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Numerical Analysis of MSW Incineration Furnace

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Abstract
According to the importance of the sanitation of Municipal Solid Waste disposal and energy recovery, incineration power plant has been accepted as an appropriate choice in several countries. Incineration power plant is more complex than common power plant and the main element of this power plant is furnace as heart of the station. Thus, in this work based on the condition of Tehran's waste an incinerator is proposed, then a numerical analysis is employed to predict some details. To modeling the incineration furnace, consider two discrete and continuous phases and the incineration process is assumed contain three sub-processes: heating, evolution of volatiles and heterogeneous surface reaction.

Keywords: Combustion-Furnace-Incineration-Numerical-Renewable Energy.

1-Introduction
According to directive 1999/31/EC of the European Parliament of 26 April 1999, landfill of flammable wastes will be prohibited by 2010 in Europe Union and because of energy recovery and hygiene of municipal solid waste disposal; incineration has been accepted as an appropriate choice. Capacities of incineration of some European Union countries are summarized in Table 1 [1].

Table 1- Incineration capacities of some European Union countries [1]

country	Ton per year	Kg per year for each person	Thermal Energy (GJ)	Electrical Energy (GJ)
Austria	450000	56	3053000	131000
Denmark	2562000	477	10543000	3472000
France	10984000	180	32303000	2164000
Germany	12853000	157	27190000	12042000
Hungary	352000	6	2000	399000
Italy	2169000	137	3354000	2338000
Netherlands	4818000	482	-	9130000
Norway	220000	49	1409000	27000
Portugal	322000	32	1000	558000
Spain	1039000	26	-	1934000
Sweden	2005000	225	22996000	4360000
Switzerland	1636000	164	8698000	2311000
England	1074000	18	1000	1895000
Total	40484000	154.5	109550000	4061000

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In other countries like Japan, 314 kg per each person is incinerated to generate electricity annually; this number is 252 kg in Singapore and 105 kg in USA. China as a member of WTE[4] has 7 incineration power plant and they incinerate 1.6×10^{6} kg MSW[5] per year [1]. Typically in the incineration process, 15% net electrical efficiency and 42% net thermal efficiency is obtained [2].

The first municipal waste incinerator was built in 1876 in the UK [3]. It featured a packed bed combustor which was operated in a discontinuous way. The early attempt to model the incineration processes in packed-beds of wastes back to at least 1970s [4]. The past few years, however, have been seeing an impressive increase in the modeling work, regard to the growing interests in the waste incineration technology during the last decade. Peters [5] summarized the general governing equations for both gaseous and solid phases in a moving bed, and Goh et al. [6, 7] carried out numerical calculations in a stationary bed of solid waste material. Yang et al. [3] developed governing equations for mass, momentum and heat transfer in a moving packed bed and described mathematically the processes of moisture evaporation, particle devolatilization, volatile combustion and char burnout.

Most of the past work, however, were more on the empirical side and the modeled numerically their laboratory prototype. Therefore they have not been able to give the spatial details of the incineration processes in a real incinerator. The current paper works numerically on a real incineration furnace. So, at first, we propose an incineration furnace on based of the quality of Tehran's waste and then analyse it numerically.

1-1-Quality of waste in Tehran

Analyse of Tehran's waste indicate that it has a following formula [8]:

$CH_{1.626}N_{0.03766}S_{0.0025}Cl_{0.010}O_{0.645}+2.702H_2O$

The moisture of Tehran's waste is high, around 60%, and this item decreases the heat value. The low heat value of Tehran's waste is about 5382 kJ/kg, it is equal to 6510 kJ/kg as high heat value. According to document is reported by The World Bank in this respect, the minimum low heat value to establish an incineration power plant is 7 MJ/kg [9]. As shown in Table 2 by decreasing the water percent in waste we could achieve to appropriate heat value to set up an incineration power plant in Tehran. Therefore the moisture should be reduced to 30% until the high heat value becomes 10.280 MJ/kg. It could be happen by separation dry municipal solid waste from wet waste in each house or by treating the waste before entering them to furnace. Moisture can also be driven out by the mass exchange between the wet solids and the drier air-flow from the grate.

Table 2- Low heat value of waste

Percent of moisture in waste	60%	30%	0%
HHV (MJ/kg)	5.4	10.28	15.14

1-2-Mass and energy balance of Tehran's waste

In this part, by using mass conservative law and following formula for waste with 30% moisture, the amounts of theoretical air for complete combustion, excess air and products are calculated:

$$CH_{1.626}N_{0.03766}S_{0.0025}Cl_{0.010}O_{0.645}+1.351H_2O+x(O_2+3.76N_2)\longrightarrow CO_2+yH_2O+0.010HCl+0.0025\,SO_2+zN_2+uO_2$$

The mass flow rate of waste is considered 400 ton/day; in respect to Tehran's waste formula it is equal to 205 kmol/hr. In the theoretical condition value of x, y, z and u is:

$x=1.084$ $y=2.159$ $z=4.0758$ $u=0$

In real condition, theoretical air is not sufficient to achieve complete combustion, so excess air is needed. The amount of excess air is strongly depended on fuel and type of furnace. Excess air for complete combustion of sewage sludge in multiple combustion chamber furnaces is about 100 to 200 percent of theoretical air, for combustion of MSW in refractory wall furnaces is about 130 to 170 percent and in water wall furnaces is about 30 to 100 percent [10]. In this paper a water wall furnace with 70% excess air is selected. With 70% excess air the value of x, y, z and u is:

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x=1.8428 y=2.159 z=6.9289 u=0.7588

Amount of auxiliary fuel depends on temperature of products in the exit of combustion chamber. This temperature is selected to minimize NOx formation and other toxic gases. Energy balance is applied to determine gas temperature at the exit of combustion chamber, if the combustion of MSW isn't sufficient to reach appropriate temperature then auxiliary fuel is utilized. All the calculation is based on first law of thermodynamic [11]:

$$Q_{c.v} + \sum_R n_i \left[\overline{h}_f^o + \Delta\overline{h}\right]_i = \sum n_e \left[\overline{h}_f^o + \Delta\overline{h}\right]_e \tag{1}$$

where $Q_{c.v}$ is thermal energy, n_i is mole flow rate at inlet, n_e is mole flow rate at outlet, $\overline{h}_f^o$ is enthalpy of formation and $\Delta\overline{h}$ is enthalpy increase from 298 K to gas temperature. Calculation is fulfilled for both 60% and 30% of moisture in waste. For 30% of moisture, combustion of MSW is sufficient to reach 870^{oC} for the out flow but for 60% of moisture about 20 MW is needed. This excess thermal energy should be provided by auxiliary fuel. Selection of type of auxiliary fuel determines mass flow rate and type of burner and other facilities that are needed.

1-3-Dimensional Design of furnace

To determine dimension of a furnace these factor is important: mass flow rate of waste, heat value of waste, type of waste feed in furnace and thickness of fuel-bed at interior and excess air [10]. As said before the mass flow rate of waste is 400 ton/day, high heat value of waste is 10.28 MJ/kg; thickness of fuel-bed is 0.6 m at inlet of waste, type of grate is rotating drum and excess air is 70%. Now by this information the initial rate of combustion could be calculated:

$$F_A = \frac{1}{3} K_L Ca^{\frac{1}{3}} \tag{2}$$

where K_L is coefficient of waste quality, Ca is capacity of fuel feed in lb/hr and F_A is initial rate of combustion in 1b/ft^2.hr. Since the high heat value of waste is more than 3000 Btu/lb the correlation of K_L is:

$$K_L = 0.0010933(HHV) + 5.207 \tag{3}$$

Wide of grate is assumed 5 m, therefore the correlation of Ca is:

$$Ca = \left[\frac{(20-W)^{1.63093}}{-15.49494} + 10.908\right]\frac{W \times 10^6}{HHV} \tag{4}$$

where W is wide of grate. Value of K_L and Ca are calculated and putted into equation 2, so the initial rate of combustion becomes: $F_A = 166.95 \quad lb/ft^2hr$.

The real rate of combustion estimated by:

$$F'_A = F_A \frac{G_A}{W_a}\left(\frac{\gamma}{a}\right)_{av} \tag{5}$$

where $\left(\gamma/a\right)_{av}$ is corrective coefficient of fuel-bed thickness and $\frac{G_A}{W_a}$ is ratio between actual air and theoretical air, so:

$$F'_A = 78.26 \quad \text{lb/ft}^2\text{hr} \tag{6}$$

Now the area of cross section of furnace at inlet could be calculated:

$$A_g = \frac{\dot{m}_w W}{F'_A} = 469.52 \quad \text{ft}^2 \tag{7}$$

where $\dot{m}_w$ is mass flow rate of waste. As said before wide of grate is 5 m, so the length of it becomes 8.3 m, since the ratio between length and wide is smaller than 2, assumption for wide is correct.

The combustion intensity is calculated from:

$$I = 0.005913 \times HHV^{7/4} \tag{8}$$

So the minimum volume of furnace is:

$$V_f = \frac{\dot{m}_w \times B}{I} = 30801.95 \ \ ft^3 \tag{9}$$

According to area of cross section of furnace, equation 7, the height of furnace becomes about 20 m. For more detail of furnace design see [12].

Up to now, we proposed an incinerator according to condition of waste in Tehran. This information of incinerator are summarized in Table 3 and used in numerical analyse.

Table 3- Furnace information used in numerical analysis

	Unit	Value
Length of furnace at inlet	m	8.3
Wide of furnace at inlet	m	5
Height of furnace	m	20
Slope of grate	-	20^o
Thickness of fuel-bed at inlet	m	0.6
Low heat value	MJ/kg	10.28
Mass flow rate of waste	Ton/day	400
Excess air	-	70%

2-Mathematical modeling

To modeling the incineration process of solid wastes in furnace, combustible particles are assumed as discrete phase and fluid flow as continuous phase which particles have random path in the continuous phase. The trajectory and heat/mass transfer calculations are based on the force balance on the particle and on the convective/radiative heat and mass transfer from the particle, using the local continuous phase conditions as the particle moves through the flow. Thus the continuous phase always impacts the discrete phase, also can incorporate the effect of the discrete phase trajectories on the continuum. This two-way coupling is accomplished by alternately solving the discrete and continuous phase equations until the solutions in both phases have stopped changing. This interphase exchange of heat, mass, and momentum from the particle to the continuous phase is depicted qualitatively in Figure1.

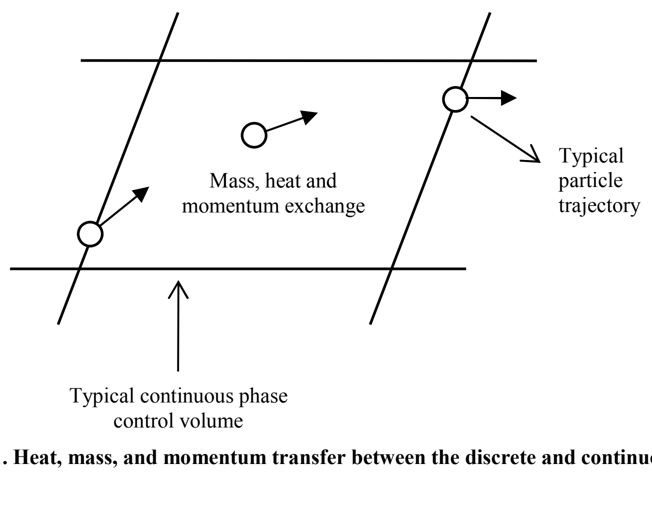

Figure1. Heat, mass, and momentum transfer between the discrete and continuous phases

The governing equations of continuous phase are continuum, momentum, and energy equation which there are a source term in each of them to relate discrete to continuous phase. Mass, energy, and force which release by combustion of particles are considered as source term in the governing equations of continuous phase.

The incineration process of solid waste particles can be divided into three successive sub-processes: heating, evolution of volatiles and heterogeneous surface reaction. These three processes may overlap to some extent. Mathematical models for each of these processes are described as follows.

2-1-Inert Heating

The inert heating law is applied while the particle temperature is less than the devolatilization temperature that is defined, T_{dev}. This condition may be written as:

$$T_P < T_{dev} \tag{10}$$

where T_P is temperature of solid waste particle. When using this Law a simple heat balance is applied to relate the particle temperature, $T_P(t)$, to the convective heat transfer and the absorption/emission of radiation at the particle surface:

$$m_P C_P \frac{dT_P}{dt} = hA_p(T_\infty - T_P) + \varepsilon_P A_P \sigma(\theta_R^4 - T_P^4) \tag{11}$$

where m_P, A_P, C_P and ε_P are mass, surface, heat capacity and emissivity of particle, respectively. h is heat transfer coefficient, σ is Boltzmann constant and θ_R is radiation temperature which is defined as $\left(\frac{I}{4\sigma}\right)^{1/4}$, where I is radiation intensity. Equation 11 assumes that there is negligible internal resistance to heat transfer, i.e., the particle is at uniform temperature throughout.

The heat transfer coefficient, h, is evaluated using the correlation of Ranz and Marshall [13, 14]:

$$N_u = \frac{hD_P}{k_\infty} = 2.0 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} \tag{12}$$

where D_P is particle diameter and k_∞ is thermal conductivity of the continuous phase.

The heat lost or gained by the particle as it traverses each computational cell appears as a source or sink of heat in subsequent calculations of the continuous phase energy equation. During this Law, particles do not participate in any chemical reaction and do not exchange mass with the continuous phase, unless waste contain moisture. If the waste contain moisture all convection and radiation heat consume to completely vaporize water from particles than the inert heating law is used.

2-2-Devolatilization

The devolatilization law is applied to a combusting particle when the temperature of the particle reaches the devolatilization temperature, T_{dev}, and remains in effect while the mass of the particle, m_P, exceeds the mass of the non-volatiles in the particle:

$$T_P \ge T_{dev} \quad \text{And} \quad m_p > (1 - f_{v0} - f_{w0})m_{P0} \tag{13}$$

where f_{w0} is the volume fraction of the water if waste contain water, otherwise f_{w0} = 0, and f_{v0} is volatile component fraction at initial condition.

Volatile matter in municipal solid waste is normally much higher than that in coals. A typical figure of volatile content in municipal refuse is 85% of the combined volatile matter and fixed carbon, compared with 37% for an average industrial coal. Depending on specific conditions, volatile yield could range from 10% to as high as 60% of the original mass, and the gases are composed mainly of hydrocarbon (C_mH_n), CO, CO_2, H_2, O_2 and other trace compounds:

$$Waste \rightarrow \mathrm{Volatile}\left(\mathrm{C_mH_n, CO, H_2, CO_2, O_2, etc}\right) + \mathrm{Char}$$

The single kinetic rate model is selected as devolatilization model in this work. The single kinetic rate devolatilization model assumes that the rate of devolatilization is first order dependent on the amount of volatiles remaining in the particle [15]:

$$-\frac{dm}{dt} = k\left(m_P - \left(1 - f_{v0} - f_{w0}\right)m_{P0}\right) \tag{14}$$

where m_{P0} is mass of particle at initial condition. The kinetic rate, k, is defined by input of an Arrhenius type pre-exponential factor and activation energy:

$$k = A_1 \exp\left(-E / RT\right) \tag{15}$$

Heat transfer to the particle during the devolatilization process includes contributions from convection, radiation and the heat consumed during devolatilization:

$$m_P C_P \frac{dT_p}{dt} = hA_P\left(T_\infty - T_P\right) + \frac{dm_p}{dt}h_{fg} + A_P\varepsilon_P\sigma\left(\theta_R^4 - T_P^4\right) \tag{16}$$

2-3-Surface Combustion

After the volatile component of the particle is completely evolved a surface reaction begins, which consumes the combustible fraction, f_{comb} , of the particle:

$$m_P < \left(1 - f_{v0} - f_{w0}\right)m_{P0} \tag{17}$$

And using this law continued until the combustible fraction is completely consumed:

$$m_P > \left(1 - f_{v0} - f_{w0} - f_{Comb}\right)m_{P0} \tag{18}$$

When the combustible fraction, f_{comb}, has been consumed, the combusting particle contain residual "ash" that reverts to the inert heating law. The surface combustion reaction consumes the reactive content of the particle as governed by the stoichiometric requirement, S_b , of the surface burnout reaction:

$$Char(s) + S_b O_g \rightarrow Products\ (g) \tag{19}$$

where S_b is defined in terms of mass of oxidant per mass of char.

A choice of heterogeneous surface reaction rate model for combusting particles is the kinetics/diffusion-limited rate model that is selected in this paper. The kinetic/diffusion-limited rate model assumes that the surface reaction rate is determined either by kinetics or by a diffusion rate. The model of Baum and Street [16] and Field [17] are used, in which a diffusion rate:

$$R_1 = C_1 \frac{\left[\left(T_P + T_\infty\right)/2\right]^{0.75}}{D_P} \tag{20}$$

and a kinetic rate:

$$R_2 = C_2 \exp\left(-E / RT_P\right) \tag{21}$$

are weighted to yield a char combustion rate of:

$$\frac{dm_P}{dt} = -\pi D_P^2 P_o \frac{R_1 R_2}{R_1 + R_2} \quad (22)$$

where P_o is the partial pressure of oxidant species in the gas surrounding the combusting particle and the kinetic rate R_2 incorporates the effects of chemical reaction on the internal surface of the char particle (intrinsic reaction) and pure diffusion.

The surface reaction consumes the oxidant species in the gas phase, i.e., it supplies a (negative) source term during the computation of the transport equation for this species. Similarly, the surface reaction is a source of species in the gas phase: the product of the heterogeneous surface reaction appears in the gas phase as chemical species. The surface reaction also consumes or produces energy. The particle heat balance during surface reaction is:

$$m_P C_P \frac{dT_P}{dt} = hA_P\left(T_\infty - T_P\right) - f_h \frac{dm_p}{dt} H_{reac} + A_P \varepsilon_P \sigma\left(\theta_R^4 - T_P^4\right) \quad (23)$$

where H_{reac} is the heat released by the surface reaction. Note that only a portion ($1 - f_h$) of the energy produced by the surface reaction appears as a heat source in the gas phase energy equation; the particle absorbs a fraction, f_h, of this heat directly to sustain burn out.

3-Results and discussion

Fig. 2 shows the conton of temperature in furnace . As mentioned maximum temperature of furnace is about 2300 K and it happens at the middle of the grate, approximately. It shows that waste is dried at the first one third of the grate length, then burning out occurs and in the last part of the grate there isn't any combustible particle therefore temperature is decreased. Secondary air, with 450 K and 5 m/sec, enters from tow nozzle in both side of the furnace duct to develop the combustion of solid particle. It causes tow vortex in both side of the duct and decrease the heat transfer from gas to wall that is not suitable.

Fig. 3 shows the contour of velocity in furnace. Those tow vortexes are clearly seen in this figure and the maximum velocity is in the outlet of the furnace (right-top of the furnace duct), because the cross section of flow is increased.

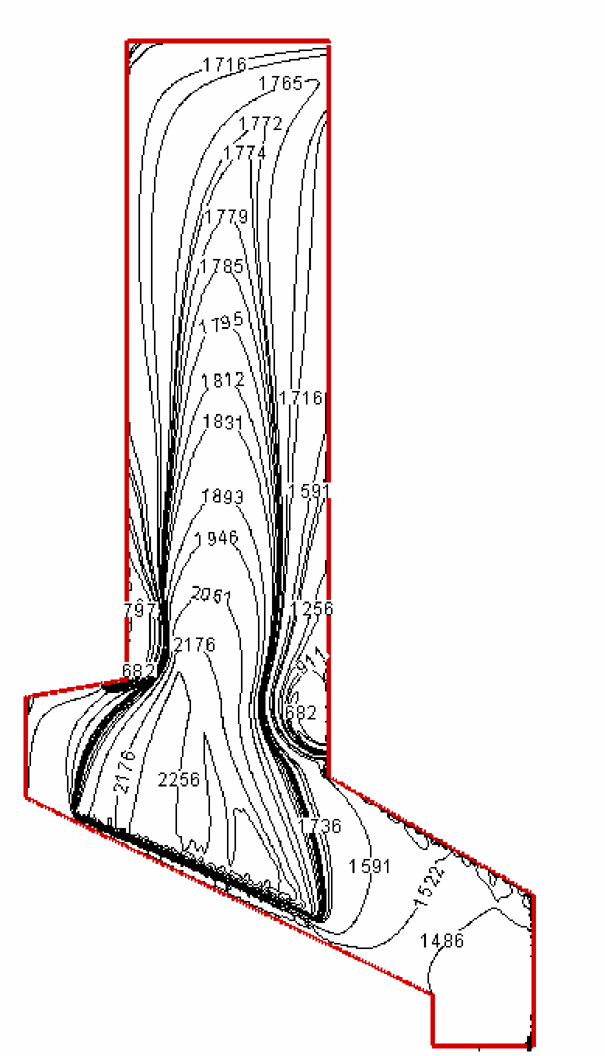

Figure 2- Contour of temperature (K)

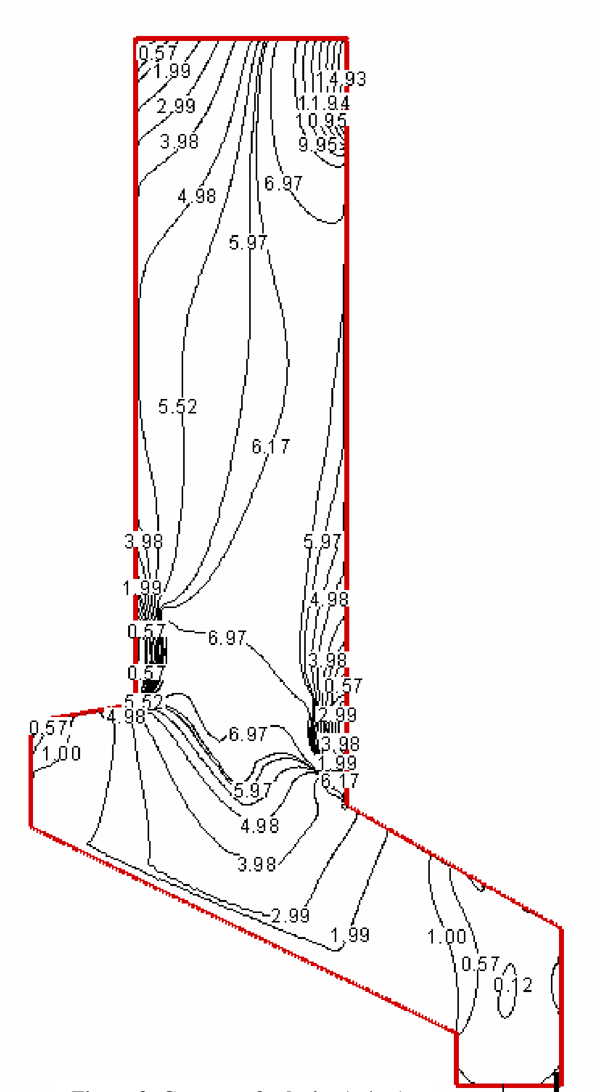

Figure 3- Contour of velocity (m/sec)

Fig. 4 indicates mass fraction of solid carbon. Which is produced after devolatilization is done completely. This figure implies that devolatilization begins shortly above the waste bed on the grate and finishes immediately.

Concentration of C(s), Co and Co_2 in figures 4, 5 and 6, at the middle part of the grate shows that main section of the grate is where the furnace duct is located. Most of the combustion process happens in this section and it could be due to the furnace duct, therefore by changing its position, main part of the combustion process occurs in somewhere else. Figures 4 and 5 demonstrate the combustion approximately completes around the inlet of the duct and duct of the furnace is employed like radiation part of the boiler in water wall furnaces.

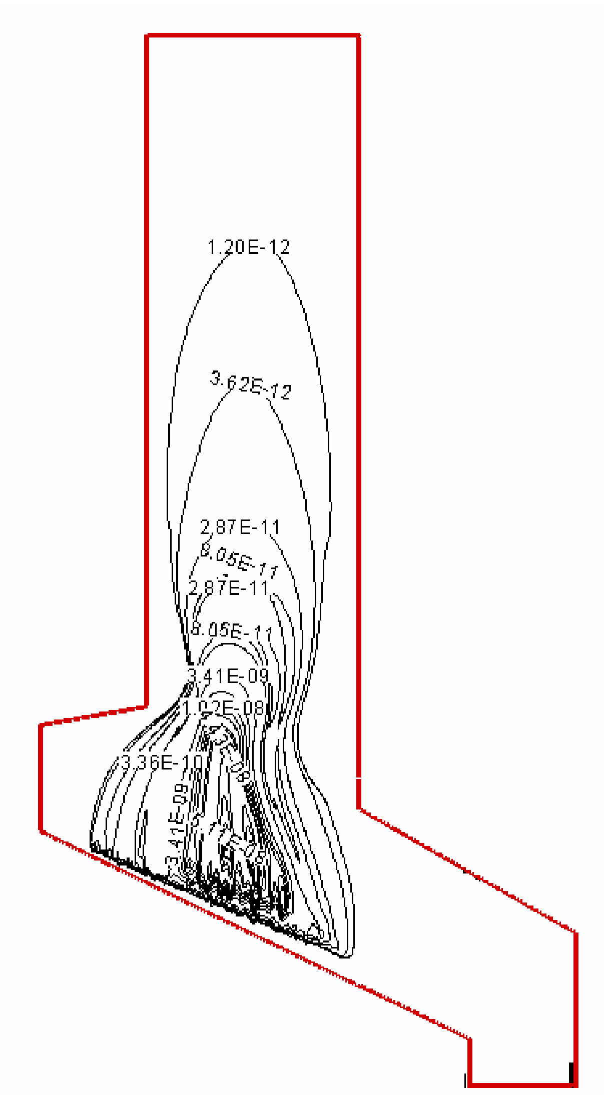

Figure 4- Contour of mass fraction of C(s)

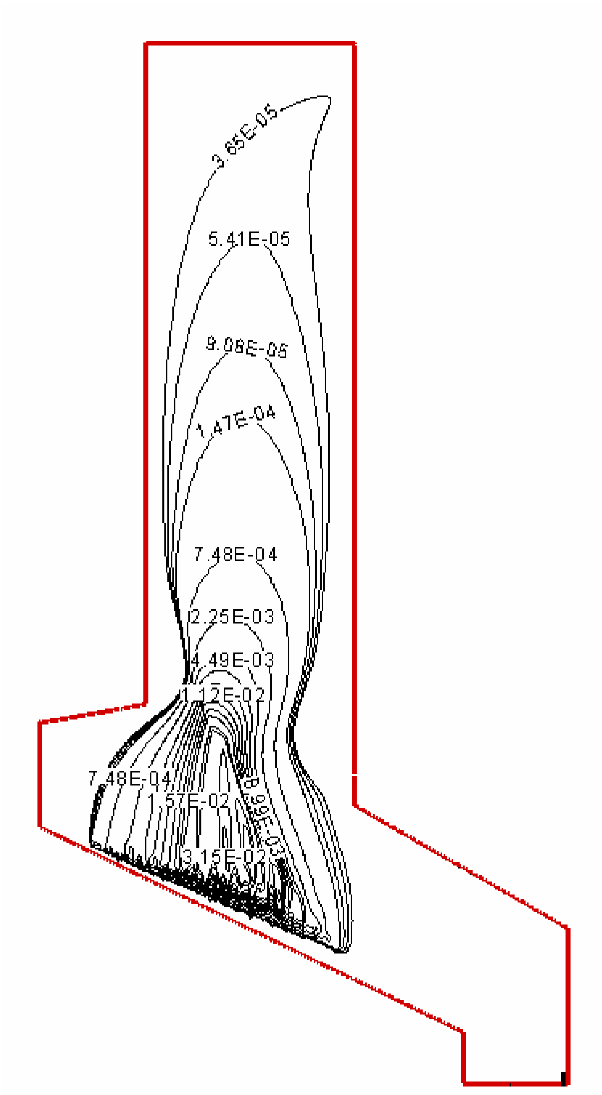

Figure 5- Contour of mass fraction of Co

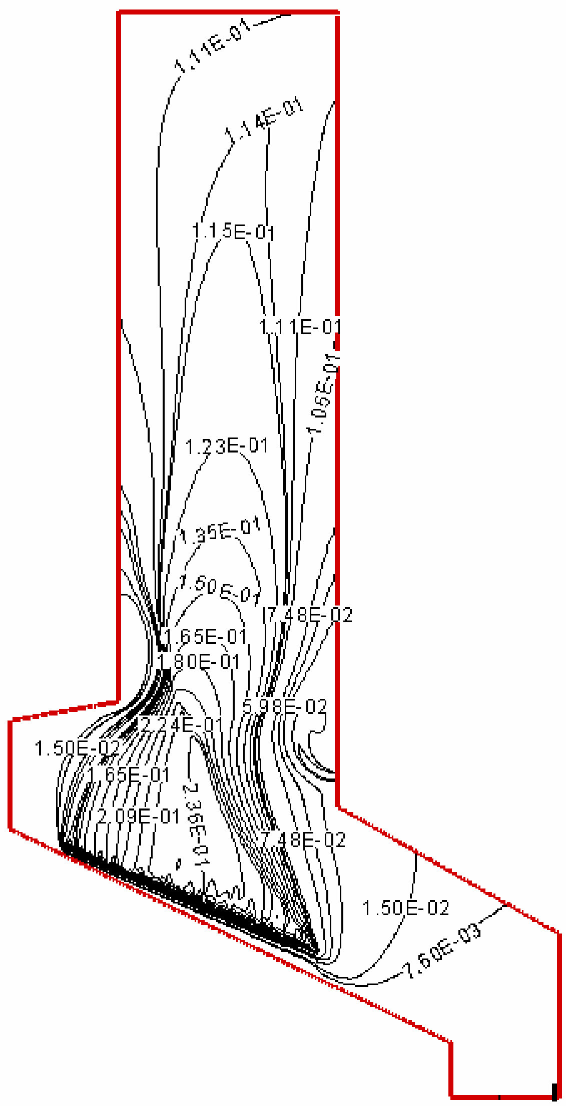

Figure 6- Contour of mass fraction of Co_2

4-Conclusion

At first, we propose an incineration furnace on based of the quality of Tehran's waste and then to modeling the incineration process of solid wastes in furnace, combustible particles are assumed as discrete phase and fluid flow as continuous phase which particles have random path in the continuous phase. Mass, energy, and force which release by combustion of particles are considered as source term in the governing equations of continuous phase. Heterogeneous surface reaction rate model for combusting particles in a packed bed are limited by not only the reaction kinetics but also the mixing of the fuel with the feed air and following results are achieved.

- According to document is reported by The World Bank, moisture of waste in Tehran should be reduced to 30% in order to reach the suitable LHV to set up an incineration power plant.
- If the moisture of waste reduced to 30%, auxiliary fuel doesn't need to reach the appropriate condition.
- Thermal energy that is released from incineration of 400 Ton waste of Tehran is about 52.7 MW and by assuming the typical net electrical efficiency of the power plant, 15%, generation of 7.9 MW of electrical energy is possible.
- Incineration process consists of three sub-processes: inert heating, evolution of volatiles and heterogeneous surface reaction.
- Maximum temperature of the incineration is about 2300 K and it occurs at the middle of the grate.

- Location of combustion on a grate is depended on the duct of furnace.
- At the first one third of the grate length waste is dried, in the next part combustion occurs and in the last part, grate only carries the ash.

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