

Numerical Simulation of Combustion Behavior in Stoker-type Incineration System[†]

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Abstract:

To improve the performance of the stoker-type incineration system, JFE Engineering has developed the numerical simulator to understand the combustion behavior in the incinerator. In the first step, the suitable reaction mechanism for combustion was selected. In next step, by using the actual-size 3-dimensional entire incinerator model, temperature and CO concentration was calculated and compared with measured temperature and CO concentration in actual plant. As a result, calculated values agreed with measured values approximately. It showed that this numerical simulator is appropriate for an analysis of the combustion behavior of the stoker-type incineration system and is useful for a development and design tool.

1. Introduction

Since the Great East Japan Earthquake in March 2011, heightened expectations have been placed waste power generation as a form of renewal energy. Accompanying this, demands for high performance in waste incinerators has also become stronger, increasing the importance of technical development.

Until now, development of waste incinerators had been carried out mainly by experimental techniques. Although numerical simulation techniques had also been attempted¹⁾, many of those efforts were fundamental studies using 1-dimensional or 2-dimensional models. As reasons for this, because the material being incinerated is waste, properties are non-uniform and quantitative fluctuations are large. Moreover, in order to make highly accurate calculations with a large-scale

3-dimensional model of actual incinerator size, it is necessary to include the detailed combustion reaction mechanism, and the fact that calculations required an enormous amount of time was also an issue. As the development of a numerical simulation technology which can easily handle actual-size large-scale 3-dimensional models would provide an extremely useful tool for research and development and design, the establishment of such a technology has been strongly desired.

With the aim of establishing a numerical simulation technology like that outlined above, JFE Engineering carried out development, focusing on the JFE Hyper 21 Stoker System, which is the company's state-of-the-art stoker-type waste incinerator. First, using a general-purpose thermal fluid code (Fluent), a simple, accurate combustion reaction mechanism for gas combustion in the incinerator was selected based on a study with a 2-dimensional model. Next, the actual-size 3-dimensional entire incinerator model was developed, in which the calculation region was expanded to the entire incinerator, and calculations were performed. The calculation results and the results of measurements of an actual incinerator were compared, and were approximately in agreement, confirming the appropriateness and usefulness of this numerical simulation technology. The results of this development are described in this paper.

2. Features of JFE Hyper 21 Stoker System

First, the JFE Hyper 21 Stoker System, which is JFE Engineering's state-of-the-art stoker-type waste incinerator, will be explained.

The JFE Hyper 21 Stoker System is based on the two

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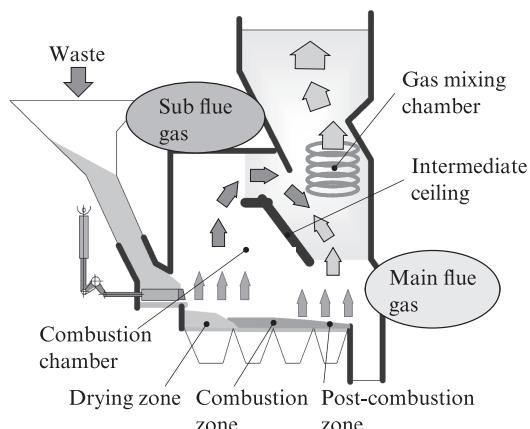


Fig. 1 Two way gas flow incinerator

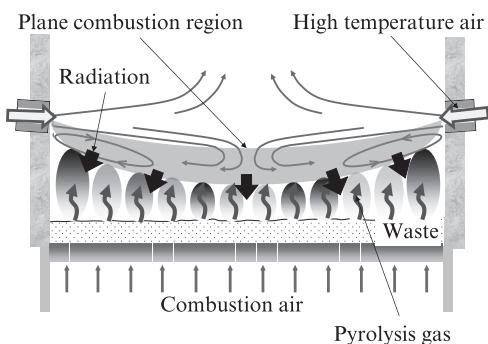


Fig. 2 Flame stabilization image in cross section at combustion beginning area

way gas flow incinerator²⁾, which was adopted independently by this company from an early date, and is a next-generation stoker-type incinerator³⁻⁵⁾ that utilizes High-temperature Air Combustion Technology (HiCOT) to realize a further reduction in environmental pollutants and substantial improvement in power generating efficiency. For the plant flow, the reader may refer to a previous report⁶⁾.

The structure of the two way gas flow incinerator is shown in **Fig. 1**. The flow in the incinerator is divided into two parts, i.e., sub flue gas and main flue gas, by providing a partition called an “intermediate ceiling” in the combustion chamber. The sub flue gas, which includes an uncombusted component, and the main flue gas, which has a comparatively large oxygen content, collide head-on in the gas mixing chamber, where they are mixed and stirred effectively.

As another technology, HiCOT is applied in the JFE Hyper 21 Stoker System. **Figure 2** presents a lateral cross-sectional view of the incinerator, showing a schematic illustration of the combustion behavior when HiCOT is applied. In the combustion beginning region, where the waste in the furnace is dried and combustion begins, high temperature air is blown directly above the waste layer from the right and left side walls of the incinerator. This causes the high temperature air and the



Photo 1 Photograph of flame in incinerator

pyrolysis gas evolved from the waste layer to collide, and also forms a counterflow field. Because the counterflow diffusion flame stabilizes easily in the low flow velocity region of this counterflow field, the effect of radiant heating expands from this flame to the waste layer. As a result, pyrolysis of the waste is accelerated and an extremely stable combustion field is formed. This makes it possible to realize stable combustion with a low excess air ratio, which had been difficult to achieve in conventional stoker-type incinerators.

Photo 1 was taken from the downstream side of the incinerator in an actual JFE Hyper 21 Stoker System during stable operation. A stable flame, including a luminous flame directly above the waste layer, can be seen, and the counterflow field shown in Fig. 2 has formed.

3. Selection of Simple Combustion Reaction Mechanism

3.1 Outline of Combustion Reaction Mechanism

The purpose of this development was to develop a numerical simulation technology for waste incinerators, which enables easy handling of a large-scale 3-dimensional model of actual incinerator size. From this viewpoint, it was considered desirable to select a simple combustion reaction mechanism which would not increase the computational load more than necessary.

Therefore, we compared and studied two simple combustion reaction mechanisms, which were thought to be practical, using the high accuracy detailed combustion reaction mechanism for CH₄, GRI1.2⁷⁾ (32 chemical species, 177 reaction formulas) as a standard. These two mechanisms were DRM19⁸⁾ (21 chemical species, 84 reaction formulas), which is a skeletal reaction mechanism based on GRI1.2, and a reaction mechanism for CO₂/H₂ proposed by Yetter⁹⁾ (13 chemical species, 35 reaction formulas).

What is important here is the composition of the waste pyrolysis gas. It is known that the main components are H₂ and CO, and the gas also contains hydro-

carbons such as CH_4 , C_2H_4 , etc.³⁾. Although DRM19⁸⁾ considers virtually all the chemical species which are thought to be components of pyrolysis gas from waste, because the reaction mechanism was originally prepared for use with CH_4 , it is necessary to determine the combustion characteristics when calculated with a pyrolysis gas composition having high concentrations of CO and H_2 . On the other hand, CH_4 , C_2H_4 , etc. can not be considered because Yetter's mechanism⁹⁾ is a reaction mechanism for use with CO/ H_2 . Therefore, it is necessary to set and perform calculations using a simulated pyrolysis gas in which the flammable components are limited to CO and H_2 .

3.2 Comparison and Study of Combustion Reaction Mechanisms by 2-Dimensional Model

In comparison and study of the combustion reaction mechanisms, a general-purpose thermal fluid code (Fluent) was used. The analysis domain was the 2-dimensional jet field shown in Fig. 3. This domain is enclosed by a symmetric plane and an adiabatic wall; the inner side is provided with a pyrolysis gas supply part, and the outer side is provided with a high temperature oxidizer gas supply part.

Table 1 shows the calculation conditions. The temperature of the pyrolysis gas was 1 000°C, and that of the oxidizing agent was 250°C, which is the same as in an actual incinerator. In Case A and Case B, the pyrolysis gas composition³⁾ which was obtained experimentally was used, and in Case C and Case D, the simulated pyrolysis gas composition was used. Here, the simulated pyrolysis gas composition was determined so that the enthalpy of formation and the atomic numbers of C and H were the same as those of the experimentally-obtained pyrolysis gas.

Table 2 shows the calculation time when using the respective combustion reaction mechanisms. In comparison with GRI1.2⁷⁾, the calculation time is shortened in

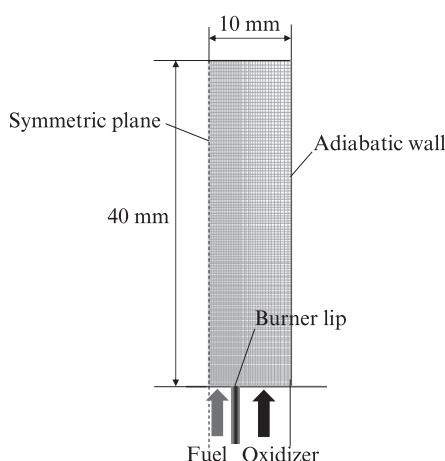


Fig. 3 Two-dimensional domain of calculation

both cases, and in particular, the calculation time was reduced to about 1/4 when using the Yetter mechanism⁹⁾. Thus, this study confirmed that a large reduction in the calculation load is possible by adopting the Yetter mechanism⁹⁾.

Figure 4 shows a comparison of the temperature distribution and maximum flame temperature. As the calcu-

Table 1 Calculation conditions

Case		Case A	Case B	Case C	Case D
Reaction model	GRI1.2 ⁷⁾	DRM19 ⁸⁾	DRM19 ⁸⁾	Yetter ⁹⁾	
Number of species	32	21	21	13	
Number of elementary reactions	177	84	84	35	
Mesh size	X (m)	0.01	0.01	0.01	0.01
	Y (m)	0.04	0.04	0.04	0.04
Number of meshes		5 054	5 054	5 054	5 054
	Velocity (m/s)	0.5	0.5	0.5	0.5
	Temperature (°C)	1 000	1 000	1 000	1 000
Pyrolysis gas	H ₂	0.003	0.003	0.009 35	0.009 35
	CH ₄	0.017	0.017	0	0
	C ₂ H ₄	0.017	0.017	0	0
	CO	0.13	0.13	0.187 04	0.187 04
	CHO	0	0	0	0
	CO ₂	0.239	0.239	0.230 61	0.230 61
	H ₂ O	0.20	0.20	0.192 81	0.192 81
	N ₂	0.394	0.394	0.380 18	0.380 18
Oxidizer	Velocity (m/s)	1.0	1.0	1.0	1.0
	Temperature (°C)	250	250	250	250
	O ₂	0.16	0.16	0.16	0.16
	CO ₂	0.09	0.09	0.09	0.09
	H ₂ O	0.08	0.08	0.08	0.08
	N ₂	0.67	0.67	0.67	0.67

Table 2 Comparison of calculation time

Reaction model	CPU time/Iteration	40 000 Iteration
GRI 1.2 ⁷⁾	1.77 s	19 h
DRM 19 ⁸⁾	0.81 s	9 h
Yetter ⁹⁾	0.45 s	5 h

CPU: Xeon5355 (2.66 GHz)×2
Fluent: Parallel×4

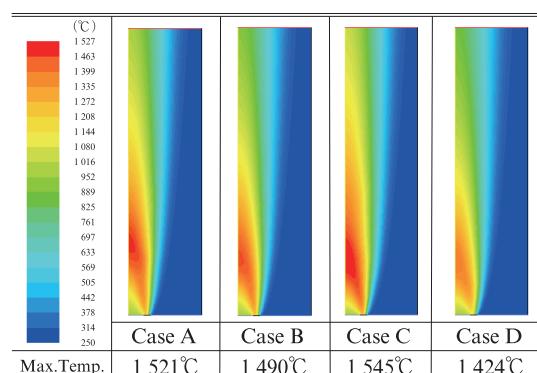


Fig. 4 Comparison of temperature distributions and maximum flame temperature

lation results of DRM19⁸⁾ (Case B) and GRI1.2⁷⁾ (Case A) show extremely close agreement, application of DRM19⁸⁾ is considered possible. Case C and Case D (results of calculation by Yetter mechanism) are cases in which the simulated pyrolysis gas composition is used. Although there is some difference in the maximum flame temperature in comparison with Case A, the temperature distribution, which is most important for understanding combustion characteristics, shows generally good agreement. Based on this fact, even though this mechanism uses a simulated pyrolysis gas composition in which the flammable components are replaced with only H₂ and CO, this is not considered to be a major obstacle, and application of a simple combustion reaction mechanism with this composition is considered possible.

From the above, based on the characteristics of each combustion mechanism, and considering calculation time to be the most important priority in this study, the Yetter mechanism⁹⁾ was selected as the simple combustion reaction model and was used in subsequent numerical simulations.

4. Combustion Analysis by 3-Dimensional Entire Incinerator Model

4.1 Calculation Conditions

Next, we examined the appropriateness and usefulness of this numerical simulation technology when applied to an actual-size 3-dimensional entire incinerator model.

Figure 5(a) shows the mesh of the 3-dimensional entire incinerator model. The scale of the incinerator was decided to be 13 000 mm in height, 9 000 mm in length, and 4 000 mm in width, which is the same as that of an actual plant (treatment capacity: 120 t/d scale). The number of meshes is approximately 85 000.

The Yetter combustion reaction mechanism⁹⁾ selected in the previous section was applied to the combustion reaction mechanism. A finite rate model¹⁰⁾ was used for combustion, a *k*- ϵ model¹¹⁾ was used for the turbulent flow, and a DO model¹²⁾ was used for radiation, respectively. A uniform temperature (1 000°C) was given as a wall surface condition, and heat loss through the wall surface was considered. As in an actual incinerator, primary combustion air (FDF), secondary combustion air (CDF), high temperature air (HADF), and recirculated exhaust gas (RDF) were supplied from the respective nozzles shown in Fig. 5(b).

Table 3 shows the calculation conditions. With this model, it is necessary to give the pyrolysis gas of the waste as the fuel. The amount and composition of the pyrolysis gas were estimated from the amount and com-

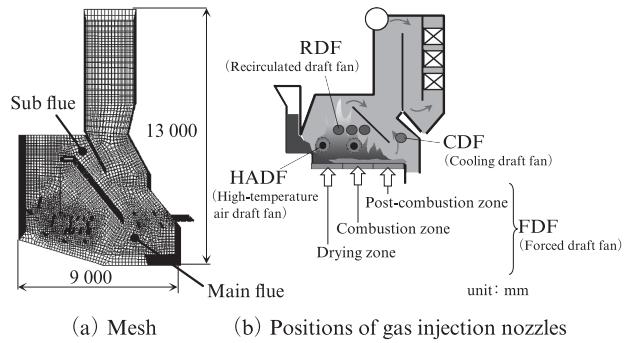


Fig. 5 The domain of the 3-dimensional entire incinerator model

Table 3 Calculation conditions

	FDF (Pyrolysis gas)			FDF (Air)			RDF	HADF	CDF
	Drying	Comb.	Drying	Comb.	Post				
Flow rate (Nm ³ /h)	5 250	5 250	1 828	2 614	786	3 100	2 100	2 710	
Temp. (°C)	600	600	60	60	60	154	220	20	
H ₂ (vol%)	11.4	11.4	0	0	0	0	0	0	
CO (vol%)	16.3	16.3	0	0	0	0	0	0	
CO ₂ (vol%)	12.8	12.8	0	0	0	11.9	6.3	0	
H ₂ O (vol%)	26.2	26.2	0	0	0	21.0	11.1	0	
O ₂ (vol%)	0	0	21.0	21.0	21.0	4.0	12.0	21.0	
N ₂ (vol%)	33.3	33.3	79.0	79.0	79.0	63.0	70.5	79.0	

FDF : Forced draft fan

CDF : Cooling draft Fan

HADF : High-temperature air draft fan

RDF : Recirculated draft Fan

Drying : Drying zone

Comb. : Combustion zone

Post : Post-combustion zone

position of waste charged to actual incinerators, and this gas was supplied from FDF. To give the FDF injection nozzle a structure close to that of the fire grate in an actual incinerator, drying zone, combustion zone, and post-combustion zone were divided into slit shapes, and a structure which enabled alternating supply of combustion air and pyrolysis gas was adopted.

4.2 Analysis of Combustion Behavior in Incinerator

Figure 6 shows the temperature distribution at a vertical cross section in the incinerator longitudinal direc-

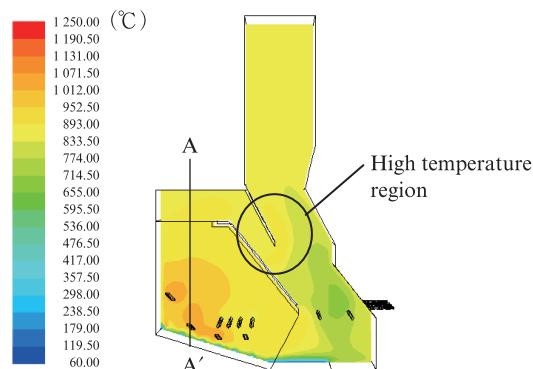


Fig. 6 Temperature distribution

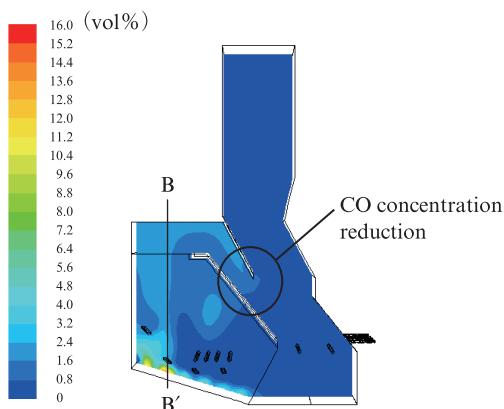


Fig. 7 CO concentration distribution

tion. From Fig. 6, it can be understood that a high temperature region exists in the sub-flue rather than in the main flue. This is because the pyrolysis gas supplied from FDF burns above drying zone and combustion zone, and the larger part of the high temperature combustion gas then flows downstream via the sub-flue.

This combustion gas flow can also be confirmed from the CO concentration distribution in the vertical cross section in the longitudinal direction shown in **Fig. 7**. That is, a region of high CO concentration is distributed in the sub-flue, and the combustion gas containing this high concentration of CO, which was generated from the combustion region directly above the fire grate, passes through the sub-flue. The CO gas that passes through the sub-flue collides with the gas from the main flue side, which has comparatively high oxygen content. The CO burns in the presence of this oxygen, and as a result, the temperature increases and the CO concentration decreases, as can be confirmed from Fig. 6 and Fig. 7. These are distinctive features of the two way gas flow incinerator, and are in agreement with the phenomena observed in actual incinerators.

Figures 8 and 9 show the temperature distribution and CO concentration distribution in a vertical cross section in the incinerator width direction (A-A' cross section in Fig. 6 and B-B' cross section in Fig. 7), respectively. From Fig. 8, it can be confirmed that the high temperature air supplied from HADF and the pyrolysis gas supplied from FDF collide in the center of the incinerator, and form a combustion region directly above the incinerator bottom (supposing the top surface of the waste layer). From Fig. 9, it can be understood that a high CO concentration region exists near the bottom of the incinerator walls. This occurs because a circulating flow is formed in the incinerator due to the effect of HADF supplied from the side walls, and part of the combustion gas generated in the incinerator center stagnates. This shows the distinctive feature of a stable and uniform combustion region of the JFE Hyper 21 Stoker System applying HiCOT.

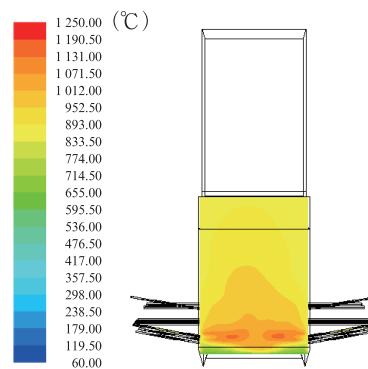


Fig. 8 Temperature distribution (A-A' Cross section in Fig. 6)

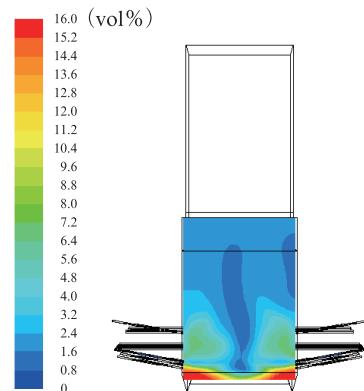


Fig. 9 CO concentration distribution (B-B' cross section in Fig. 7)

As discussed above, this study demonstrated that the features of both the two way gas glow incinerator and HiCOT can be reproduced satisfactorily in the 3-dimensional entire incinerator model in which the combustion region is expanded to the entire incinerator. This confirmed the appropriateness of this numerical simulation technology for analysis of the combustion behavior in incinerators.

4.3 Comparison with Measured Results of Actual Incinerator

Next, in order to make a quantitative evaluation, the results of these calculations and the results of measurements of an actual incinerator were compared. The measurement points in the actual plant were the combustion chamber and the gas mixing chamber. The temperature was measured at 5 points, and the CO concentration was measured at 3 points. **Figures 10 and 11** show a comparison of the calculated results and the measured results at the actual incinerator for temperature and CO concentration, respectively. The difference in the calculated and measured temperature was within $\pm 50^{\circ}\text{C}$, and that of the CO concentration was within ± 1.5 vol. %. Thus, the temperature and CO concentration could be calculated more accurately by incorporating the Yetter combustion reaction mechanism⁹⁾ in the model, and values which were approximately close to the measured values of an

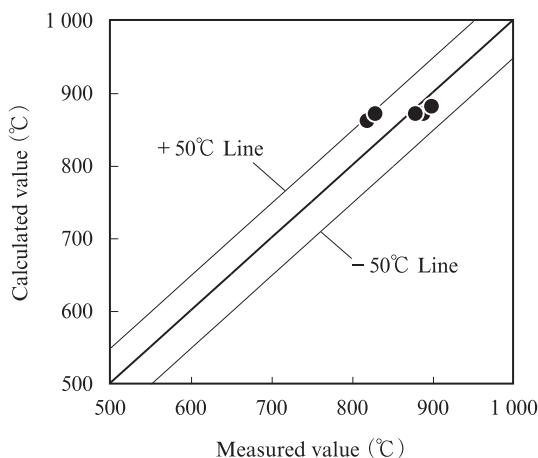


Fig. 10 Comparison between calculated temperature and measured temperature

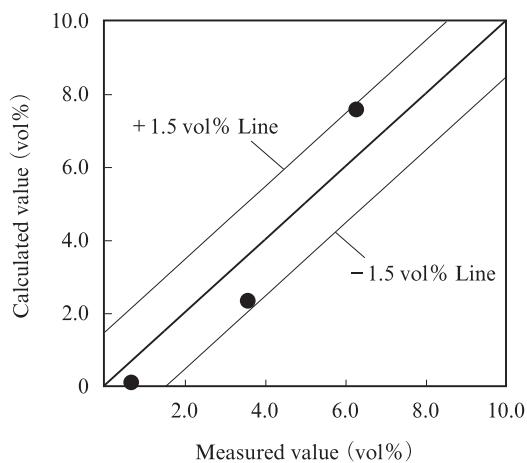


Fig. 11 Comparison between calculated CO concentration and measured CO concentration

actual incinerator could be obtained.

The study described above showed that the 3-dimensional entire incinerator model can also reproduce the combustion behavior in the incinerator quantitatively, and thus demonstrated that this numerical simulation technology is a useful tool for research and development and design.

5. Conclusion

In response to the increasing need to encourage

wider use of waste power generation, JFE Engineering is grappling with the development of numerical simulation technologies that provide useful tools for research and development and design, with the aim of developing higher performance stoker-type waste incinerators.

In this paper, first, the combustion reaction mechanism proposed by Yetter⁹⁾ was selected as a combustion reaction mechanism which enables easy handling, including large-scale 3-dimensional models of actual incinerator size. The 3-dimensional entire incinerator model was then developed, and the usefulness of the numerical simulation technology as a tool for research and development and design was clarified by a quantitative evaluation.

In the future, the authors intend to work energetically to further improve and sophisticate this numerical simulation technology.

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References

- 1) Yasuda, Toshihiko; Shigemasa, Sachiko; Furabayashi, Michitaka; Tomiyama, Shigeo. Numerical Prediction of Waste Bed Combustion in Municipal Solid Waste Incinerator. Proceedings of the 42nd Symposium (Japanese) on Combustion. 2004, p. 417–418.
- 2) Iwasaki, Toshihiko; Nakayama, Takashi; Denda, Tomohiro; Kinoshita, Seiji; Nakagawa Tomonori; Ayukawa, Susumu. Advance in Waste Incineration Technology. Journal of the Combustion Society of Japan. 2011, vol. 53, no. 164, p. 85–90.
- 3) The research and development project on advanced high-temperature air combustion technology. NEDO Report. 1999, p. 213–240.
- 4) The research and development project on advanced high-temperature air combustion technology. NEDO Report. 2000, p. 253–292.
- 5) The research and development project on advanced high-temperature air combustion technology. NEDO Report. 2001, p. 235–295.
- 6) Denda, Tomohiro; Nakayama, Takashi; Kinoshita, Seiji; Nakagawa Tomonori; Ayukawa Susumu. Proceedings of the 22nd Annual Conference of Japan Society of Material Cycles and Waste Management. 2010, p. 351–352.
- 7) <http://www.me.berkeley.edu/gri-mech/>
- 8) <http://www.me.berkeley.edu/drm/>
- 9) Yetter R. A.; Dryer F. L.; Rabitz H. A Comprehensive Reaction Mechanism For Carbon Monoxide/Hydrogen/Oxygen Kinetics. Combustion Science and Technology. 1991, vol. 79, p. 97–128.
- 10) ANSYS Fluent 12.0 theoretical guide book. chapter 7.
- 11) ANSYS Fluent 12.0 theoretical guide book. chapter 4.
- 12) ANSYS Fluent 12.0 theoretical guide book. chapter 5.