CFD Modeling of Grate Furnace Designs for Municipal Solid Waste Combustion

Ahmad Hussain
Email: ahassain@kau.edu.sa

King Abdulaziz University, Rabigh 25911, Saudi Arabia

Abstract 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. As rapid development continues, so does the amount of MSW and thus a lack of space for new landfills. Thus a better way of disposing MSW would be to incinerate. The basic design requirements of high-performance incinerators are the 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. Also turbulent mixing enhances uniform distributions of temperature and oxygen availability. With today's ever increasing computer power, CFD modeling has now become a useful tool for modeling complex geometry and flow conditions in the incinerators. CFD combustion and flow simulations can enable detailed parametric variations of design variables. Bed combustion was done using FLIC 2.3C and the CFD modeling of an industrial scale MSW incinerator design was done using FLUENT Ver. 6.2.18. The 2D modeling was based on conservation equations for mass, momentum and energy. The k-ε turbulence model was employed for turbulent flow modeling. The meshing was done using Gambit 2.2.3. The Generalized Finite Rate model was used to simulate hot flow inside the chamber. Simulations have resulted in predicting the combustion behavior in various grate furnace designs. The emissions behaviour in various sections of the combustors have been modeled to a reasonable accuracy.

Keywords: Bed combustion, CFD, FLIC , emissions, flow simulations, MSW, temperatures profiles, turbulent mixing, , NOx

I. Introduction

As the Malaysian economy continues to grow, so does the increment of MSW. As the population grows and prospers, land will become scarce, thus causing the lack of space for land-filling of MSW. This is not only happening in Malaysia but in all developing countries. The rate of exponential expansion of big cities around the globe is causing an exponential increase in the total amount of MSW. This causes a big concern among governments and city councils as land suitable for land-filling is getting less and less. Two of the most common solutions are recycling and incineration. Recycling effort among a huge population of a city is hard to coordinate as it takes a holistic approach to educate and encourage the citizens to recycle. It is an expensive solution in terms of effort and time, although it is much cheaper in terms of cost to execute. In addition, only recoverable material can be recycled such as metals, paper and glass which only take a small portion of the whole MSW. The organic portion of MSW still has to be land-filled.

However, with incineration, the volume of MSW can be reduced to as mush as 90%. The remaining by-product is either land-filled or reused to create other products such as use in ceramics or in cement aggregate. Other benefits of incineration include the destruction of toxic materials, sterilization of pathogenic wastes, recovery of energy and the re-use of some residues.

Municipal waste incineration is frequently accompanied by the recovery of energy in the form of steam or electricity generation. Incinerators can also be designed to accommodate processed forms of MSW known as refuse-derived fuels or RDF, as well as co-firing with fossil fuels. Municipal waste incinerators can range in size from small package units processing single batches of only a few tons per day to very large units with continuous daily feed capacities in excess of 250 tons. The capital investment costs of such facilities can range from tens of thousands to hundreds of millions of dollars which imposes a limitation of plant size using this method.

However, large municipal waste incinerators have the potential to be significant sources of environmental pollution. In addition to the release of acid gases (sulfur oxides, nitrogen oxides, hydrogen chloride) and particulate matter, poorly designed or operated incinerators can lead to the unintentional formation and release of persistent organic pollutants such as dioxins and furans [PCDD/PCDF], and unintentionally produced polychlorinated biphenyls [PCBs] and hexachlorobenzene [HCB]. The environmentally sound design and operation of municipal waste incinerators requires the use of best environmental practices and best available techniques to prevent or minimize the formation and release of pollutants.

II. Modeling of the Combustor

The various grate furnace designs which were considered for CFD simulations are given in Fig. 1.
The flowchart in Fig. 2 depicts the overall work plan for this simulation work. Firstly the models of the MSW combustors are drawn in Solid Works. Having been saved as a *.STEP file, the models are imported into GAMBIT for meshing and also to define the types of boundary edges. Once this is done, the properly meshed file is then exported as a *.MSH file suited for FLUENT. At the same time, the bed or solid combustion simulation is also done using FLIC to model the bed combustion to get the proper parameters to export into FLUENT to run the hot gases flow and combustion. In FLIC which is a code written at the Sheffield University of Waste Incineration Centre (SUWIC) is used to simulate waste bed combustion. Fig. 3 represents the philosophy of the waste bed combustion as done by FLIC code. Fig. 4 shows the different stages in combustion which can be modeled using FLIC. The waste available on the grate is set at 290 kg with an initial bed height of about 720mm. The iterative calculations took an approximate time of about 1 hour 36 minutes. After getting the results, the values of parameters along the grate such as the velocity, mass fraction of elements were exported into FLUENT for gas flow and combustion simulations.

The typical proximate and ultimate analyses of the simulated MSW are described in Table 1.

Table 1 Composition of MSW [1]

Proximate Analysis	**Weight (%)**
Moisture Content	55.01
Volatile matter content	31.36
Fixed Carbon Content	4.37
Ash Content	9.26
Elemental analysis (dry)	
Carbon Content	46.11
Hydrogen Content	6.86
Nitrogen Content	1.26
Oxygen Content	28.12
Sulfur Content	0.23
Ash Content	17.06

III. Combustion Modeling of MSW

In Fluent, there are basically four types of combustion models, namely the generalized finite-rate, non-premixed, premixed, and the partially premixed. All have their own distinct criteria and areas of application. However, we only look into one type of model as found most suitable for this work. This is because for the premixed and partially premixed model, the combustions occurs at the molecular level, like an explosion, and it cannot be used with the pollutant (i.e. soot and NOx)

The Generalized Finite-Rate Model approach is based on the solution of transport equations for species mass fractions, with the chemical reaction mechanism justly defined. The reaction rates are computed from Arrhenius rate expressions, from the eddy dissipation model of Mahnussen and Hjertager or from the EDC model. Models of this type are suitable for a wide range of applications including premixed, partially premixed, and non-premixed combustion. Accurate modelling of the sophisticated thermal and chemical processes in packed-bed incineration of waste is a challenge to scientists, considering the wide variations in waste composition and the many different pollutants they may be generating. Nevertheless, mathematical modelling is a necessity, and a comprehensive and advanced computer program needs to be developed which can predict not only the burn-out of various wastes but also the formation of major pollutants and toxic materials [2].

Most of the past work, however, were more on the empirical side and usually have not been able to give the spatial details of the incineration processes within the packed-beds. The current paper works on a much more detailed scale on modeling. 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 channeling effect and analysis of the transient effects of changing the waste input or other bed operating conditions [3].

The FLUENT modeling is based on the three-dimensional conversation 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-ε was employed; this consists of two transport equations for the turbulent kinetic energy and its dissipation rate. The FLUENT code utilizes an unstructured non-uniform mesh, on which the conservation equations for mass, momentum and energy are discretized. The k-ε model describes the turbulent kinetic energy and its dissipation rate and thus compromises between resolution of turbulent quantities and computational time [4]. In order to simulate combustion of MSW, the models used in FLUENT are being shown in Table 2.

Table 2: List of FLUENT models used in simulation

Model	**Settings**
Space	2D
Time	Steady
Viscous model	Standard k-epsilon turbulence model
Wall Treatment	Standard Wall Functions
Heat Transfer	Enabled
Radiation model	P1 Model
Species Transport	Generalized Finite Rate
Reactions Model	Eddy Dissipation
NOX Model	Thermal & Prompt

The profile of the bed surface was imported from the FLIC program and read into FLUENT to depict the flow of gaseous emissions from the waste bed combustion. The FLUENT NOx model provides the capability to model thermal, prompt, and fuel NOx formation as well as NOx consumption due to reburning in combustion systems. To predict NOx emissions, FLUENT solves a transport equation for nitric oxide (NO) concentration. The NOx transport equations are solved based on a given flow field and combustion solution. In other words, NOx is post processed from a combustion simulation. It is thus evident that an accurate combustion solution becomes a prerequisite of NOx prediction. For example, thermal NOx production doubles for every 90 K temperature increase when the flame temperature is about 2200 K. Great care must be exercised to provide accurate thermophysical data and boundary condition inputs for the combustion model. Appropriate turbulence, chemistry, radiation and other sub models must be employed. [5]

To be realistic, one can only expect results to be as accurate as the input data and the selected physical models. Under most circumstances, NOx variation trends can be accurately predicted but the NOx quantity itself cannot be pinpointed.

IV. FLIC Program Simulations

After having run FLIC to a bed combustion time around 1 hours and 40 minutes. The Data Group from FLIC code generated the composition of the gaseous emission at the bed top, the moisture evaporated, volatiles released and char burned. The code also predicted the t total mass loss as well as heat energy balance in the bed. The profiles of the waste bed generated from the FLIC code is shown in Fig. 5 and Fig. 6. Once all the results are done in FLIC, the profiles of gaseous emission rate and bed temperature are imported into the FLUENT program one can start gas flow modeling.

V. Combustion Simulations from FLUENT

Each simulation took around 4000 to 8000 iterations to converge. From the contours of static pressure in all three geometries we get a maximum static pressure of 0.36 Pascal to 0.11 Pascal and a minimum of -1.9 Pascal to -1.24 Pascal. These figures are small compared to the atmospheric pressure thus we can conclude that in terms of design, there should not be any trouble caused by the pressure in the chamber.

From the contours of velocity, we get a maximum velocity of 3.3 m/s in the center orientated incinerator. One can notice that the velocities of all three are at its maximum around the neck area where combustion gases exits from the primary chamber. The contours of the velocity stream shows that in the counter case, we might face some problem due to slugging, fouling and corrosion on the left-side wall around the neck area. In the third case, the parallel case, we may face the same problem at the right-side wall of the neck area. This is due to the fact that the stream of gas emissions is concentrated near the wall.

From Fig. 9, the maximum temperature for all three cases ranges from 1400K to 1440K, concentrated at the middle part of the grate. This particular area is the area where the combustion of volatiles occurs, thus the high temperature. One can conclude that the best area to recover heat from the combustion of wastes is at the middle zone of the incinerator where the highest incident radiation is around 960 kW/m^2 to 1000 kW/m^2.

The combustion of the volatiles is described in two reactions:-

$$2CO + O_2 \rightarrow 2CO_2 \qquad (1)$$

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

One can notice from the contours of the mass fraction that CO is concentrated at the middle part of the grate where devolatilization occurs from the waste bed. It is then in turn combusted with O_2 to form CO_2. We notice that the concentration of CO_2 is the highest in the middle region and O_2 the least in this region. The variation of CO2 is shown in Figure 10. The contours in Fig. 11 depicts the areas where NOx is mostly concentrated which is at the upper part of the geometries. The highest level is found in the counter geometry having a value of around 31 ppm and the lowest in the parallel geometry at around 15 ppm.

VI. Conclusion

From the results taken from FLIC and FLUENT, it was clearly shown that all the three main phases of combustion i.e., the drying zone, devolatilization zone and the char burnout zone can be clearly depicted.

The FLIC code has been accurate at simulating the bed combustion of MSW with the composition obtained from the KL MSW sampling. One can see clearly that the drying stage at the beginning of the grate and the combustion area in the middle of the grate. At the end of the grate one can also see the accumulation of ash. Similar trend can also be seen in the FLUENT simulation where the results of the FLIC code were imported into the FLUENT program.

From the FLUENT results, the maximum temperature inside the chamber is around 1400K at the primary combustion zone in the middle of the grate. The maximum incident radiation is around 1000kW/m^2 and is prominent in the middle areas of all three geometries. This means that this zone is the best area for heat recovery. Of all three designs, the thing which are of concern are slagging, fouling and corrosion in the counter and parallel geometries. As seen in the contours of velocity stream, one can notice the flow of gases concentrated on one side of the wall. Another concern that may arise is the concentration of water in the beginning zone of the parallel geometry. It seems that the retention time of water in the air is concentrated at the cone area of the combustor. This may cause some concern of corrosion due to high humidity at that area.

In conclusion, the simulation of a MSW combustor has been successfully done using the FLIC code and the FLUENT program. However further improvements can be done using the operational data of an existing MSW combustor which can be used to validate the results obtained through CFD modeling.

Acknowledgment

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References

[1] Kathiravale S., Yunus M.N.M., Sopian K., Shamsuddin A.H. and Rahman R. A. (2003) Modeling the heating value of Municipal Solid Waste. Fuel 82: 1119–1125.

[2] Yang Y.B., Sharifi V.N. and Swithenbank J. (2004) Effect of air flow rate and fuel moisture on the burning behaviours of biomass and simulated municipal solid wastes in packed beds. Fuel 83: 1553–1562.

[3] Meneses M., Schuhmacher M and Domingo J.L. (2004) Health risk assessment of emissions of dioxins and furans from a municipal waste incinerator: comparison with other emission sources. Environment International 30: 481– 489

[4] Ladislav B., Vit K., Stehlik P., Josef C. and Jaroslav O. (2002) Low NOx burners—prediction of emissions concentration based on design, measurements and modelling. Waste Management 22: 443–451

[5] Fluent 6.1, User's guide, Fluent Incorporated, USA, 2011.

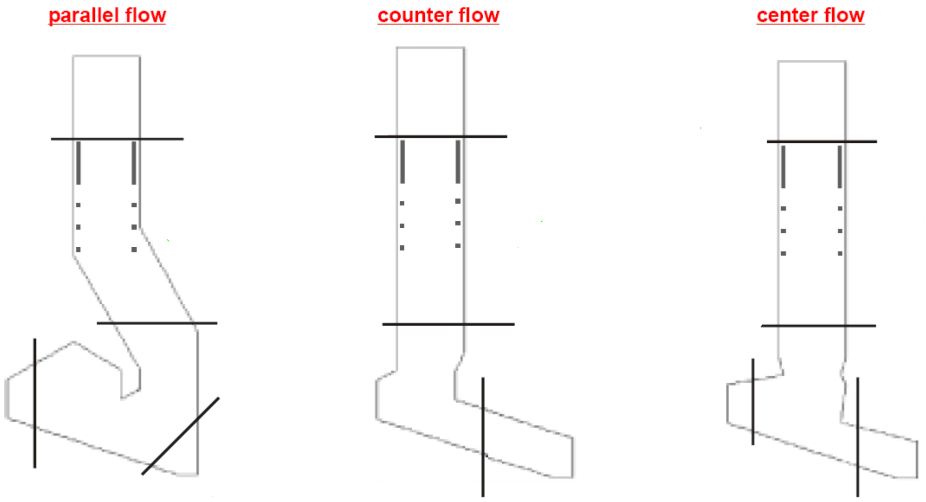

Fig. 1. Types of grate furnace design geometries

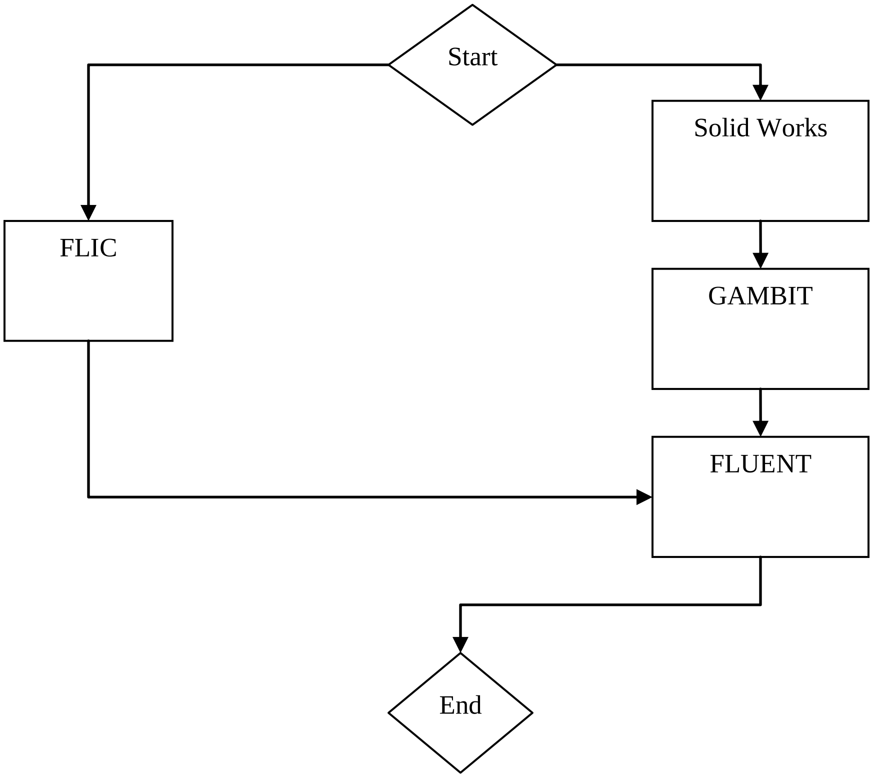

Fig. 2. Figure 2 Flowchart for CFD simulations

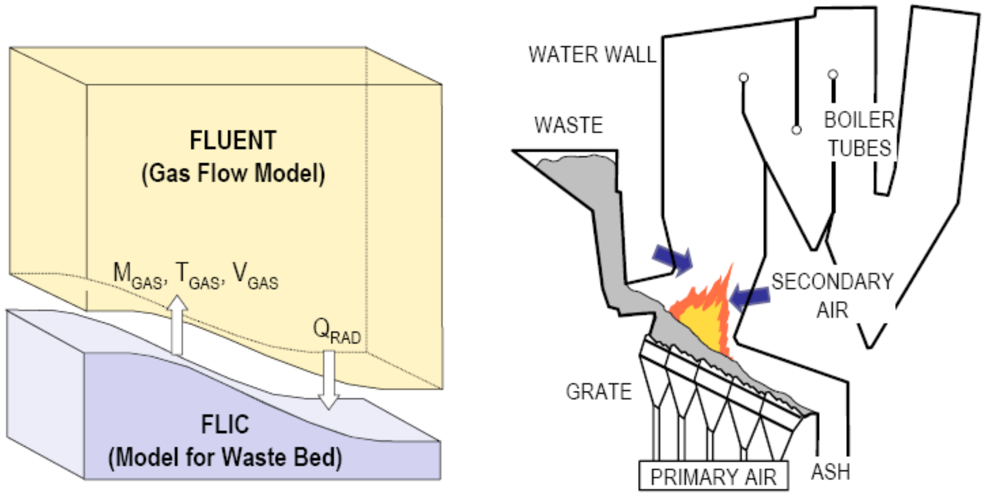

Fig. 3 FLIC methodology for waste bed combustion and using FLUENT for gas flow modeling

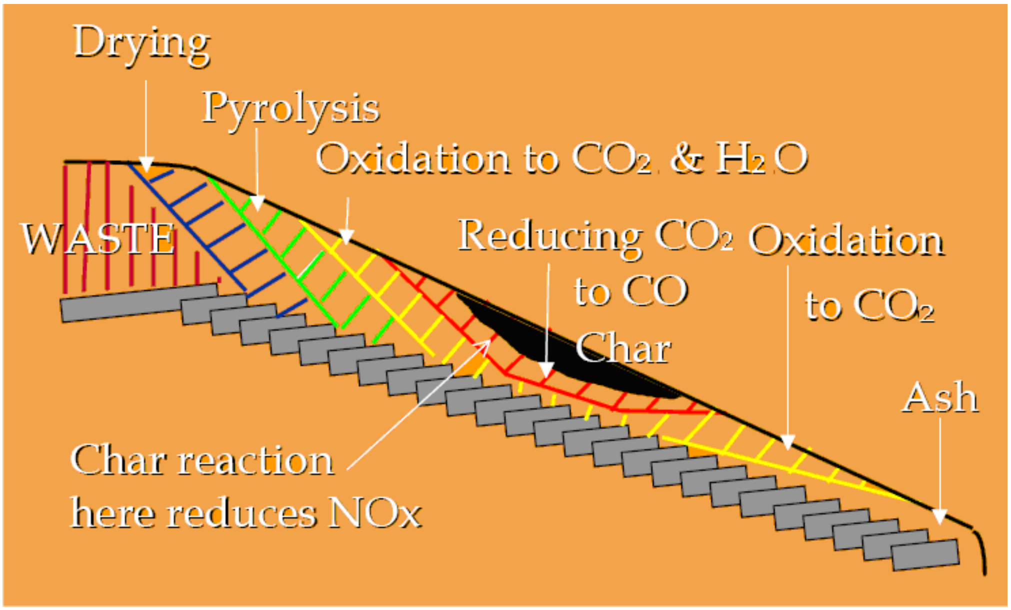

Fig. 4. Profile of the waste bed combustion in grate furnace designs

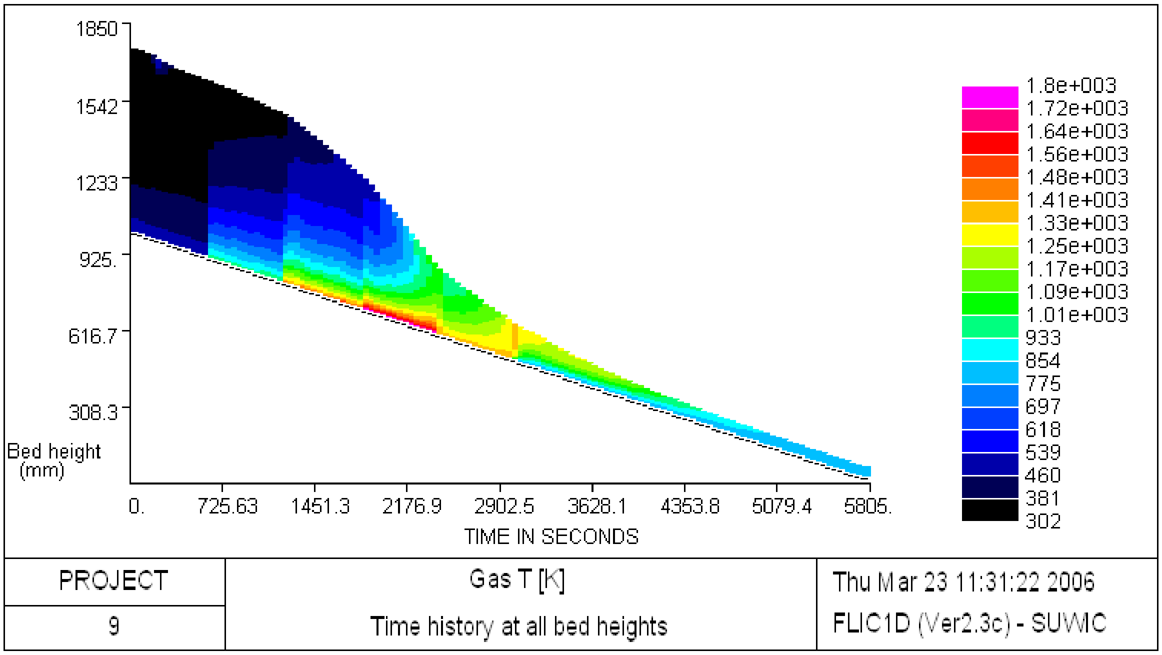

Fig. 5. Gas Temperature (K) along bed generated by FLIC code

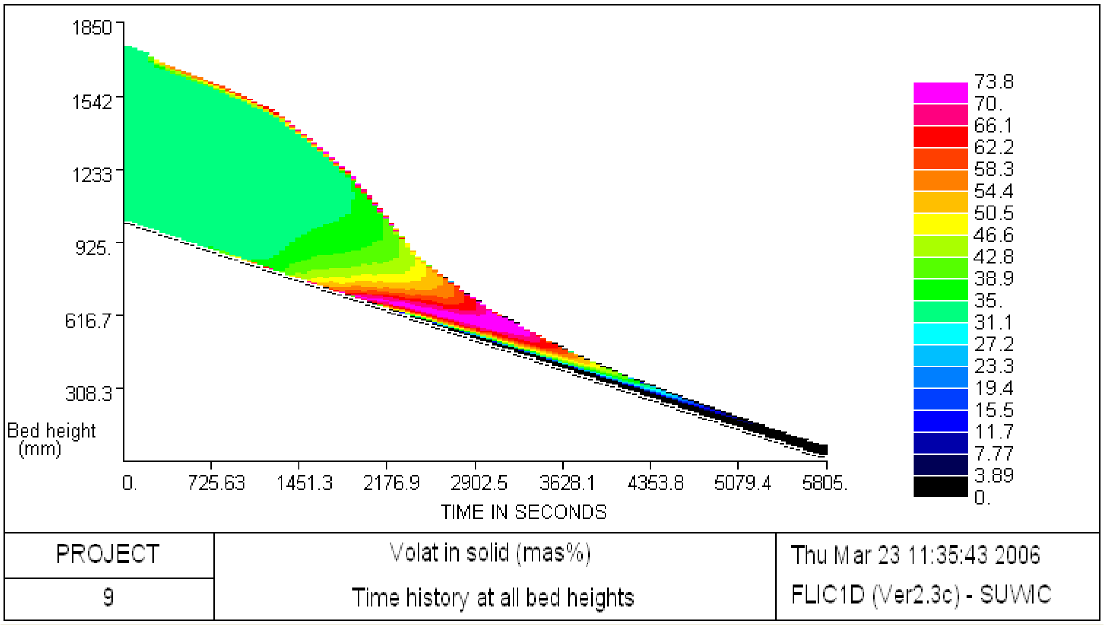

Fig. 6. Volatiles left in solid after gasification

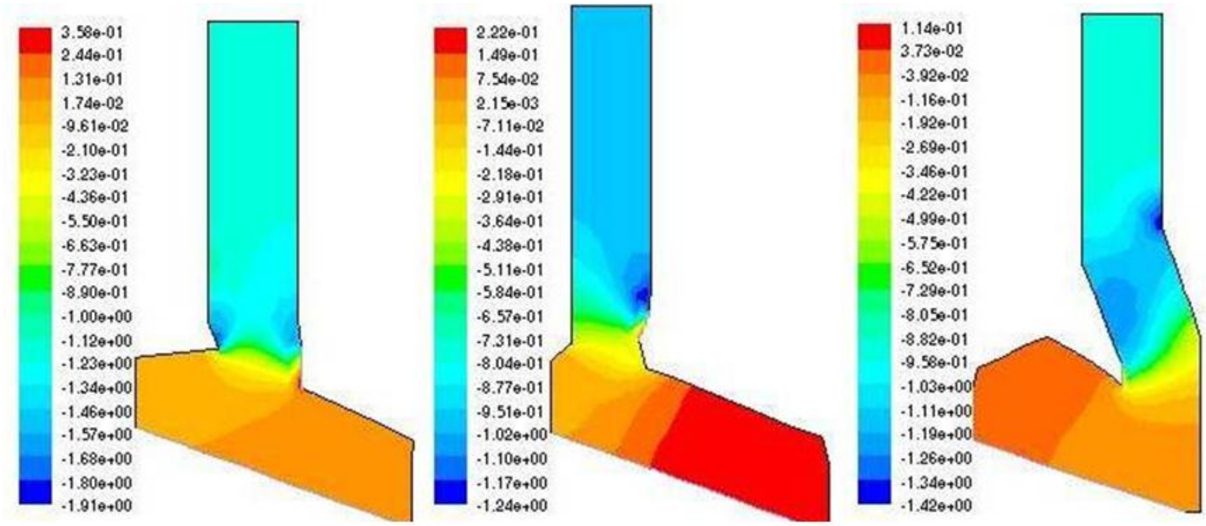

Fig. 7. Contours of Static Pressure

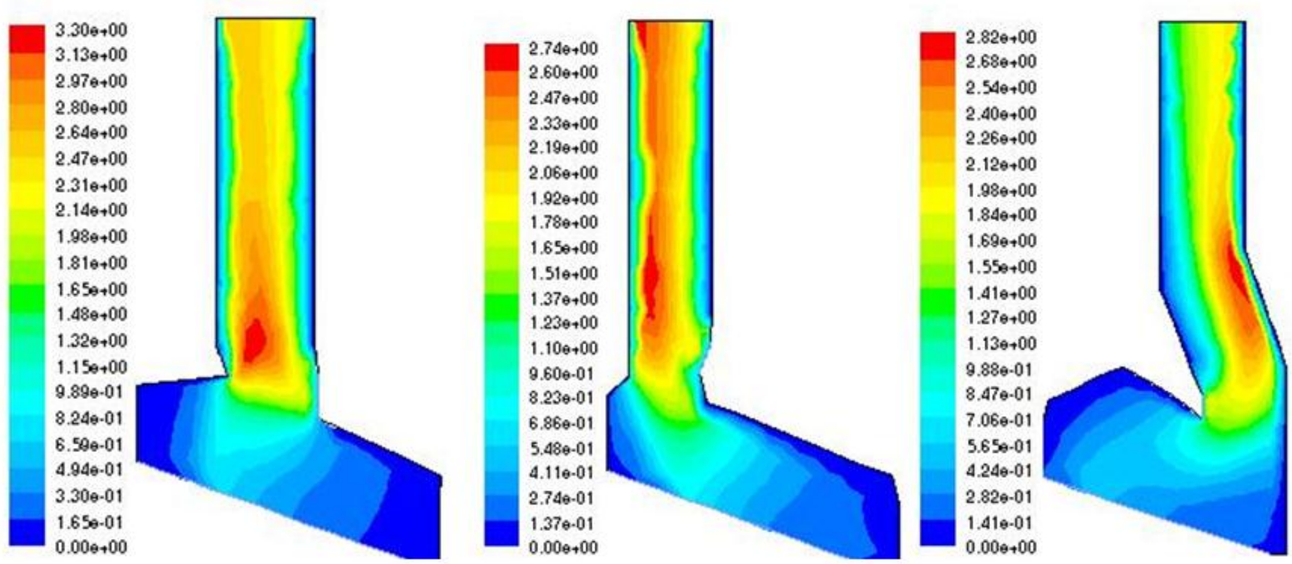

Fig. 8 Contours of Velocity

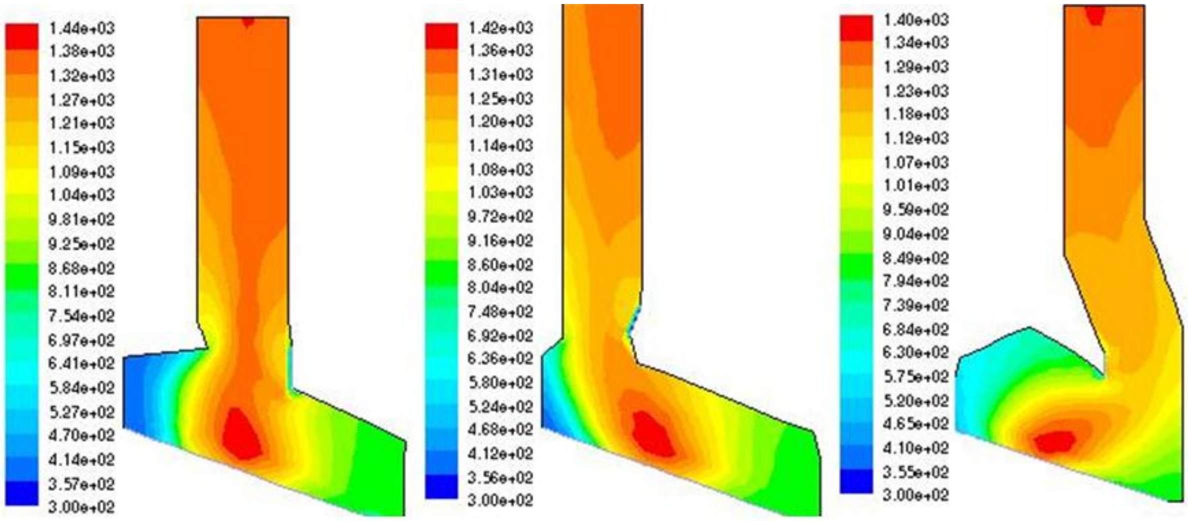

Fig. 9. Contours of Static temperature

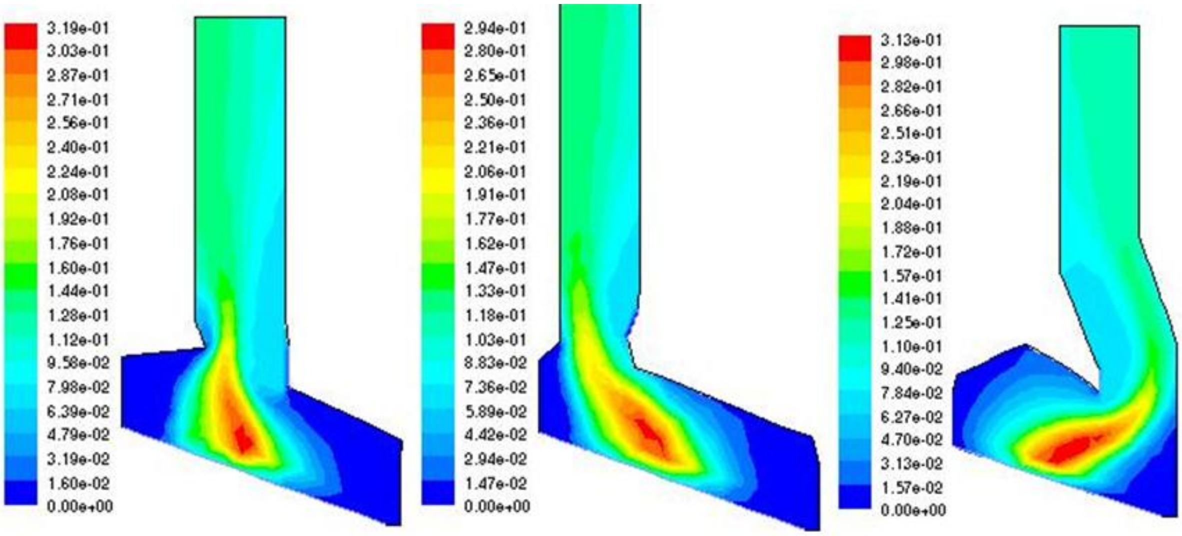

Fig. 10. Contours of Mass Fraction of CO_2

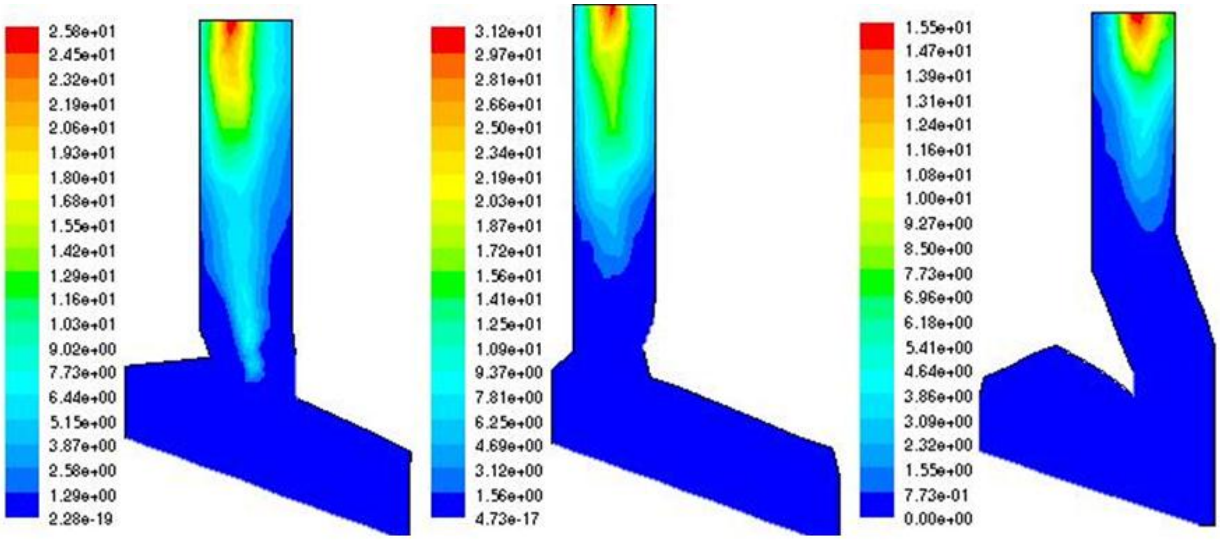

Fig. 11. Contours of NOx (ppm)