

A TEMPERATURE STUDY OF DOUBLE LAYERS CHARCOAL KILN USING CFD

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Abstract

This research aimed to study the temperature efficiency of vertical charcoal metal kiln compared between the original kiln and improved charcoal kiln with thermal insulation to prevent heat loss. The computational fluid dynamics (CFD) model was used for analysis. The improved charcoal kiln with thermal insulation to prevent heat loss to change airflow within kiln's chamber. Components of improved kiln consisted of; 1) The insulated cover lid made from fiberglass in cylindrical shape with thickness of 10 cm., height of 100 cm., and diameter of 65 cm., wrapped with steel sheet 2 mm. of thickness; 2) The metal combustion chamber in cylindrical shape, with 56 cm. of diameter, 89 cm. of height and 0.2 m³ of capacity; 3) Metal grate placed 10 cm. inside the combustion chamber; 4) The kiln base for fuel input, with space for airflow to the chimney and for sand input in order to prevent heat loss while testing; and 5) The 4 inches pipe-shaped steel chimney, with thickness of 2 mm. and height of 200 cm. The computational fluid dynamics (CFD) model found that the maximum temperature was similar. When, it was compared the double layers vertical charcoal metal kiln to prevent heat loss with the original kiln, it was found that the average temperature was improved at 277.54°K, the charcoal kiln temperature efficiency was improved at 51.47 percentage, the average air velocity was improved at 1.26 m/s, of which resulted from the change of airflow direction (stream line).

Keywords: Charcoal, Charcoal kiln, CFD, Temperature efficiency, Air velocity

Introduction

As the world developing, the human population is also increasing which results in the greater demand for energy consumption. Nowadays, the energy consumption rates is 52% increasing due to the increasing of human population (John, 1991). Main energy sources are fossil fuels such as oil, charcoal and natural gas. Fossil fuels are

the conventional energy that causes global environmental problem such as dust (Florinda *et al.*, 2019). Therefore, the renewable energy has been invented and developed to replace the fossil fuels (Abas *et al.*, 2015). Biomass materials contain natural energy in organic form. It can be used as energy sources such as rice husk, straw, sugarcane

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residue, sugarcane stalk, palm shell, palm bunch, coconut shell, wood waste, grass etc. Plant stores energy in different parts which results from the photosynthesis process. Therefore, plants biomass can be used as fuel for combustion and obtain heat energy (Ahmed, 2012; Ayhan *et al.*, 2016).

There were several studies on biomass fuel, especially the production of charcoal from the process of wood burning by using various type of kilns (Adam, 2009). Many countries has developed methods of charcoal burning for energy utilization (Sami *et al.*, 2001; Hassan *et al.*, 2000; Adam, 2009; Alphonse *et al.*, 2012; Erick *et al.*, 2000; García *et al.*, 2013; Kimaryo *et al.*, 1989; Wilbel *et al.*, 2010), including Thailand (Forest Products Research Division, 1984; Yanyong *et al.*, 2009). There were low-cost charcoal kilns, high efficiency kiln and original kiln that was inefficient (Idi *et al.*, 2018a; Idi *et al.*, 2018b; Paddon *et al.*, 1980; Mustika *et al.*, 2018). Kiln's quality was improved in combination with electric energy and automatic control system, which resulted in a better combustion (Vilela *et al.*, 2014). The original kilns was improved by adding a cooling zone to improve the efficiency of charcoal production (Mussie and Hassan, 2014). Moreover, there were studies on the environmental effects from charcoal burning (Fabien *et al.*, 2009; Tunga *et al.*, 2014), the studies on woods arrangements to improve the efficiency of charcoal burning (Luwaya *et al.*, 2014), and studies on woods pile arrangements in large kiln to reduce thermal impacts in cooling zone (Morad *et al.*, 2017). From the previous studies on the effect of kiln walls and the relevant factors to improve the efficiency of charcoal kiln, it was found that a solid wall structure could reduce the damage kiln's structural and extend its utilization lifetime (Bustos-Vanegas *et al.*, 2008). There were also studies on the increasing of charcoal production (Ramosa and David, 2014). In addition, the thermal efficiency of various type of kiln was studied and mathematical model was implemented for comparison. The biomass fuel kilns used in the study were household stoves and kilns for ceramics, pots, jars, and earthenware (Hassanein *et al.*, 2015; Vicente *et al.*, 2009; Edwin, 2015). There was a study on the method of thermal expansion measurement in order to determine the temperature of traditional burning of ceramic. The analysis showed that the thermal expansion of ceramics was the same and burning temperature was the same as well (William, 1980). The study of 3D simulations in the injector nozzles were conducted to evaluate the temperature distribution inside the continuous kiln, in case using hot air emerge from the cooling zone (Adnan *et al.*, 2017). For charcoal kilns, there were studies on the physical

characteristics and operating conditions of fireplaces and stoves that commonly used in Portugal for domestic heating based on biomass combustion (Calvo *et al.*, 2014). Moreover, as for charcoal burning, the technical feasibility of cotton stalk carbonization and torrefaction was studied. The experiments used metallic homemade cylindrical furnace with 60 cm in diameter and 90 cm in height. A partial combustion process was used both for carbonization and torrefaction. From the experiment was aimed to determine the mass and energy yield, proximate analysis and the unburnt cotton stalks proportion (ratio of non-carbonized cotton stalks over carbonized cotton stalks) for each process. The anhydrous mass yield for the best carbonization process was about 28.4% while energy yield was 45.8%. The carbonized cotton stalk had 24.15% and 67.44% of volatile matter and fixed carbon content, respectively (Harouna *et al.*, 2015). There are 3 types of charcoal burning from the furnace to produce biochar. The ratio of biochar to feedstock was (0.38) and quality was (TGI = 0.14), which increased slightly for the larger kilns. Quality of biochar was found to be mainly related to pyrolysis time. The costs for the biochar stove and pit kiln were US\$ 65-77, while the large size steel kiln was US\$ 154 (Mia *et al.*, 2015). The research showed that if wood burning system is effectively controlled by well-developed charcoal burning technology, the problems such as dust and smoke during winter season and the residue of charcoal from burning would decreased or solved (Sparrevik *et al.*, 2015). Currently, biomass charcoal burning, which is the burning of wood chips and residues from agricultural activities such as branches of eucalyptus woods, is commonly used as firewood, due to its characteristics of flammable with less ashes (Pereira *et al.*, 2012). The charcoal kilns with the control of temperature air ventilation can increase the efficiency of charcoal burning, and reduce loss in charcoal burning process. There are various studies on the kiln development, as well as the mathematical models of thermal in charcoal burning process. There was a study of computational fluid dynamics (CFD) model that used for the charcoal combustion evaluation (Yiran and Yansong, 2019). The models were applied in thermal analysis of various types of kilns (James *et al.*, 2009; Atieh, 2011; Ariyaratne *et al.*, 2014; Ariyaratne *et al.*, 2015; Gajendra and Shabina, 2016; Aphichat *et al.*, 2017; Aphichat *et al.*, 2018), including the loss of kiln wall due to charcoal burning (Jaime *et al.*, 2018). At present, the responsible and relevant government agencies has encouraged the use of efficiency kiln for charcoal production. Charcoal can be used for cooking fuel and sale for income for people in

remote areas. However, there was no study on heat loss prevention and re-use the heat of the artificial charcoal kilns in Thailand, which results in low efficiency of charcoal burning due to heat loss in kiln's surface area. The re-use of heat released from chimney by a loop recovery can accumulate the heat in furnace, which makes the charcoal burning more efficient, and reduce the burning time and increase the burning temperature. Moreover, there was lack of studies on mathematical model analysis for charcoal burning using kiln that recover the heat for heat accumulation.

Therefore, this research aimed to study the thermal characteristics of a vertical cylinder charcoal kiln with double wall layers to prevent heat loss. In this research, the CFD mathematical model was used for analysis. The charcoal burning was compared between using original kiln and improved kiln. The results from this study can be used for efficiency charcoal burning, reduce the burning time and develop charcoal kilns that are practical for community.

Materials and Methods

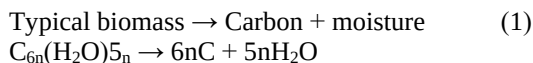
Carbonization

Carbonization is a process of converting an organic substance into carbon containing residue. For wood, it means heating wood with restricted air flow, resulting in the production of charcoal that has four main stages following (Witold *et al.*, 2020);

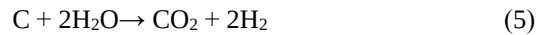
1. Initial dehydration was endothermic of the wood (200°C).
2. Pre-carbonization that pyrolygneous liquids can be condensed (170-250°C)
3. Exothermic reaction, light tars and pyrolygneous liquid come out steadily (250-300°C).
4. Drive off volatile components, increasing carbon content of charcoal (>300°C).

Pyrolysis

Pyrolysis means chemical decomposition of organic materials by heating in the absence of oxyge that is similar with carbonization but higher temperature, higher energy gaseous products. The pyrolysis product are charcoal, wood or pyrolygneous acid, vinegar, wood tar and wood (Saravanakumar and Haridasan, 2013; Nan *et al.*, 2020; Tintner *et al.*, 2020; Babinszki *et al.*, 2021; Felix *et al.*, 2021). The reaction involved with carbonization of biomass is;



Secondary reactions which also occur during the process are;



The improved vertical charcoal kiln energy accumulation with

The heat transfer among of the gas, solid and kiln wall is considered with the energy balances for gas, solid and kiln wall (Young, 2012). the energy balances can be formulated following;

$$\begin{aligned} \frac{1}{V_g} \frac{\partial(Q_g C_g T_g)}{\partial T} &= \frac{\partial(Q_g C_g T_g)}{\partial Z} - C_1(T_g - T_s) \\ &\quad - C_2(e_g T_g^4 - A_v T_s^4) - C_3(T_g - T_w) \\ &\quad - C_4(e_g T_g^4 - A_v T_w^4) \end{aligned} \quad (6)$$

The energy balance for the solid material following;

$$\begin{aligned} \frac{1}{V_s} \frac{\partial(Q_s C_s T_s)}{\partial T} &= \frac{\partial(Q_s C_s T_s)}{\partial Z} - C_1(T_g - T_s) \\ &\quad - C_2(e_g T_g^4 - A_v T_s^4) + C_5(T_w - T_s) \\ &\quad - C_6(e_w T_w^4 - A_v T_s^4) - \frac{\partial Q_s}{\partial Z} H_v \end{aligned} \quad (7)$$

The energy balance for the kiln wall following;

$$\begin{aligned} \frac{\partial(M_w C_w T_w)}{\partial T} &= \frac{\partial(M_w C_w T_w)}{\partial Z} + C_3(T_g - T_w) \\ &\quad + C_4(e_g T_g^4 - A_v T_s^4) - C_5(T_w - T_s) \\ &\quad - C_6(e_w T_w^4 - A_v T_s^4) \end{aligned} \quad (8)$$

The material balance for the solid is also given as;

$$\frac{1}{V_s} \frac{\partial Q_s}{\partial T} = - \frac{\partial Q_s}{\partial Z} - \frac{h_t A (T_g - T_s)}{H_v} \quad (9)$$

The balance for the gas is given as ;

$$\frac{1}{V_g} \frac{\partial Q_g}{\partial T} = \frac{\partial Q_g}{\partial Z} + \frac{h_t A (T_s - T_g)}{H_v} \quad (10)$$

The original vertical charcoal kiln

The original vertical charcoal kiln consisted of the combustion chamber, made of metal in cylindrical shape with diameter of 56 cm, height of

89 cm, and capacity of 200 liters (0.2 m^3). Chamber had a removable lid with a steel chimney diameter of 15 cm. The chamber base was put 15 cm. belowground and in a pit diameter of 60 cm. Then, bricks were stacked surround the chamber up to 12 cm from top of chamber. Clay was wrapped surround the chamber during burning process to prevent heat loss, as shown in Figure 1. For the model of original vertical charcoal kiln, as shown in Figure 2.



Figure 1. The original vertical charcoal kiln in Thailand



Figure 2. The model of original vertical charcoal kiln in Thailand

The improved vertical charcoal kiln

The improved vertical charcoal kiln with thermal insulation was designed using the principle of Accumulation Energy to alter air flow inside the kiln. The components of improved vertical charcoal kiln consisted of: 1) The insulated cover lid made from fiberglass in cylindrical shape with thickness of 10 cm, height of 100 cm, and diameter of 65 cm, wrapped with steel sheet 2 mm thick; 2) The metal combustion chamber in cylindrical shape, with diameter of 56 cm, height of 89 cm, and capacity of 0.2 m^3 ; 3) Metal grate placed 10 cm inside the combustion chamber; 4) The kiln base for fuel input, with space for airflow to the chimney and for sand input in order to prevent heat loss while testing; and 5) The 4 inches pipe-shaped steel chimney, with thickness of 2 mm and height of 200 cm, as shown in Figure 3 and Figure 4.



Figure 3. An improved vertical charcoal kiln

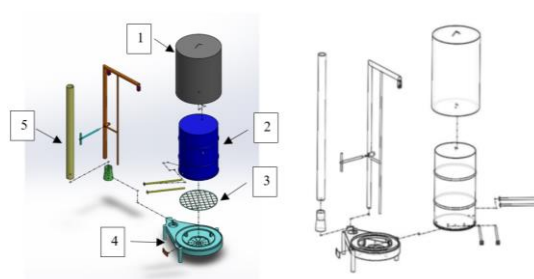


Figure 4. The design of an improved vertical charcoal kiln

A computational fluid dynamics (CFD) model of charcoal kiln was constructed for comparative analysis. Internal air of charcoal kiln was analyzed using model as shown in Figure 5. Charcoal kiln was analyzed by compare the internal temperature and velocity of air circulation in the combustion chamber. The conditions used for the analysis were given in Table 1 and Table 2. The condition for modeling was showed in Table 3.

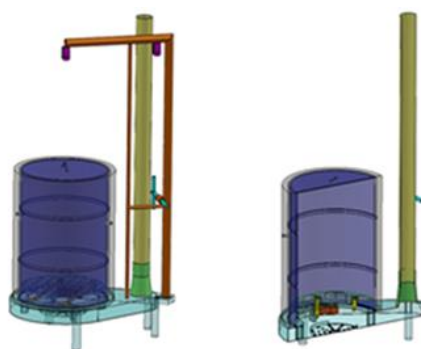


Figure 5. The model of an improved vertical charcoal kiln

Table 1. Assumptions used in analysis

No.	Condition
1	Analysis of fluid properties depends on the coordinates and time (transient)
2	Use of air properties as a fluid property in analysis
3	Analysis in 3D
4	Analysis by considering the gravity
5	The viscosity model uses the Standard k-epsilon equation (2 eqn).
6	Solve the Temperature-Velocity Coupling SIMPLE Schematic

Table 2. Conditions used in analysis

No.	Parameter	Unit
1	Velocity starts in the model.	*m/s
2	Air temperature	K
3	Heat transfer coefficient	W/m ² K
4	Simulation time	hr
5	Time step size	s

Table 3. Temperature comparison between original and improved kilns with thermal insulation

Variable	Original kiln	Improved kiln
Maximum temp. (K)	1,053.17	1,050.98
Minimum temp. (K)	297.80	798.48
Average temp. (K)	539.26	816.80
Max. air velocity (m/s)	4.05502	4.27147
Min. air velocity (m/s)	0.000157	0.001991
Avg. air velocity (m/s)	1.56267	2.82058

The strength analysis in steady state (Jarinee and Kiatfa, 2013; Çengel and Ghajar, 2015; Aphichat *et al.*, 2017; Aphichat *et al.*, 2018) by implementing the energy equations was showed as Equations (1)-(4).

Continuity

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho u) = 0 \quad (11)$$

x-momentum

$$\frac{\partial(\rho u)}{\partial t} + \text{div}(\rho u u) = -\frac{\partial p}{\partial x} + \text{div}(\mu \text{grad} u) + S_{Mx} \quad (12)$$

y-momentum

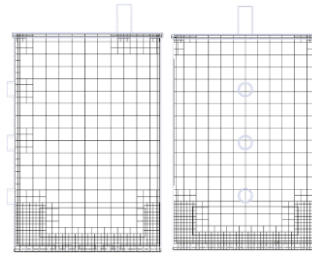
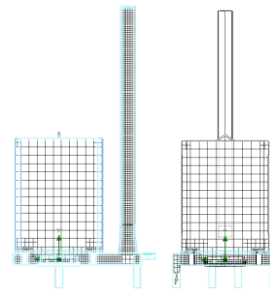
$$\frac{\partial(\rho v)}{\partial t} + \text{div}(\rho v u) = -\frac{\partial p}{\partial y} + \text{div}(\mu \text{grad} v) + S_{My} \quad (13)$$

z-momentum

$$\frac{\partial(\rho w)}{\partial t} + \text{div}(\rho w u) = -\frac{\partial p}{\partial z} + \text{div}(\mu \text{grad} w) + S_{Mz} \quad (14)$$

The mathematical model of charcoal kiln designated air with steady density and flow in steady state. The mathematical model used in this study was standard k-ε model. Earth's gravity was designated for Y axis, of -9.81 m/s², and determined the conditions for analysis. Then, the condition was defined for model analysis, which were heat source at temperature of 1,073.15 K (800°C), charcoal cooling at 100 watts. Then, the temperature, pressure, wind speed and air flow were analyzed using mathematical model. This analysis is based on the assumption that the heat flux from the heat source is constant, without numerical chemical reactions and fuel combustion situations (Mohamad and Mohamad, 2017). The heat flux used in the analysis was carried out by actual on-site testing and the obtained test results were determined in the computational fluid dynamics analysis.

The analysis started with grid independent to determine the appropriate size before the analysis. Crude grid analysis was conducted as the fundamental element and observed the maximum temperature in the model. Then, the elements were divided into smaller sizes to observe the elements level that maximum temperature did not differ from the previous level, as shown in Figure 6 and Figure 7.

**Figure 6. Grid independence of original vertical charcoal kiln****Figure 7. Grid independence of improved vertical charcoal kiln**

Results and Discussion

The analysis of grid independence found that the average temperature found to be steady as the number of elements reached approximately 6×10^5 elements. Therefore, the models with other conditions will use the same elemental conditions for analysis, as shown in Figure 8.

There are two kiln models consisted of original kiln and improved kiln with thermal insulation. Each kiln had different air circulation and temperature distribution. Heat in original kiln distributed from front to top and released to outside environment through chimney. Therefore, temperature at front and bottom kiln was higher than in the middle kiln. While heat in the improved kiln distributed from the bottom to the top, and then circulated back to the bottom to release heat out of combustion chamber through chimney to outside

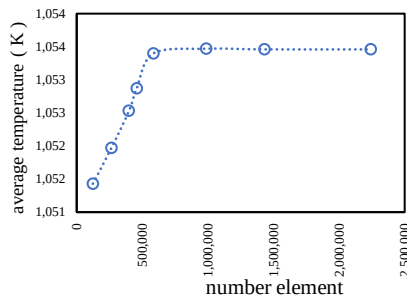
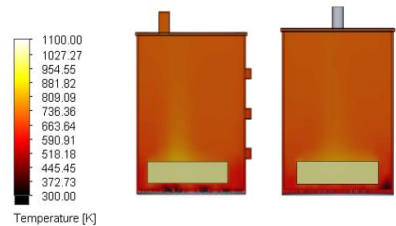
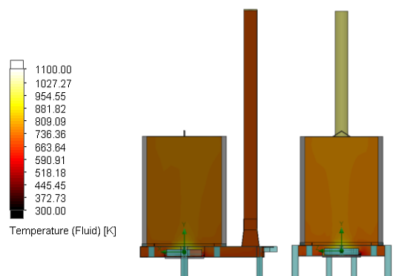


Figure 8. mesh independent



(a) Temperatures inside the original kiln



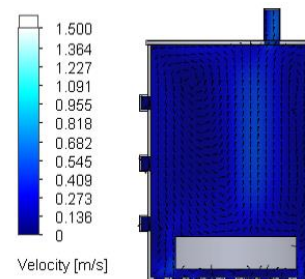
(b) The temperature inside the improved kiln with thermal insulation.

Figure 9. Grid independence of improved vertical charcoal kiln

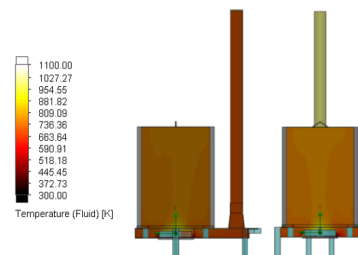
environment. As a result, the temperature within improved kiln was higher than the original kiln. The analysis results were shown in Table 1 and Figure 9.

The results of internal air velocity showed that hot air inside the chamber moved from the front through the middle of the chamber, then released to outside environment through chimney. The steady state analysis found the differences of air velocity within the chamber. As for the original kiln, hot air velocity at the chimney area was highest, followed by velocity at fire area. The air velocity was low at the middle of the chamber due to firewood blockage when compared to air velocity at sidewall of the kiln, as shown in Figure 10(a). While air velocity and pressure of the improved kiln with thermal insulation were higher than those in the original kiln, as shown in Figure 10(b).

The direction of internal hot air circulation in the kiln found that air circulation in each model had different directions. The original kiln had air circulation at fire area. Air volume at the top kiln through the chimney was higher than in the middle, resulting in higher velocity than other parts of the kiln. While air in the improved kiln circulated at the middle chamber, before moving towards the chimney. The analysis was shown in Figure 11.



(a) Air velocity vector of the original kiln



(b) Air velocity vector of the improved kiln with thermal insulation.

Figure 10. Air velocity of original and improved kiln with thermal insulation

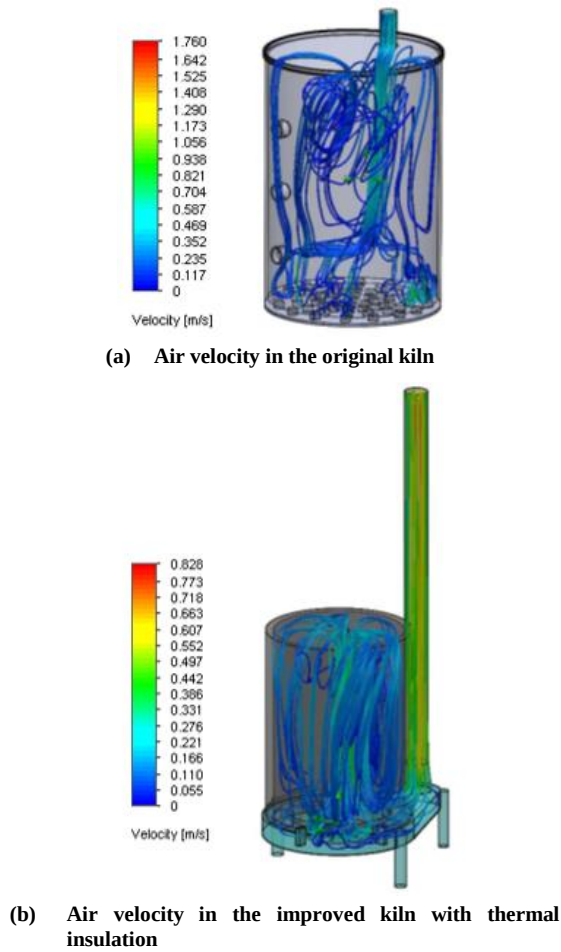


Figure 11. Air velocity in the kiln

Conclusions

The results from Computational Fluid Dynamics (CFD) found that when changing the airflow, the maximum temperature of improved kiln was 1,050.98 K (777.83°C), and the maximum temperature of original kiln was 1,053.17 K (780.02°C). The average temperature of improved kiln was 816.80 K (543.65°C), and the average temperature of original kiln was 539.26 K (266.11°C), the average temperature was improved at 277.54°K, the charcoal kiln temperature efficiency was improved at 51.47 percentage. The average air velocity of improved kiln was 2.82 m/s, and average air velocity of original kiln was 1.56 m/s. Air velocity improved on the average of 1.26 m/s. Thus, it can be concluded that the metal kiln

with thermal insulation that developed based on the principle of energy accumulation, can enhance the efficiency of metal kiln.

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Nomenclatures

A	gas-solid surface (m ² /m)
A _v	absorptivity
C	model parameters
C _g	specific heat of gas (kJ/(kg K))
C _s	specific heat of solid (kJ/(kg K))
C _w	specific heat of kiln wall (kJ/(kg K))
e _g	gas emissivity
e _s	solid emissivity
e _w	emissivity of internal surface of wall
h _{gs}	heat transfer coefficient between the solid and gas (W/m ² K)
h _{gw}	heat transfer coefficient between the wall and gas (W/m ² K)
h _t	convection coefficient between the gas and solid (W/m ² K)
h _w	heat transfer coefficient between the wall and solid (W/m ² K)
H _v	latent heat of vaporization of VOC (kJ/kg)
M _w	wall mass per unit kiln length (kg/m)
Q _g	gas flow rate (kg/s)
Q _s	solid flow rate (kg/s)
T _g	gas temperature (K)
T _s	solid temperature (K)
T _w	temperature of internal surface of the wall (K)
t	time (s)
V _g	gas velocity (m/s)
V _s	solid velocity (m/s)
z	kiln tall (m)

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