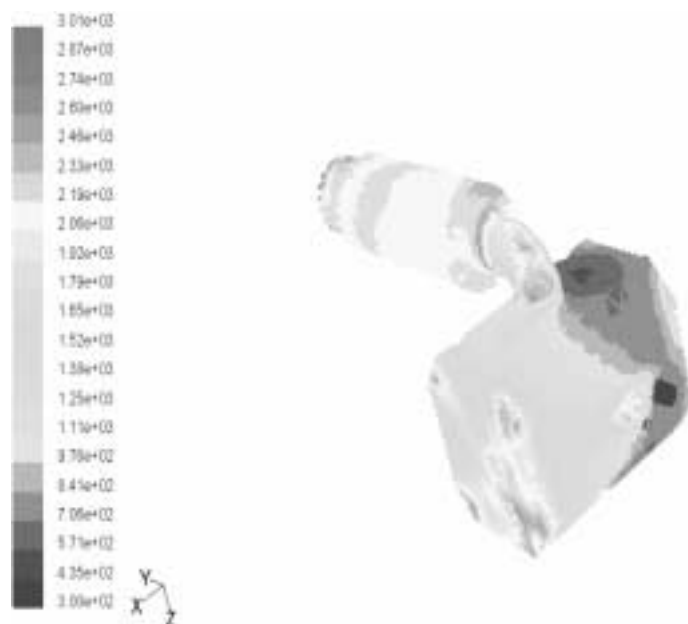


Figure 6. Contours for static temperature for mix fuel combustion.

short-cuts or big holes in the bed to the over-bed space without the expected reaction with those particles. Because of this and depending on the scale of channelling, the temperature distribution across bed is no longer uniform, and the bed conditions drift away from the ideal uniformity [9,10]. A significant temperature increase occurs as the flow enters the secondary combustor, because of the presence of secondary burners. The temperature reaches its highest value of 1900 K.

This is higher than the maximum temperature in MSW combustion only (about 1300 K). This is as it should be. Model prediction indicates that the combustion mode in this region is mainly by carbon or char burning. Turbulent flow in a packed bed of solids is quite different from flow inside a duct. Large-scale turbulence is possible within a packed bed due to the restriction imposed by the narrow and irregular channels through which fluid has to pass, and the spectrum of turbulence moves towards smaller scale. This means an increase in dissipation rate of turbulent kinetic energy. Particle resistance to the flow becomes much more important and the subsequent large pressure drop will dominate the flow field distribution [11].

A vital area for fundamental investigation includes such problems as transient phenomena, such as the breaking of waste particles, and the 'catastrophic' creation of new burning channels occurring during waste incineration. The underlying theory of bed behaviour must be extended to include these transient events. Most of the combustible material in waste is burned in the bed and its immediately adjacent freeboard region, producing carbon dioxide (CO_2) and water (H_2O) [12].

Figures 7–10 demonstrate the mass fractions of CO_2 and CO in both types of combustors. The temperature rose sharply within the primary combustors. In the secondary combustors, the CO_2 has converted to CO due to high temperature in those sections. The fluctuations in the gaseous concentrations were caused by the channelling phenomenon in

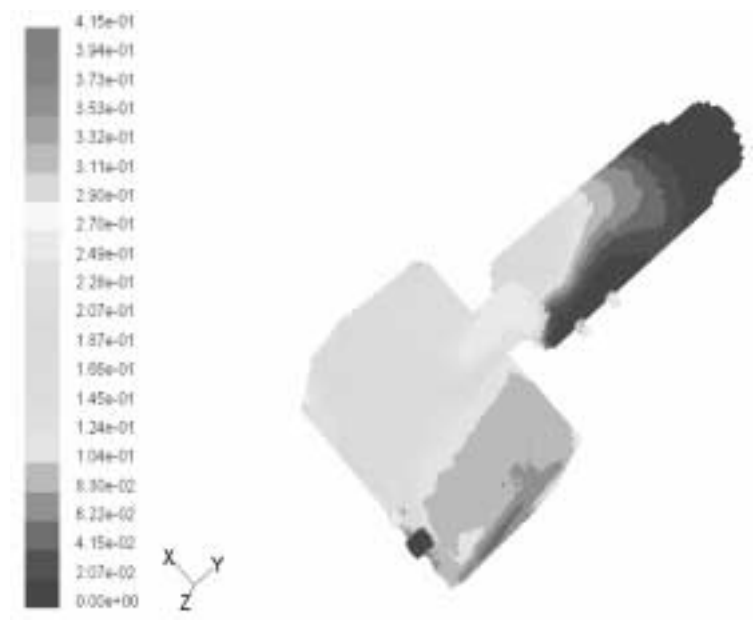


Figure 7. Contours of mass fraction of CO_2 for MSW mode only.

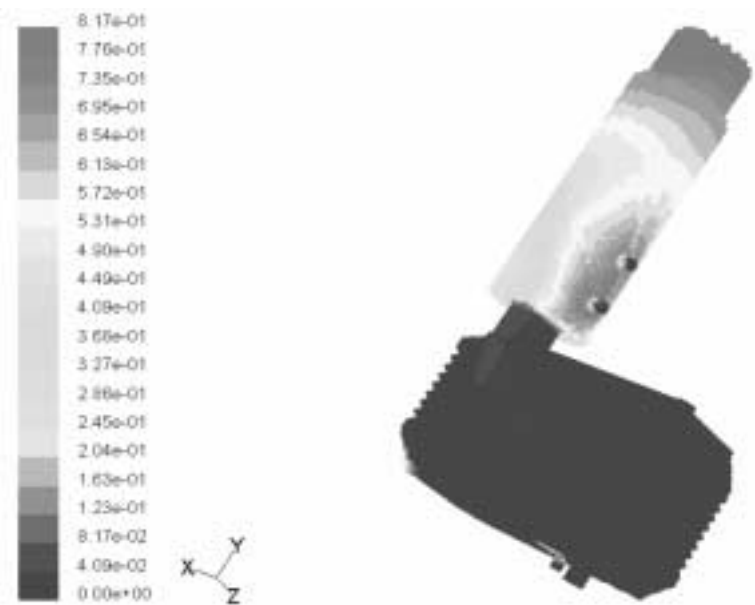


Figure 8. Contours of mass fraction of CO for MSW mode only.

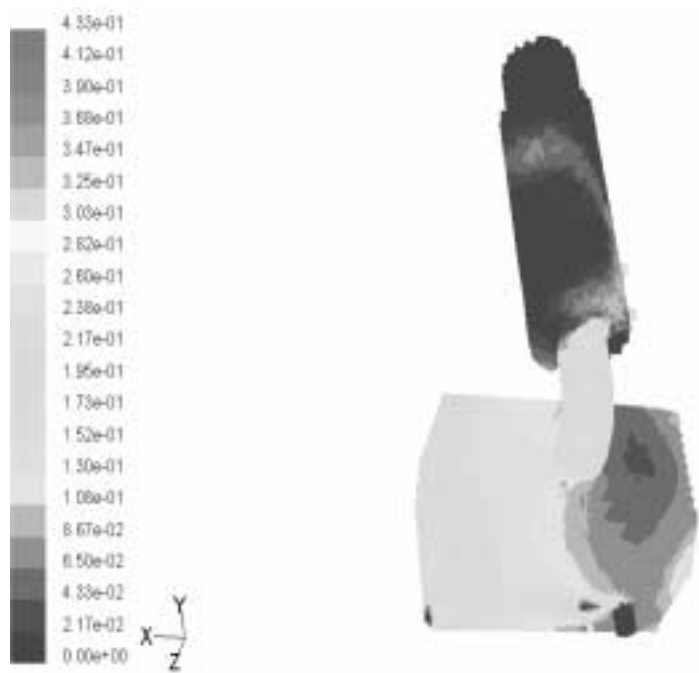


Figure 9. Contours of mass fraction of CO_2 in mixed fuel mode.

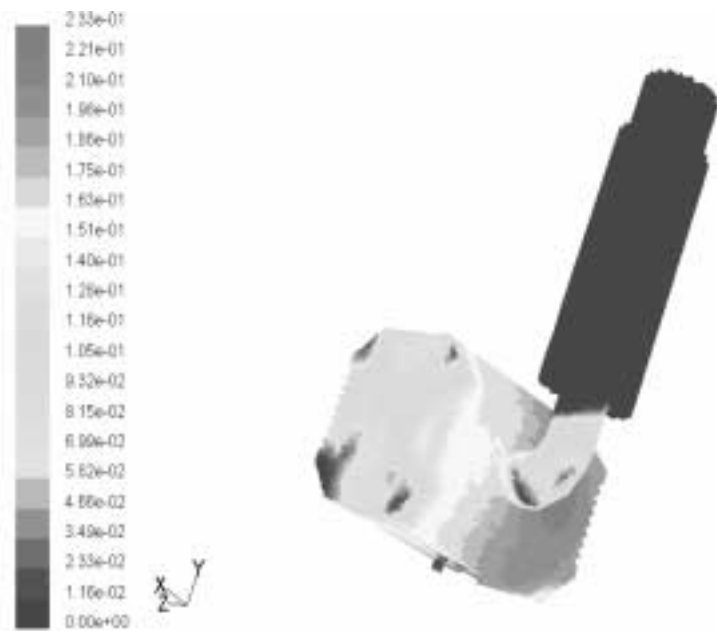


Figure 10. Contours of mass fraction of CO in mixed fuel mode.

the bed and a subsequent catastrophic change (e.g. sudden local collapse of the bed) in local bed conditions including void fraction, particle surface area, etc. [13]. Bed channelling is an unwanted phenomenon because it reduces the efficient contact between feed air and burning solids, resulting in low combustion efficiency. This is a very important phenomenon in practical situations, although many designers of MSW incinerators try to avoid this by proper grate design that creates right disturbances in the bed [14].

The high CO region in the secondary combustor corresponds to the end of moisture evaporation in the waste, faster devolatilization of the solids, and combustion of volatile gases and fixed carbon. The insufficient air in the secondary combustor results in high CO concentration in the region, which is towards the end the whole combustion process. As can be seen from figures 11 and 12, the consumption of oxygen (O_2) is more pronounced in mixed fuel configuration, as combustion is more rapid due to the introduction of wood off-cuts.

A different situation occurs in case of nitrogen oxide (NO_x) emissions. Kinetic effects along with other factors are more important. NO_x emissions depend not only on the type of combustion technology but also on its size and the type of fuel used [15,16]. For a detailed investigation of combustion chambers, some comprehensive models for simulation of fluid flow, heat transfer, combustion and pollutant formation based on CFD are needed. FLUENT has the capability of predicting the Thermal, Prompt and Fuel NO_x . From figures 13–16 it is evident that the nitrogen dioxide (NO_2) formation is more pronounced in MSW. This has resulted in more NO_x production. The estimated NO_x for MSW fuel only are about 1500 mg/m³ and for mixed fuel they are 735 mg/m³.

Although the MSW combustion modelling is a difficult and time consuming job, even better combustion results can be obtained if certain modifications can be made in the existing unit. But before this, certain simulations must be done based on current design trends.

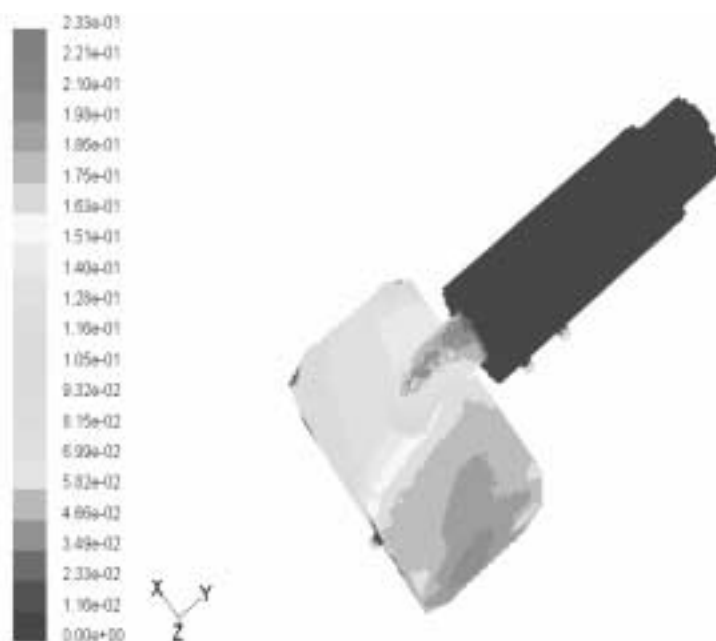


Figure 11. Contours of mass fraction of O_2 for MSW mode only in combustor.

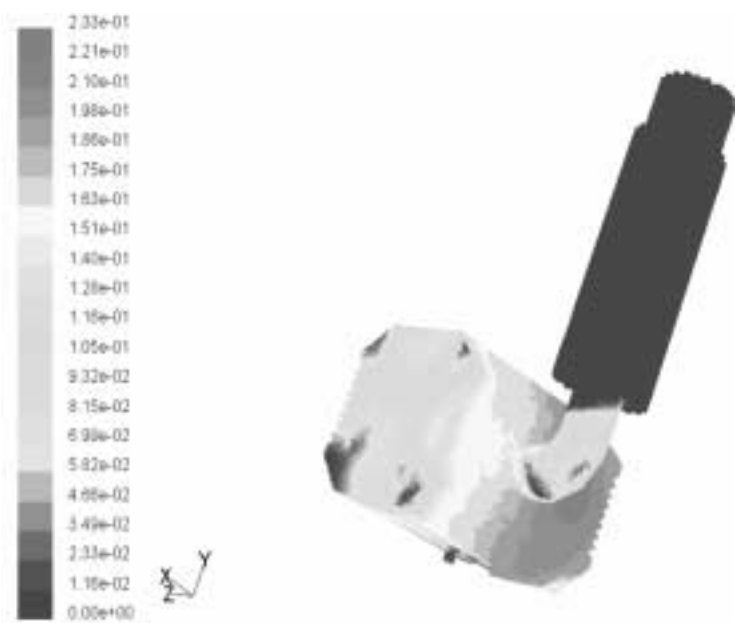


Figure 12. Contours of mass fraction of O_2 for mixed fuel in combustor.

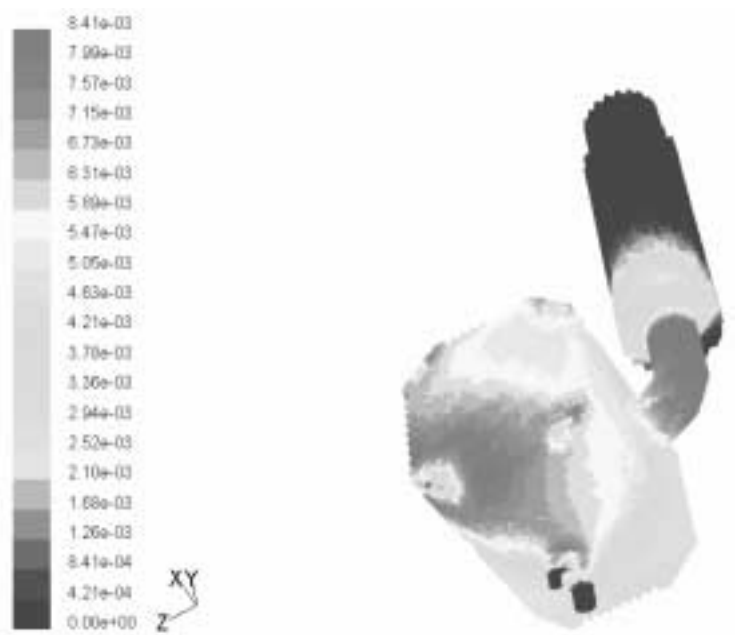


Figure 13. Contours of mass fraction of NO for MSW in combustor.

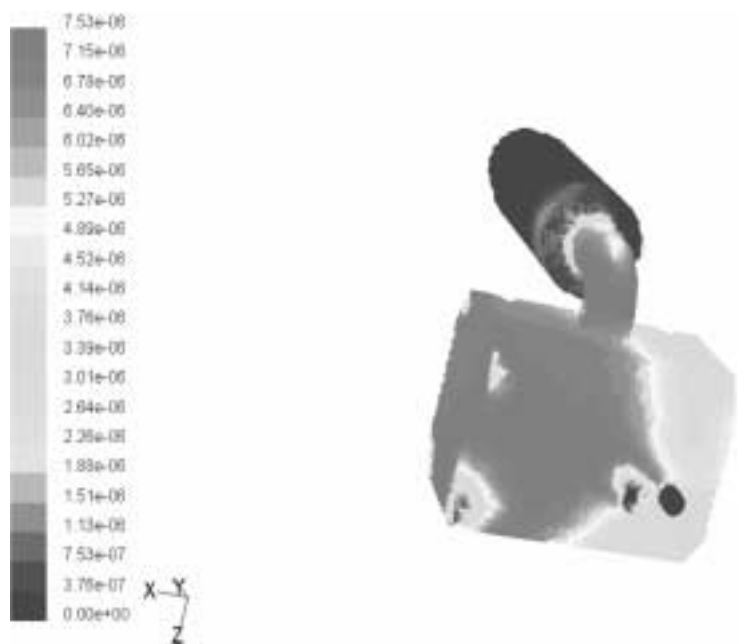


Figure 14. Contours of mass fraction of NO_2 for MSW in combustor.

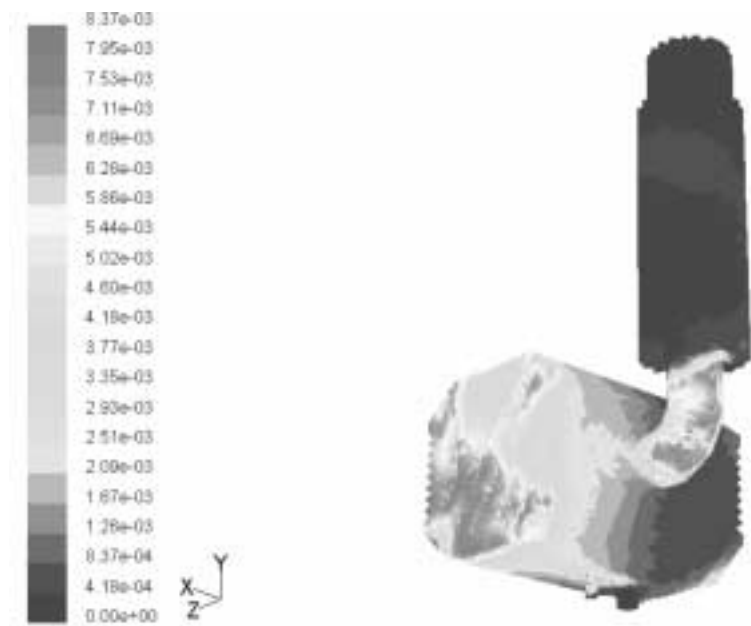


Figure 15. Contours of mass fraction of NO for mixed fuel in combustor.

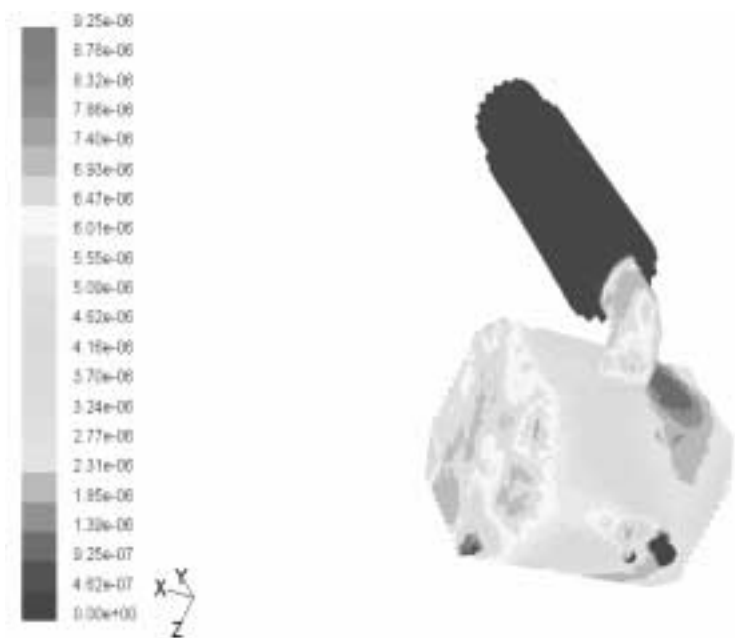


Figure 16. Contours of mass fraction of NO for mixed fuel in combustor.

The existing MSW combustors worldwide employ grate design, which is shown in figure 17, so it will be worthwhile to see combustion simulations with this kind of geometry while keeping the operating conditions of our actual MSW combustor. The new grid geometry incorporates the inclined grate.

The existing geometry of the combustor can be modified to adopt the configuration of current MSW combustors, as shown in figure 18. The grates have been explicitly provided for drying, primary combustion, after burning zone and ash collection. Separate inlets for MSW and air have been provided to facilitate the Non Premixed combustion modelling in FLUENT. Another view of the combustor is shown in figure 18.

In order to make the combustor closer to modern grate combustors, holes have been provided in the Zone 1 and Zone 2. In each of the zones there are six holes of 60 mm diameter. This arrangement is illustrated in figure 19. The simulation work can be done to obtain results related to grate design.

Conclusions

A 3-D combustor modelling was done using FLUENT. Simulation results predict that for a large part of the burning process, the total mass loss rate was constant until the solid waste was totally dried out and a period of highly rising CO emission followed. The maximum temperature in the primary combustors for MSW and Mix fuel combustion were found to be 1600 K and 1900 K respectively. The high CO region in the secondary combustor corresponds to the end of moisture evaporation in the waste, faster devolatilization of the solids, and combustion of volatile gases and fixed carbon. It was also found that the consumption of

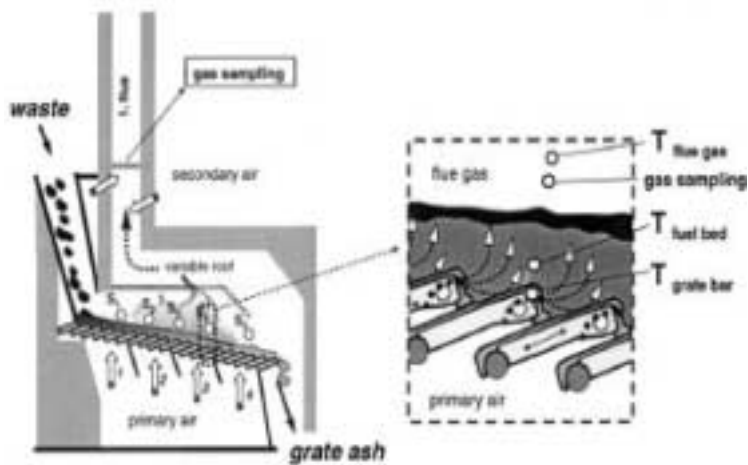


Figure 17. Grate design of current MSW combustor (from Frey [16]).

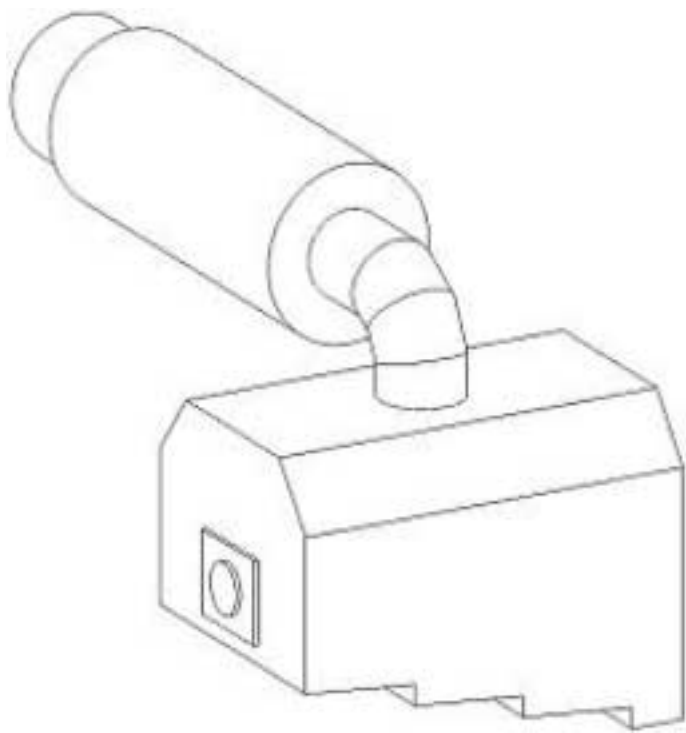


Figure 18. Modified design of combustor to accommodate grate design.

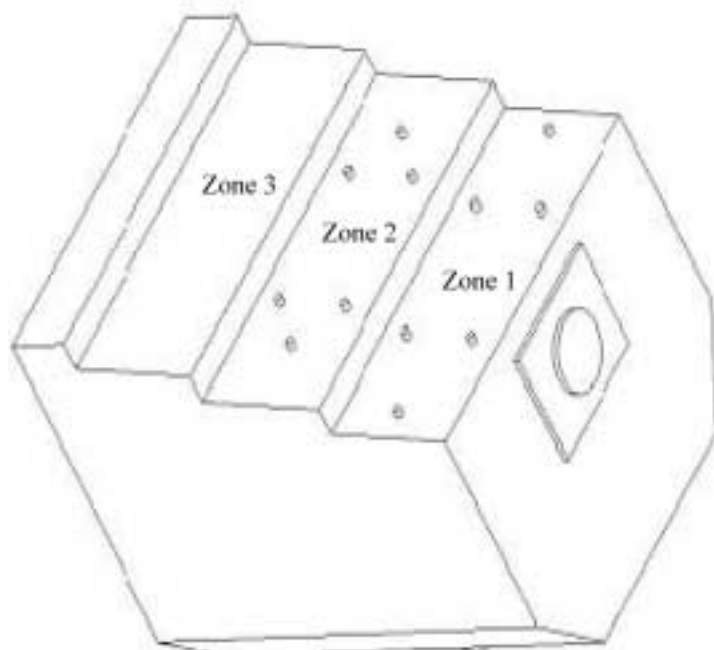


Figure 19. Holes for providing air as done in current grate design.

O₂ is more pronounced in mixed fuel configuration, as combustion is more rapid due to the introduction of wood off-cuts. The estimated NO_x for MSW fuel only were 1500 mg/m³ and for mixed fuel 735 mg/m³.

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