

## Optimal design of high temperature vacuum furnace using response surface method<sup>†</sup>

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### Abstract

A new method using the response surface method and optimization technique has been developed instead of the original method based on trial and error. In order to construct a response surface, thermal analysis was performed under the condition of using the calculated thermal conductivity of the insulator in a previous study. In order to set up the response surface, the D-Optimal method was used in the process of selecting experimental points. Using a weighting factor, an optimization study was carried out under the condition of satisfying user requirements. Finally, the merits and drawbacks of the new method were described by comparing with the optimal design method based on the thermal analysis database which was developed in a previous study. The optimal results show that the developed method can be used to design an energy efficient, low manufacturing cost, high temperature vacuum furnace with avoiding unnecessary iterative manufacturing, and anticipating the performance before manufacturing.

*Keywords:* High temperature vacuum furnace; Optimal design; Response surface method

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### 1. Introduction

The vacuum furnace is one piece of equipment that can be used in heat treatment. It is composed of a heater, insulator, chamber, control system and cooling system as shown in Fig. 1. These elements can be selected by the user's requirements and operating conditions. The heater and the insulator are the most important parts of the vacuum furnace, which will directly affect the energy efficiency, manufacturing and operating costs[1].

The original method, which is based on trial and er-

ror, mainly depends on experience. The heater and insulator are selected according to the user's requirements of operating temperature and ambient gas in the first step of the original design method. Then, chamber sizes and shape are selected according to the uniform temperature zone sizes. In the following step, the shape of the vacuum furnace, vacuum system and control system are defined. Finally, sample loading type is defined according to the sizes and weight of the workpiece. This method is experiential and sequential, so a problem occurring in the process of design and manufacturing may not be considered. The performance cannot be predicted before manufacturing. The manufacturing and operating costs may be increased because of over design. In a word, optimization is needed[2, 3].

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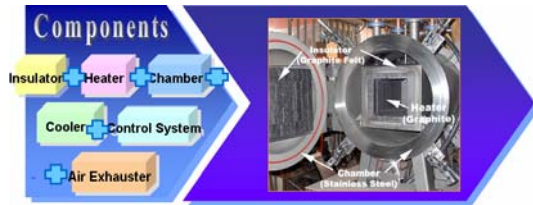


Fig. 1. Components of vacuum furnace.

In this study, a new method based on the response surface method and optimization technique has been developed which can be used to design a high temperature vacuum furnace. At first, thermal analysis was carried out for constructing the response surface under the condition of using the calculated thermal conductivity of the insulator in a previous study[4]. In the process of constructing the response surface, the D-optimal method was used to select experimental points. In the following step, an optimization study was carried out using the new method. For this optimal design, total required heat, manufacturing cost and combined operating cost and manufacturing cost were selected, respectively, as the objective function by using a weighting factor. The geometry of the vacuum furnace including the thickness of the insulator and heat zone sizes were the design variables. The interval between heater and insulator was fixed(15 mm) in this study, and uniform temperature zone sizes were imposed as the design constraints. Finally, the merits and drawbacks of the new method were described.

## 2. Thermal analysis of vacuum furnace

Heat transfer in vacuum furnace mainly includes conduction heat transfer and radiation heat transfer[5]. When ambient gas is used in heat treatment, natural convection must be considered. In order to carry out thermal analysis of the vacuum furnace, CFD-ACE analysis code was used[6]. The shape for analysis was composed of important design elements such as heater, insulator and chamber as shown in Fig. 2. In the analysis, the heater was modeled as a plate with a certain thickness(15 mm). An unstructured grid was used in the analysis in order to make the heat zone as one block. The outside of the chamber was set at a fixed temperature(27°C). In this study, the heater's boundary condition is the Neumann boundary condition(applied heat). In the analysis, the thermal conductivity of the insulator calculated in a previous

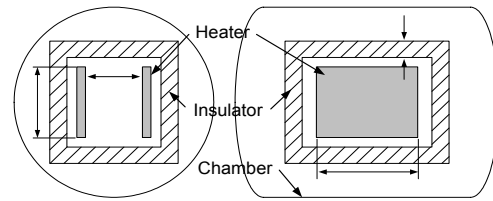


Fig. 2. Simplified shape of vacuum furnace.

study was used. As a result, the temperature of the center and uniform temperature zone sizes can be obtained.

## 3. Response surface method

In order to investigate the combined response of design variables, the required heat was expressed as a function of the design variables using the response surface method.

### 3.1 Response surface method

The response surface method is a widely adopted tool for the quality engineering field[7]. It involves regression surface fitting to obtain approximate responses, design of experiments to obtain minimum variances of the responses and optimizations using the approximated responses. For the most of the response surfaces, the functions for the approximations are polynomials because of simplicity, though the functions are not limited to the polynomials. In this study, the response surface was composed of quadratic order polynomials as Eq. (1). to set up a smooth curved surface.

$$c_m(x_i) = c_0 + \sum_{i=1}^k c_i x_i + \sum_{i=1}^k c_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k c_{ij} x_i x_j \quad (1)$$

$C_m(x)$  is required heat, and the design variables are the insulator thickness, the height(or width) of heat zone, and the depth of the heat zone. The  $c_i$  are the coefficients to be defined.  $K$  is number of design variables. When the response model is defined as quadratic order polynomial, the number of coefficients  $c_i$  can be expressed as  $(k+1)(k+2)/2$ .

In order to judge the goodness of the approximation of the response surface, the adjusted coefficient of multiple determination  $R^2_{adj}$  is used. The  $R^2_{adj}$  has maximum value of 1, and the minimum value is 0. If

Table 1. Lower and upper boundary of design variables.

Design variables	Minimum	Maximum
Thickness(Insulator)	80 mm	100 mm
Height(Heat zone)	100 mm	200 mm
Depth(Heat zone)	200 mm	300 mm

Table 2. Analysis results of the selected experimental points.

No.	Thickness (Insulator)	Heat Zone		Required heat	Work Zone		
		Height	Depth		Height	Width	Depth
1	0	0	0	4.6	150	150	230.3
2	0	1	0	7.0	200	200	233.3
3	1	0	-1	3.4	150	150	180.1
4	1	0	0	3.6	150	150	229.8
5	1	0	1	4.7	150	150	283.0
6	-1	0	0	5.0	150	150	233.1
7	0	-1	0	2.55	100	100	236.2
8	1	-1	0	2.26	100	100	232.1
9	1	1	1	7.7	200	200	281.2
10	-1	1	-1	6	200	200	185.6
11	0	-1	1	2.7	100	100	285.5
12	-1	-1	-1	2.4	100	100	188.3
13	0	-1	-1	2.28	100	100	185.0
14	1	1	-1	5.78	200	200	180.5
15	-1	-1	1	3.4	100	100	286.8

the response surface is good enough, the value becomes closer to 1.

For the problems that have complicated constraints or the design space is not a rectangle space, the conventional DOE such as the orthotropic designs can not be applied, and the computer-aided DOE methods are the only candidates. The D-optimal method is one of the popular computer-aided DOE methods. In this study, for setting up the response surface, the D-Optimal method was used in the process of selecting experimental points.

### 3.2 Construction of response surface

In reality, the design of a vacuum furnace based on experience has defined the field of shape, which can be used to define the maximum and minimum value of each design variable. Table 1 shows the lower and upper boundary of the design variables. In this study, the height and width of the heat zone have been considered as a same design variable.

For improving the reliability of the response sur-

Table 3. Coefficients of the response surface for required heat and depth of uniform temperature zone.

No.	Coefficients for required heat	Coefficients for depth of uniform temperature zone
1	4.427	231.822
2	-0.435	-1.632
3	2.293	-1.404
4	0.776	49.906
5	-0.003	-0.248
6	0.384	1.733
7	0.023	0.724
8	-0.032	0.359
9	-0.241	1.214
10	0.513	-0.534

face, 15 experimental points were selected as shown in Table 2 which is 1.5 times the unknown coefficients. When the tolerance of the temperature was set as 5°C, the height and width of the uniform temperature zone were the same with height and width of the heat zone as shown in Table 2, so only the required heat and depth of the uniform temperature zone were selected to construct response surfaces. As the evaluation standard of reliability of response, the value of  $R^2_{adj}$  is 0.95 which near the value of 1. The calculated unknown coefficients are listed in Table 3.

The required heat becomes larger when the height(width) or depth of the heat zone is increased as shown in Fig. 3 and Fig. 4 due to the effects of distance, view factor etc., and the effect of height(width) of the heat zone is larger than the effect of the heat zone depth. But the required heat becomes smaller when the thickness of the insulator is increased, as shown in Fig. 5. From the result, the thickness of the insulator must be larger in order to reduce the required heat, but it will increase the manufacturing cost. In a word, it is the reason that optimization is needed because of the different effect of each design variable.

## 4. Optimal design using response surface method

### 4.1 Optimal design strategy

The design elements of the vacuum furnace include temperature, ambient gas, the shape of the vacuum furnace, requirement of heat, heater and insulator type, control system, cooling system etc.

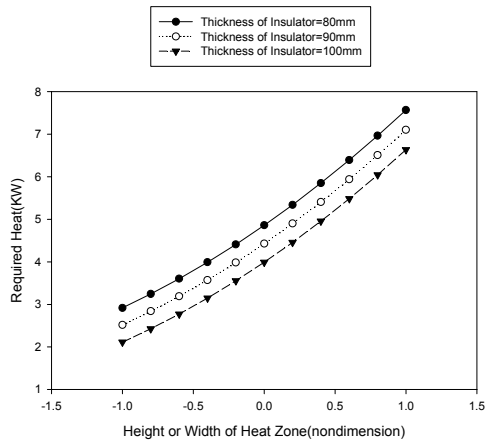


Fig. 3. Required heat affected by increasing the height (or width) of heat zone.

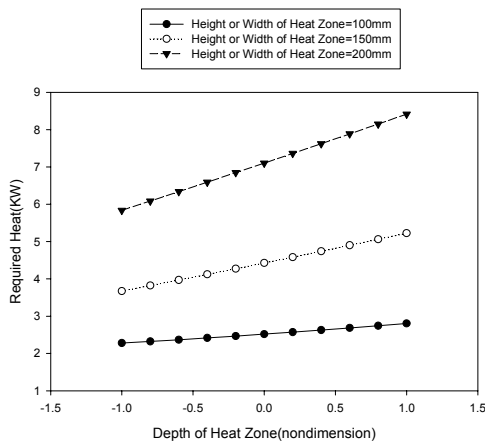


Fig. 4. Required heat affected by increasing the depth of heat zone.

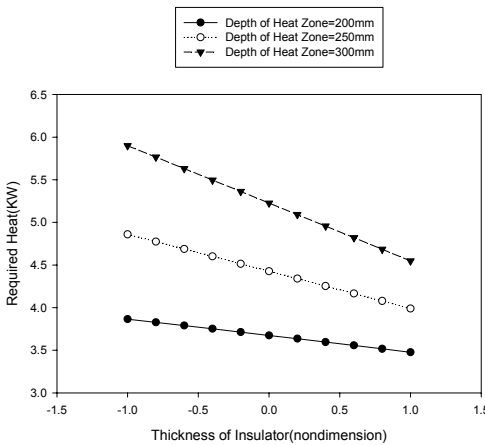


Fig. 5. Required heat affected by increasing thickness of insulator.

In this study, DOT software was used to carry out optimization based on the gradient method[8]. In this program, the algorithm of MMFD(modified method of feasible directions), SQP(sequential quadratic programming) and SLP(sequential linear programming) can be used to carry out the optimization[9].

Fig. 6 shows the process of optimal design using the response surface method. At first, design variables and constraints are initialized, and then the objective function and constraints based on constructed response surfaces are calculated, changing design variables until minimizing the objective function with satisfying constraints. This optimal design process will be used to help the designer to reduce design time and computational effort.

#### 4.2 Optimal results using response surface method

By using the constructed response surface, the optimal design was carried out under the condition of fixing the interval between heater and insulator. In this problem, the operating temperature was set to 2000°C, and constraints were the uniform temperature zone sizes of 150×150×250 (unit: mm).

A weighting factor was used in the process of optimal design of a vacuum furnace. Not only operating cost but also the manufacturing cost must be considered, when optimal design is carried out. The most important part of the operating cost is the required heat, and the most important part of manufacturing cost is the insulator cost, which is 20~30% of the total manufacturing cost. The objective function is expressed as Eq. (2).  $W$  is the weighting factor,  $q_{original}$  is required heat of original vacuum furnace described in a previous study and  $V_{original}$  is volume of the insulator

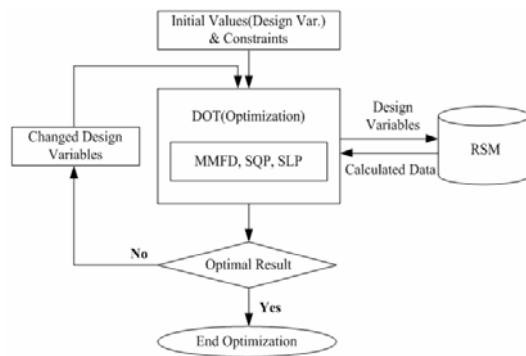


Fig. 6. Optimal design strategy using response surface method.

which can be expressed by design variables[4].

$$f = w \times \frac{q}{q_{original}} + (1-w) \times \frac{V}{V_{original}} \quad (2)$$

If only required heat is considered, the thickness of the insulator is increased. So the manufacturing cost will rise with the increase of the insulator thickness as shown in Table 4. When the weighting factor is 0, this is the case of only considering the manufacturing cost. When the weighting factor is 1, this is the case of only considering the required heat.

The results using response surface method and thermal analysis database were compared as shown in Table 5, and it can be seen that the results are nearly the same. The merit of the new method is that computational effort can be much more reduced than the optimal method using the thermal analysis database when the number of design variables is increased because the number of analysis points of the optimal method using the thermal analysis database becomes 2 times when 1 design variable is added. The drawback of the new method is that the response surface is difficult to construct when there is a wide range of design variables.

The new method using response surface method and optimization technique can reduce manufacturing and operating costs. Avoiding unnecessary iterative manufacturing, it is easy to speculate on the performance before manufacturing. In a word, optimum vacuum furnaces can be designed by using the new developed method.

Table 4. Optimal design results using different weighting factor.

Weighting factor	Thickness (Insulator)	Height (Heat Zone)	Depth (Heat Zone)	Required heat
0.0	80.0 mm	150.0 mm	266.9 mm	5.21 KW
0.65	94.5 mm	150.0 mm	268.7 mm	4.48 KW
1.0	100.0 mm	150.0 mm	269.3 mm	4.20 KW

Table 5. Comparison of analysis results between response surface method and thermal analysis database.

Thickness (Insulator) Unit: mm	Height (Heat zone) Unit: mm	Depth (Heat zone) Unit: mm	Required heat	
			Response surface method	Thermal analysis database
80.0	150.0	266.9	5.21 KW	5.21 KW
94.5	150.0	268.7	4.48 KW	4.47 KW
100.0	150.0	269.3	4.20 KW	4.20 KW

## 5. Conclusion

A new method using the response surface method and optimization technique has been developed. In order to construct a response surface, thermal analysis was carried out with the thermal conductivity of the insulator calculated in a previous study. In order to improve the accuracy of the constructed response surfaces, 15 experimental points were selected by using the D-optimal method. With consideration of operating cost and manufacturing cost, an energy efficient and low manufacturing cost vacuum furnace has been designed by using the response surface method and optimization technique under the condition of checking the accuracy. The merits and drawbacks of the newly developed optimal method were described by comparing with the optimal method using the thermal analysis database. The new method will be widely used because of high design efficiency and low computational effort.

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