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Calculation of optimum length for pyrolysis reactor

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Abstract
Within the scope of sustainable development approach all over the world, waste management strategies are adopted, aiming at removing wastes from a threat in terms of environment and human health and transforming them into an input for the economy. Municipal solid waste disposal methods have long been a subject of intense debate. For years, this debate has been moving between burning waste or burying it in landfills. Recently, wastes are mostly disposed of on landfills. Until recently, the method of combustion was seen as an alternative. According to the environmentalist approach, it is being challenged to burn waste for reasons such as destroying natural resources, causing air pollution and climate change. Work on more efficient and controlled thermal processing methods has been started. The research for a better disposal method reveals the disposal of municipal solid wastes by pyrolysis method. In the pyrolysis process, organic (carbon containing) compounds are heated in an oxygen-free environment and degraded to their basic components. In this study, the mathematical model of the pyrolysis reactor was established, the mass and momentum equations for the flow in the reactor were solved, the temperature distribution in the reactor was calculated and the heat loss calculations are made. Then, finite element model of the pyrolysis reactor was established, velocity and temperature distributions in the reactor were observed after defining the necessary boundary conditions. These values were compared with the values obtained from the analytical solution. According to these values, the optimum length of the reactor was calculated taking into consideration the residence time.

Keywords: CFD; finite element analysis; pyrolysis

1. Introduction

Today, one of the biggest problems of the cities is that there is a population increase in proportion to the industrialization and that the environment is rapidly polluted by the increasing amount of solid waste. As a result of changing consumption habits, the amount of solid waste produced per person increases day by day. This problem raises concerns about the economics and environmental friendliness of the technologies used in the disposal of waste[1,4]. As a result of changing consumption habits, the amount of solid waste produced per person increases day by day. Urban solid waste disposal methods have long been a subject of intense debate. This debate has been going on for years between burning wastes or burying them in landfills. In the past, almost all the waste had been thrown into the garbage fields and not disposed of. In recent times, wastes are mostly disposed of on landfills. Until recently, the method of combustion was seen as an alternative. According to the environmentalist approach, it is opposed to burning the garbage because it destroys natural resources, reduces recycling due to the need for constant waste feed, causes climate changes, and causes air pollution and toxic ashes. The search for a better disposal method reveals the disposal of urban solid wastes by the pyrolysis method[4-9].

Pyrolysis is the thermal decomposition process took place in an inert atmosphere. The pyrolysis process usually takes place between 400-850 ºC. As pyrolysis product gas components, volatiles, carbon and ash revealed. The resulting carbon black can be used in tire production and the resulting ash is used as construction material [10–15]. Pyrolysis has many advantages. Some of them can be listed as follows;

- Prevents air pollution.
- It is safer and more environmentally friendly than incineration, landfill and other gasification methods.
- The waste is converted into new products such as useful liquid fuel, carbon black and combustible gases.
- The products obtained can be used both to feed the system and to generate electricity.

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- It is a sustainable method for recovery by recycling waste.
- Make areas occupied by landfills available for agricultural or other purposes.
- Reduce carbon emissions.
- Reducing the volume of solid waste and forming sterile products prolongs the life span of storage areas.
- The system nourishes itself in terms of energy needs.
- Useful product is obtained from treated solid wastes.

2. Material and method

The modeling of the rotary kiln pyrolysis reactor will be carried out under the following assumptions;

- The gas phase behaves similar to ideal ghase.
- Radially well mixed.
- Fixed solid particle size
- The gas phase contains only pyrolysis gas
- The axial distribution will be ignored[16,17].

2.1. Mass balance for pyrolysis reactor

According to Figure 1, the particle i enters the control volume in the direction z, in the mass flow rate Fi, in the density ρ_i , at the value of enthalpy H_i and in the area A_i. During the flow in the control volume, the mass flow rate of the particle i will vary with the chemical reactions (reaction rate r_w of the wood and individual stoichiometric coefficient υi).

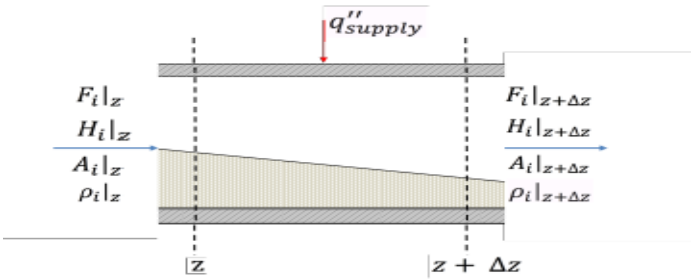

Figure 1. Control volume of rotary kiln pyrolysis reactor[16]

The total mass balance over the control volume can be written as:

Present state - previous state = input - output + production – consumption

$$\Delta z\left[\sum_{i=1}^{n}\rho_i A_i\, I_{z,t+\Delta t}-\sum_{i=1}^{n}\rho_i A_i\, I_{z,t}\right] = \Delta t\left[\sum_{i=1}^{n}F_i I_{z,t}-\sum_{i=1}^{n}F_i I_{z+\Delta z,t}\right] + \sum_{i=1}^{n}\upsilon_i r_w A_w \Delta z \Delta t \quad (1)$$

By dividing both sides of the above equation by Δt.Δz;

$$\frac{\left[\sum_{i=1}^{n}\rho_i A_i\, I_{z,t+\Delta t}-\sum_{i=1}^{n}\rho_i A_i\, I_{z,t}\right]}{\Delta t} = \frac{\left[\sum_{i=1}^{n}F_i I_{z,t}-\sum_{i=1}^{n}F_i I_{z+\Delta z,t}\right]}{\Delta z} + r_w A_w \sum_{i=1}^{n}\upsilon_i \quad (2)$$

If the limit Δz,Δt→ 0 ; the total mass balance for the kiln will become the following;

$$\sum_{i=1}^{n}\frac{\partial}{\partial t}(\rho_i A_i) = -\sum_{i=1}^{n}\frac{\partial F_i}{\partial z} + r_w A_w \sum_{i=1}^{n}\upsilon_i \quad (3)$$

According to the total mass balance equation, the mass accumulation in a furnace varies according to the mass transfer and the chemical reaction. Also, if we write the total mass balance equation for each particle;

$$\frac{\partial}{\partial t}(\rho_i A_i) = -\frac{\partial F_i}{\partial z} + r_w A_i \upsilon_i \quad (4)$$

If the mass conservation equation is to be applied to the rotary kiln pyrolysis reactor, then the variables i will change to w (wood), c (char), and g (gas) and the following equations will be obtained;

$$\frac{\partial}{\partial t}(\rho_w A_w) = -\frac{\partial F_w}{\partial z} + r_w A_w \upsilon_w \quad (5)$$

$$\frac{\partial}{\partial t}(\rho_c A_c) = -\frac{\partial F_c}{\partial z} + r_w A_w \upsilon_c \quad (6)$$

$$\frac{\partial}{\partial t}(\rho_g A_g) = -\frac{\partial F_g}{\partial z} + r_w A_w \upsilon_g \quad (7)$$

Given that υ_w is -1, the total mass balance equation in the rotary kiln pyrolysis reactor will be:

$$\left(\frac{\partial}{\partial t}(\rho_w A_w) + \frac{\partial}{\partial t}(\rho_c A_c) + \frac{\partial}{\partial t}(\rho_g A_g)\right) = -\left(\frac{\partial F_w}{\partial z} + \frac{\partial F_c}{\partial z} + \frac{\partial F_g}{\partial z}\right) + r_w A_w(\upsilon_w + \upsilon_c + \upsilon_g) \quad (8)$$

Reaction rate and stoichiometric coefficients are time dependent functions. Therefore, energy equations must be solved together with mass equations[16,17].

2.2. Energy Balance for Pyrolysis Reactor

For a rotary kiln pyrolysis reactor, the energy equation can not be derived directly as the mass equation because both the solid and gas phases are present in the system. Moreover, the characteristics of the rotary kiln, such as the energy generated from the reaction and the cross-sectional area, must also be included in the model. As a result, the process should be followed step-by-step to energy balance derivation. Firstly, the energy equations of allcomponents in the control volume according to Fig. 1 need to be derived according to the following formula;

Present state - previous state = input - output + heat source

$$\Delta z\left[\sum_{i=1}^{n} \rho_i A_i H_i\, I_{z,t+\Delta t} - \sum_{i=1}^{n} \rho_i A_i H_i\, I_{z,t}\right] = \Delta t\left[\sum_{i=1}^{n} F_i H_i I_{z,t} - \sum_{i=1}^{n} F_i H_i I_{z+\Delta z,t}\right] + \ddot{q}_k A_{kab} \Delta t \quad (9)$$

Here, $\ddot{q}_{kayn}$ is the heat flux(W/m^2) on the outer surface of the kiln.. By dividing both sides of the above equation by Δt.Δz;

$$\frac{\left[\sum_{i=1}^{n} \rho_i A_i H_i I_{z,t+\Delta t} - \sum_{i=1}^{n} \rho_i A_i H_i I_{z,t}\right]}{\Delta t} = \frac{\left[\sum_{i=1}^{n} F_i H_i I_{z,t} - \sum_{i=1}^{n} F_i H_i I_{z+\Delta z,t}\right]}{\Delta z} + \frac{\ddot{q}_{kayn} A_{kab}}{\Delta z} \quad (10)$$

When we take the limit as in mass balance, the equation will be as follows.

$$\sum_{i=1}^{n} \frac{\partial}{\partial t}(\rho_i A_i H_i) = -\sum_{i=1}^{n} \frac{\partial}{\partial z}(F_i H_i) + \dot{q}_k \quad (11)$$

Here $\dot{q}_k$ is the amount of heat per unit length(W/m). If the partial differential is applied, the equality will be as follows.

$$\sum_{i=1}^{n}\left(H_i \frac{\partial}{\partial t}(\rho_i A_i) + \rho_i A_i \frac{\partial H_i}{\partial t}\right) = -\sum_{i=1}^{n}\left(H_i \frac{\partial F_i}{\partial z} + F_i \frac{\partial H_i}{\partial z}\right) + \dot{q}_k \quad (12)$$

If we think that the enthalpy can be calculated as a form of heat, enthalpy can be expressed as;

$$H_i = H_{i0} + \int_{T_0}^{T} C_{pi} dT_i \quad (13)$$

So, the enthalpy derivation can be written as

$$\partial H_i = C_{pi} \partial T_i \quad (14)$$

After changing the term enthalpy as a function of temperature and writing the equation obtained in the mass balance equation instead of $\frac{\partial F_i}{\partial z}$, the equation will be as follows;

$$\sum_{i=1}^{n} H_i \frac{\partial}{\partial t}(\rho_i A_i) + \sum_{i=1}^{n} \rho_i A_i C_{pi} = \sum_{i=1}^{n} H_i \frac{\partial}{\partial t}(\rho_i A_i) - r_w A_w \sum_{i=1}^{n} \upsilon_i H_i - \sum_{i=1}^{n} F_i C_{pi} \frac{\partial T_i}{\partial z} + \dot{q}_k \quad (15)$$

After handling similar terms in the above equation, the final shape of the total energy balance on the control volume can be expressed as:

$$\sum_{i=1}^{n}\left(\rho_i A_i C_{pi} \frac{\partial T_i}{\partial t}\right) = -r_w A_w \sum_{i=1}^{n} \upsilon_i H_i - \sum_{i=1}^{n} F_i C_{pi} \frac{\partial T_i}{\partial z} + \dot{q}_k \quad (16)$$

The energy accumulation in the rotary kiln is influenced by reaction energy, material flows, energy and heat source[16].

2.3. Pyrolysis Reactor Length Determination

The values to be used for wood pyrolysis process are as follows.

Heat transfer coefficient (k) = 0.0454 W / mK

Specific heat $(c_p) = 1500 \frac{J}{kgK}$

Density (d) = $355 \frac{kg}{m^3} =$

$$l_c = \frac{V}{A} = \frac{20 * 30 * 5mm^3}{2(20 * 30 + 20 * 5 + 30 * 5)}$$

$$= 1{,}76\ mm \quad (17)$$

$$Bi = \frac{hl_c}{k} = 0{,}096 < 0{,}1 \quad (18)$$

so the system is a stacked system.

For the stacked system, the temperature changes over time;

$$t = \frac{\rho V c}{hA} ln\left(\frac{\theta_i}{\theta}\right) = \frac{\rho c l_c}{h} ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right) \quad (19)$$

When we write the values in the above equation, It has been estimated that the time required for wood parts to reach 773 K is 9,8 min. This time refers to the time the particles stay in the pyrolysis reactor. After creating the mathematical model; A finite element model of the pyrolysis reactor was constructed and when the mesh operation was carried out, more frequent meshing was performed at the temperature transition points as shown in Figure 2 and the temperature values at these points were tried to be observed more precisely. Then, as shown in Figure 3, the inlet and outlet locations of the reactor were determined and analysis of the wood particles was carried out according to the variables (temperature, flow rate, etc.) in these regions.

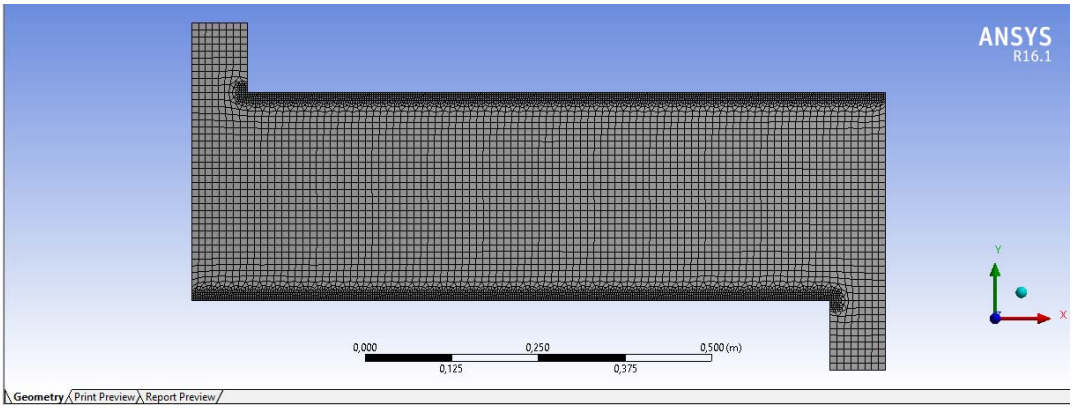

Figure 2. Pyrolysis reactor mesh structure

Figure 3. Pyrolysis reactor inlet and outlet

Values such as density, thermal conductivity and viscosity of wood parts are taken from the Fluent database. As boundary conditions;

- The speed of 0.001 m/s and the temperature of 393 K are defined at the inlet of the reactor.
- The outer surface of the pyrolysis reactor is assumed to be at a temperature of 873 K.

The analysis was solved according to these boundary conditions and the temperature and velocity distributions in the reactor were found as follows in Figure 4 and Figure 5.

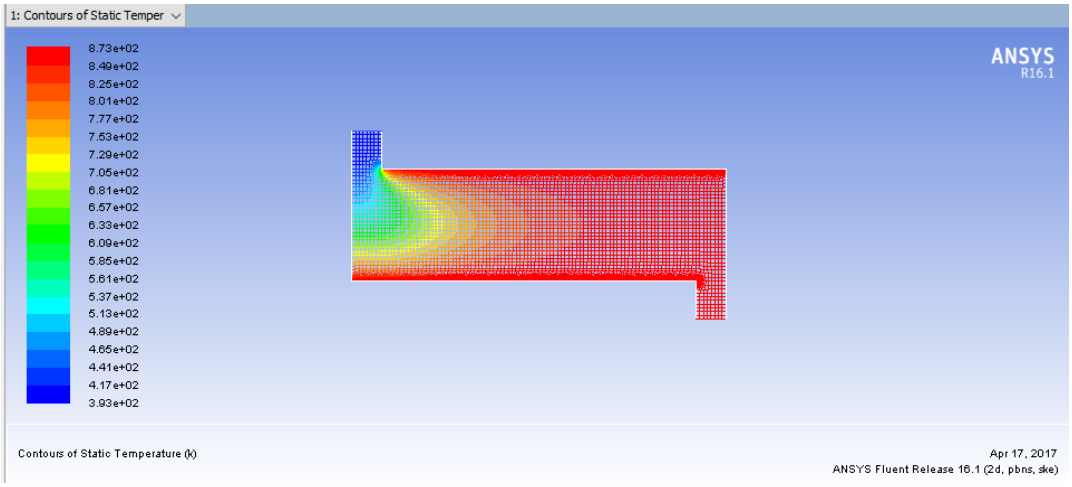

Figure 4. Temperature distribution in pyrolysis reactor

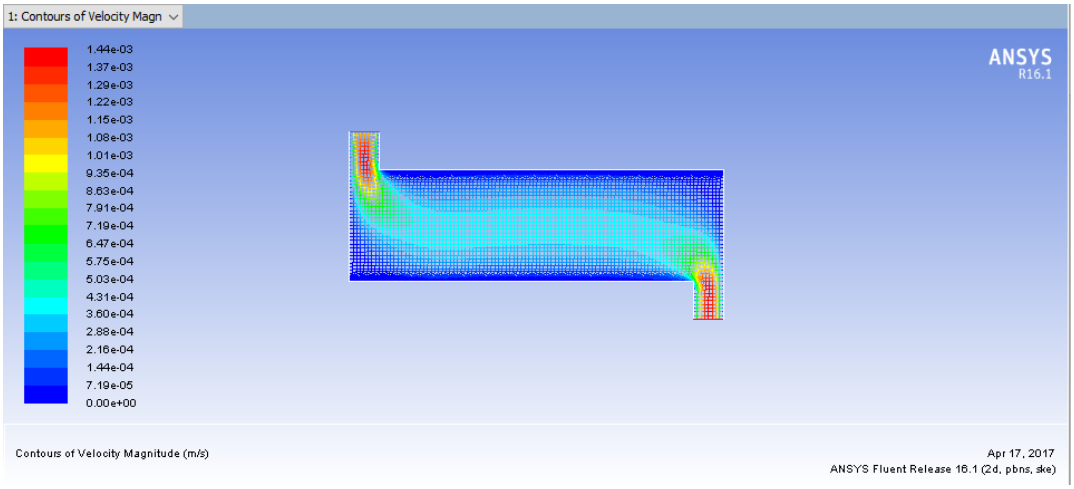

Figure 5. Velocity distribution in pyrolysis reactor

3. Results

The total residence time in the mathematical model was 9.8 minutes. When we strike this value with 0,001 m / s which we gave as input condition, we find 0,588 m. This value indicates the length of time the wood pieces need to go in order to reach the desired temperature. Taking into account the possible heat losses, it is considered that the optimum length for the pyrolysis reactor is 1000 mm.

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