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DEVELOPMENT AND INVESTIGATION OF THE REDUCED MATHEMATICAL MODEL OF THE PROCESS OF BAKING CARBON PRODUCTS

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Розробка оптимального керування процесом випалювання вуглецевих виробів передбачає врахування впливів характерних зон печі та однорідності температурного поля по заготовкам. Дане твердження вимагає розробку математичної моделі печі випалювання з розподіленими параметрами. Відомо, що час розрахунку таких моделей досить великий, а відтак їх застосування в реальному часі не можливе. Відповідно до вище сказаного для подальшої розробки системи оптимального керування процесом випалювання існує потреба у спрощенні повної математичної моделі, що забезпечує потрібний час розрахунку.

Розроблена та досліджена спрощена математична модель процесу випалювання, яка відрізняється від відомих моделей меншим часом розрахунку при дотриманні поставлених вимог щодо її точності.

Встановлено, що для випадків використання n>15 перших базис-векторів забезпечує виконання обмеження по допустимій похибці апроксимації значень коефіцієнтів Фур'є. Можливість вибору оптимальної структури ідентифікаційних моделей визначає можливість отримання температурних знімків спрощеної математичної моделі з необхідною точністю.

Отримані результати дозволяють гнучко обрати варіант спрощеної математичної моделі відповідно до технічних можливостей обчислювальної техніки.

Враховуючи, що у процесі випалювання вуглецевих виробів визначальними температурами є температури заготовок, то для дослідження якості спрощених моделей були обрані Control points лише по заготовкам.

Оскільки процес випалювання вуглецевих виробів складається з трьох основних етапів, то для адекватного моделювання такого процесу було реалізовано три спрощені математичні моделі даних етапів.

Дослідження точності спрощених моделей включало порівняння значень температур, розрахованих за спрощеною моделлю, з температурами, обчисленими за початковою моделлю, яка у даному випадку розглядалася як генератор експериментальних даних

Ключові слова: процес випалювання, температурні поля, метод розділення змінних, вуглецеві вироби

1. Introduction

Manufacturing of carbon products is an extremely power-intensive and therefore costly technological process. One of the key stages in the whole technological process is baking carbon products, carried out in a closed-top multi-chamber furnace. The multi-chamber baking furnace is an object with extremely high energy consumption and even an insignificant reduction in fuel consumption, taking into account current cost, leads to significant savings and cheaper finished products.

Successful solution of the problem of increasing the efficiency of this process by introducing optimal operation modes determines real opportunities for reducing the energy consumption of this production.

The solution of this problem involves research on the baking process, the results of which will be used to create an optimal process control system.

Baking carbon products in the multi-chamber furnace is characterized by complex physical and chemical processes and significant spatial distribution of temperatures throughout the volume. The neglect of these features leads to fundamental errors in solving automatic control problems. In this regard, such processes are mathematically described by rather complex distributed-parameter models.

The calculation time of the above models ranges from several hours to several dozen hours, which considerably slows down the study of the baking process and makes it impossible to use them further in the development of a real-time process control system.

Since it is impossible to carry out pilot studies on industrial equipment for technical and economic reasons to solve the above problem, mathematical modeling is used as a method of research.

As the main purpose of baking is full heating and temperature uniformity of workpieces, modeling should be carried out with the distributed-parameter model. It is known that the calculation time of such models is quite large, which causes the problem of mathematical model reduction. To date, there are specialized computing systems that can easily handle the described models, but their application in the industrial sector is inappropriate for a number of reasons. Therefore, the problem of limited computational capabilities remains open, and ways to solve it are relevant.

2. Literature review and problem statement

Materials [1] describe the problems of management of distributed-parameter systems. The issue of approximate solution of various problems takes a significant place in these studies. The work is based on studies of the problem of approximate solution of optimal control problems, which is based on the approximation of the controlled system by Fourier series expansion.

The work [2] proposes a method of reduction of limited-volume models, which ensures that the resulting model is conservative, thus preserving the structure inherent in limited sampling volumes. Conventional model reduction methods often cause a loss of mass, momentum or energy in liquid streams, which leads to unstable model reduction. The method discussed in [2] preserves the mass and momentum in finite volume sampling, but this method does not keep fluid flow energy.

Materials in [3] describe the method of Craig-Bampton component mode synthesis (CMS). This method can be considered as an engineering approach to the reduction of the number of equations, and hence to loss of accuracy due to the lack of description of the physico-chemical process characteristics.

The paper [4] examines the method of reduction of the expanding IRS system by obtaining an equivalent transformation based on dynamic rather than static reduction. This method is considered as a reduction of the number of equations, and therefore loss of accuracy due to the lack of description of the physico-chemical process characteristics.

The paper [5] describes the dimensionality reduction method, called discrete empirical interpolation, which is a modification of the orthogonal decomposition method. The authors propose the discrete empirical interpolation method suitable for dimensionality reduction of systems of specific ordinary differential equations. The question remains how inaccuracies of coefficients in approximation may affect the final solution.

The authors [6] presented a new model of reduction based on orthogonal decomposition for solving Navier-Stokes equations, which is a hybrid of two existing approaches, namely, the quadratic expansion method and the discrete empirical interpolation method. It was noted in the paper that unstructured grids can cause stability problems for reduced order models.

The paper [7] describes a method combining orthogonal decomposition and concepts of the balanced implementation theory. The method is especially effective with a small number of results of interest. In the given algorithm, there are several solutions that should be made arbitrarily, relying on experience and intuition. The lack of description of these solutions is the drawback of this method.

The author of [8] presents the main ideas, concepts and methods for simplifying the kinetics of reactions: quasi-stationary, quasi-equilibrium, slow invariant manifolds and boundary degrees. The given methods are aimed at simplifying the chemical and biochemical kinetics of the model, which is inappropriate in this study.

In [9], a comparative study of seven model reduction algorithms is conducted and conclusions about the most effective of them when applied to six different dynamic systems are drawn. The results show that the use of the Krylov method requires the selection of interpolation points. However, the selection of these points is not an automated process and should be defined by the user, and the point selection algorithm is not described.

The main shortcomings of existing reduction methods are ambiguity in the selection of algorithm parameters or loss of physico-chemical characteristics due to the reduction of the number of equations, which is unacceptable when modeling the process of baking carbon products. In [10], it is shown that the methods of the first group are characterized by the loss of properties, which are determined by the spatial distribution of controlled processes. Consequently, they contradict the requirements for the mathematical model of the baking process.

Given the above, to ensure the physico-chemical characteristics and distribution of furnace parameters, it is advisable to apply the methods of the second group. They are characterized by an approximate representation of exact solutions of partial differential equations modeling the behavior of distributed-parameter objects. One such method is orthogonal decomposition (Fourier method), which is best suited to solve the problem and meets all the conditions of the finite model.

3. The aim and objectives of the study

The aim of this work is to construct and study the reduced mathematical model of the process of baking carbon products based on the orthogonal decomposition method. This will significantly reduce calculation time in compliance with the requirements of the initial complex mathematical model.

To achieve this aim, the following objectives were accomplished:

– to determine the basis vectors and Fourier coefficients;

– to choose the optimal structure of identification models;

– to investigate the accuracy and adequacy of the obtained reduced mathematical model.

4. Materials and methods of reduction of the mathematical model of the process of baking carbon products

4. 1. Method of reduction of the mathematical model by the Fourier method

Since the Fourier method is the orthogonal decomposition method and the method of the second group, it is necessary to form samples of temperature fields with the initial complex mathematical model.

Reduction of the mathematical model of the process of baking carbon products requires obtaining fairly accurate modeling results not only during the whole modeling time, but also throughout the whole device, which is satisfied by the variable separation method.

The process of baking carbon products consists of three main stages, such as flue gas heating, “under fire” chamber and cooling. Accordingly, for the adequate modeling of such a process and obtaining the corresponding temperature fields, three complete mathematical models of these stages were implemented on the basis of the mathematical model presented in [11]. Thus, the reduced mathematical model of the baking process will include three reduced models of the main process stages.

The mathematical implementation of this method is given in [12] and determines the representation of approximate modeling results by the bounded series

$$\hat{T}(\xi,t)=\sum\nolimits_{i=1}^{n} a_i(t)\varphi_i(\xi), \qquad (1)$$

where φ_i – basis vectors, a_i – values of Fourier coefficients.

In view of the above, the model reduction algorithm includes:

1. Formation of samples of temperature fields with three initial complex mathematical models, three main stages of the campaign, throughout the modeling time and throughout the baking furnace volume.
2. Determination of the series of basis vectors based on the formed samples of temperature fields.
3. Choosing the best model structure describing the dependencies between $u(t)$ and $\{a_i(t)\}_{i=1}^{n}$.

4. 2. Calculation of basis vectors and Fourier coefficients

As a result of singular value decomposition, the values of basis vectors φ_i were obtained, some of which are presented in Table 1–3. Then the values of the Fourier coefficients (Table 4–6) were determined by the formula (1). Since in this case the computational grid is 18.644 knots, and the number of time steps is 480 hours, calculation results are given only partially.

Table 1

Values of basis vectors for the reduced model of air cooling of the furnace chamber

i ξ	1	2	3	...	K
1	–0.00881275	0.00109225	0.00362483	...	0.001615686426
2	–0.00909725	0.001877298	0.00581828	...	–0.002641292723
3	–0.00873969	0.001036539	0.00318769	...	–0.013192636318
4	–0.00924921	0.000946707	0.0072734	...	–0.000312211223
5	–0.00926741	0.001181525	0.0074772	...	0.003119028133
...	...	...	...	...	...
L	–0.00918001	0.001083891	0.00643872	...	0.00991501328390

Table 2

Values of basis vectors for the reduced model of flue gas heating of the furnace chamber

i ξ	1	2	3	...	K
1	–0.00651927	–0.00345675	–0.0065497	...	–0.00042032235265
2	–0.00631024	–0.00386776	–0.0079724	...	–0.001121240848478
3	–0.00657570	–0.00326930	–0.0061790	...	0.003174325474985
4	–0.00618794	–0.00330912	–0.0091424	...	–4.39514395905e–05
5	–0.00614540	–0.00315756	–0.0095306	...	–0.00019734264029
...	...	...	...	...	...
L	–0.00614641	–0.00311091	–0.0095918	...	–0.000567698956155

Table 3

Values of basis vectors for the reduced model of the furnace chamber heating during natural gas combustion

i ξ	1	2	3	...	K
1	–0.00777750	–0.00538909	0.00038946	...	0.00271268452697
2	–0.00775877	–0.00707303	0.00259699	...	–0.007262256218404
3	–0.00778102	–0.00502355	2.9184e–05	...	0.00929180972554
4	–0.00775588	–0.00750436	0.00452306	...	–0.001962873255037
5	–0.00775142	–0.00773580	0.00500481	...	0.0006750066028036
...	...	...	...	...	...
L	–0.00774061	–0.00737207	0.00290409	...	–0.00226721050656

Table 4

Values of coefficients $a_i(t)$ for the reduced model of air cooling of the furnace chamber

t i	1	2	3	4	...	K
1	–159666.60	–159741.40	–159543.86	–158640.12	...	–108392.34
2	–14,149	–14377.628	–13985.091	–12074.4	...	–5453.0216
3	–25812.031	–25847.576	–25642.069	–24771.8	...	–300.85632
4	–5593.8867	–5600.4843	–5419.6085	–4777.508	...	1995.88646
...	...	...	...	...	...	...
K	–2.891e–05	–0.0185042	–0.0047972	–0.0043852	...	3.00532e–05

Table 5

Values of coefficients $a_i(t)$ for the reduced model of flue gas heating of the furnace chamber

t i	1	2	3	4	...	K
1	–34584.8	–33644.597	–33926.856	–34431.05	...	–56711.148
2	–1083.7427	–2173.7684	–1816.5613	–1319.9563	...	519.31363
3	–6285.0128	–6595.2336	–6514.4854	–6317.149	...	1262.46
4	–3151.31	–3556.79	–3440.4324	–3122.141	...	–630.822
...	...	...	...	...	...	...
K	0.00021720	5.4489e–05	0.00022263	–0.0002076	...	–0.0023041

Table 6

Values of coefficients $a_i(t)$ for the reduced model of the furnace chamber heating during natural gas combustion

t i	1	2	3	4	...	K
1	–162630.44	–162990.99	–162429.38	–161755.36	...	–172434.36
2	–1819.8016	–1254.3905	–2075.8492	–3058.9365	...	5542.23760
3	–312.56606	–17.745882	–454.97879	–962.09776	...	–1434.4278
4	322.015976	188.584054	128.332304	263.336444	...	–479.77911
...	...	...	...	...	...	...
K	0.00022711	0.00749919	–0.0045488	0.00050447	...	0.000213122

The calculation time of reduced mathematical models depends directly on the dimension of the corresponding matrices. Obviously, the next step should be to determine the admissible dimensions of the matrices, taking into account the given permissible error.

4. 3. Choosing the optimal model structure

To estimate the quality of approximation, the error for cases of using n=1..30 of first basis vectors was calculated.

$$e_A=\frac{\sum_{\xi=1}^{L}\sum_{t=0}^{K}(T_{snap}(\xi,t)-T_A(\xi,t))^2}{KL}, \qquad (2)$$

where $T_A=F_n\mathrm{A}_n$ – approximated temperature matrix, F_n, A_n – first n basis vectors and Fourier coefficients, respectively. For the given maximum permissible error $e_{\max}=0.1$, the use of more than 15 basis vectors in further studies proved to be inappropriate, since such a number has already provided the condition $e_A<e_{\max}$. Further increase in the number of basis vectors would lead to the error decrease, but also to a slowdown of the model calculation, which is inappropriate within this work. We accept $n_{\max}=15$.

As a result of identification, for each of n=1...15, the following models were found which most accurately describe the connection between the values of the coefficients $a_i(t)$

and the input signals of the model $u(t)$. In all cases, ARX autoregression models with the following structure coped with the task best of all:

$$y(t)+a_1y(t-1)+...+a_{na}y(t-na)= \\ =b_1u(t-nk)+...+b_{nb}u(t-nb-nk+1)+e(t). \qquad (3)$$

Table 7–9 contains data on the configuration of optimal identification models for each n.

Table 7

Data on optimal structures of identification models of air cooling of the furnace chamber

n	na	nb	nk
1	1	5	5
2	1	2	2
3	1	5	5
4	1	2	3
5	1	2	3
6	1	2	3
7	1	1	4
8	1	1	4
9	1	1	4
10	1	1	4
11	1	2	4
12	1	1	4
13	1	1	4
14	1	1	4
15	1	1	4

Table 8

Data on optimal structures of identification models of flue gas heating of the furnace chamber

n	na	nb	nk
1	1	2	2
2	1	2	2
3	1	1	2
4	1	3	2
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	2
10	1	1	2
11	1	1	2
12	1	1	2
13	1	1	2
14	1	1	2
15	1	1	2

The errors of the obtained models were calculated by the formula (3), where T_A was replaced with T_M – the matrix of temperatures modeled by the reduced models.

Table 9

Data on optimal structures of identification models of furnace chamber heating during natural gas combustion

n	na	nb	nk
1	1	4	5
2	1	1	1
3	1	4	5
4	1	1	1
5	1	1	1
6	1	1	1
7	1	1	1
8	1	1	1
9	1	1	2
10	1	1	4
11	1	1	1
12	1	1	1
13	1	1	1
14	1	1	1
15	1	1	1

The model with n=1 showed the worst results expected due to the poor quality of approximation of temperature images by only one basis vector, but accuracy increases significantly with increasing their number (Table 10).

Table 10

Square error of reproduction of temperature images

Structure No./Stage	Cooling	Flue gas heating	"Under fire" chamber
1	4474.82265765	1063.3982465	1295.7262703
2	2318.82575130	681.73729622	737.57468543
3	256.816261076	724.74649292	36.145530539
4	123.94032455	335.18327552	146.30939708
5	101.34883148	309.27127258	109.51076554
6	98.015308988	291.40143175	68.809944111
7	103.34683314	290.69538448	79.505159875
8	93.850797632	221.31068331	63.681677027
9	72.858692183	200.50024623	71.950127685
10	72.567943544	190.83444156	52.850688386
11	38.189108850	183.77816952	55.789743076
12	55.176655556	169.05799027	57.942293222
13	30.441986682	177.41770938	56.8910246698
14	30.426011949	145.93273566	60.7601747592
15	21.879654817	144.70491576	24.017044386

So, as a result of calculation of the error of the reduced models, it was found that the reduced models using the first 15 basis vectors (n=15) are the most accurate for all stages. Obviously, with increasing the number of basis vectors, it is possible to achieve better reproduction of temperature images, but this will lead to an increase in calculation time, which is inappropriate.

4. 4. Investigation of the accuracy and adequacy of the obtained reduced mathematical model

Given that in the process of burning carbon products, the defining temperatures are workpiece temperatures, control points of workpieces were chosen for the quality study of reduced models. The arrangement of the control points is as follows (Fig. 1):

– on the axes of the workpieces at a distance of 100 mm from the upper (2, 6, 10, 14, 18) and lower (4, 8, 12, 16, 20) ends, respectively;

– on the periphery of the workpieces of the lower row: at a distance of 100 mm from the upper (1, 3, 5, 7, 9, 11, 13, 15, 17, 19).

The study of the quality of the developed reduced mathematical models included the study of their accuracy and adequacy for each chosen control point and for each operating mode of the baking chamber.

The accuracy of mathematical models was estimated by three kinds of error – absolute, relative and normalized absolute. The results of the accuracy study for all operating modes are presented in Table 11–13.

The results listed in Table 11–13 indicate that the developed reduced mathematical models rather accurately track the results of calculations for the initial complex model.

The adequacy of the reduced mathematical model was investigated using Student's and Fisher's criteria [13]. The results of the study are shown in Table 15–17.

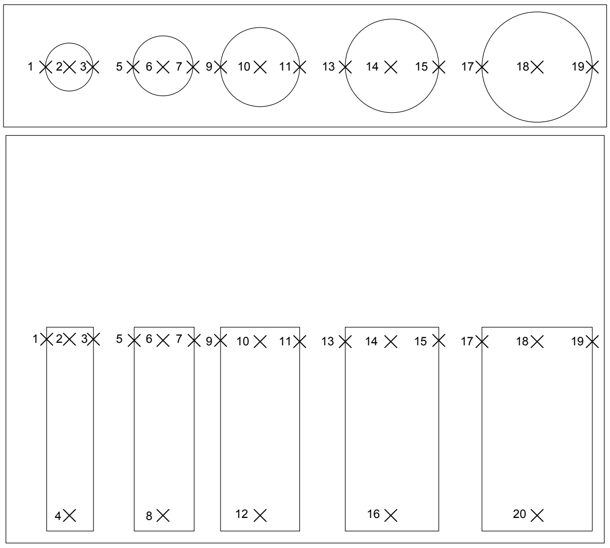


Fig. 1. Arrangement of control points in the baking campaign modeling

Table 11

Results of the accuracy study of the flue gas heating model

Measure of accuracy	Control points									
	No. 1	No. 3	No. 5	No. 7	No. 9	No. 13	No. 14	No. 15	No. 17	No. 19
Mean absolute error (°C)	9.55	11.2	11.25	9.7	9.77	8.42	10	10.42	8.55	10.47
Mean relative error (%)	2.52	3.23	3.16	2.85	2.65	2.37	2.8	3.2	2.3	2.1
Normalized mean absolute error (%)	0.81	0.95	0.95	0.82	0.83	0.71	0.85	0.88	0.72	0.89

Table 12

Results of the accuracy study of the "under fire" chamber model

Measure of accuracy	Control points									
	No. 1	No. 3	No. 5	No. 7	No. 9	No. 13	No. 14	No. 15	No. 17	No. 19
Mean absolute error (°C)	13.1	10.1	11.9	10.2	10.5	8.3	8.3	9.6	10.1	9.5
Mean relative error (%)	1.23	1.03	1.19	1.08	1.0	0.79	0.86	1.00	1.03	0.81
Normalized mean absolute error (%)	1.11	0.86	1.01	0.86	0.89	0.7	0.71	0.81	0.86	0.8

Table 13

Results of the accuracy study of the air cooling model

Measure of accuracy	Control points									
	No. 1	No. 3	No. 5	No. 7	No. 9	No. 13	No. 14	No. 15	No. 17	No. 19
Mean absolute error (°C)	9.55	11.2	11.25	9.7	9.77	8.42	10	10.42	8.55	10.47
Mean relative error (%)	2.52	3.23	3.16	2.85	2.65	2.37	2.8	3.2	2.3	2.1
Normalized mean absolute error (%)	0.81	0.95	0.95	0.82	0.83	0.71	0.85	0.88	0.72	0.89

Table 14

Results of the accuracy check of the general model

Measure of accuracy	Control points									
	No. 1	No. 3	No. 5	No. 7	No. 9	No. 13	No. 14	No. 15	No. 17	No. 19
Mean absolute error (°C)	10.26	10.98	11.38	9	9.92	8.4	9.72	10.26	8.86	10.28
Mean relative error (%)	2.26	2.79	2.77	2.49	2.32	2.05	2.41	2.82	2.08	1.88
Normalized mean absolute error (%)	0.87	0.93	0.97	0.83	0.84	0.71	0.82	0.87	0.75	0.87

Table 15

Results of the adequacy study of the flue gas heating model

Criterion	Control points									
	No. 1	No. 3	No. 5	No. 7	No. 9	No. 13	No. 14	No. 15	No. 17	No. 19
Student's calculated	1.48	1.46	1.38	1.44	1.42	1.47	1.54	1.56	1.57	1.59
Student's table	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68	1.68
Fisher's calculated	0.97	1.05	1.05	1.01	0.95	1.02	0.97	0.95	0.98	1
Fisher's table	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

Table 16

Results of the adequacy study of the "under fire" chamber model

Criterion	Control points									
	No. 1	No. 3	No. 5	No. 7	No. 9	No. 13	No. 14	No. 15	No. 17	No. 19
Student's calculated	1.6	1.66	1.71	1.74	1.68	1.63	1.75	1.73	1.78	1.69
Student's table	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Fisher's calculated	1.31	1.19	1.05	0.83	0.84	0.83	1.19	1.06	1.02	0.91
Fisher's table	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32	2.32

Table 17

Results of the adequacy study of the air cooling model

Criterion	Control points									
	No. 1	No. 3	No. 5	No. 7	No. 9	No. 13	No. 14	No. 15	No. 17	No. 19
Student's calculated	1.48	1.46	1.38	1.44	1.42	1.47	1.54	1.56	1.57	1.59
Student's table	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Fisher's calculated	0.97	1.05	1.05	1.01	0.95	1.02	0.97	0.95	0.98	1
Fisher's table	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5

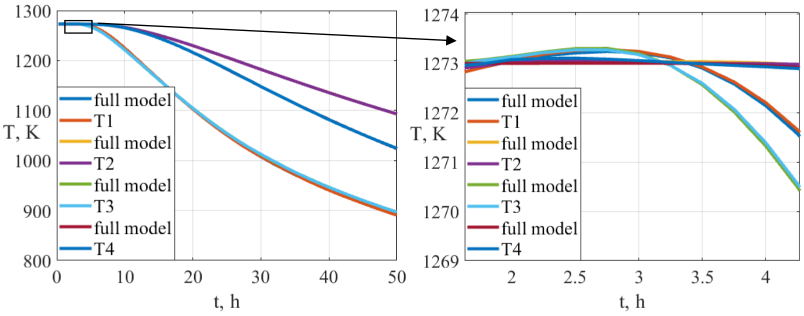
By comparing the calculated values of Student's and Fisher's criteria for control points with table ones, we can conclude that there is no reason to reject hypotheses about the adequacy of reduced mathematical models. Therefore, we will assume that these mathematical models adequately reproduce calculation results for the initial complex mathematical model.

5. Results of reduction of the mathematical model of the process of baking carbon products

Since modeling of the reduced models results in temperature dynamics throughout the volume, it is expedient to represent temperatures only in some control points for graphical representation of the results.

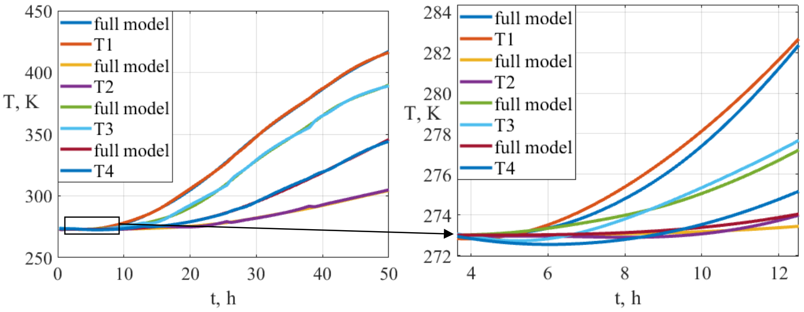
Taking into account restrictions for the paper volume, the results of simulation are presented only for 4 control points.

As can be seen from Fig. 2–4, the temperature curves, plotted by the reduced and full mathematical models, practically coincide for all control points in all operating modes (cooling, flue gas heating, under fire chamber). The mean modeling error is: for the cooling mode – 4.6 K (equivalent to 1.4 % in the modeling range), for the flue gas heating mode – 12 K (10% in this heating range and will decrease with increasing heating range), for the under fire chamber mode – 4.8 K.



a *b*

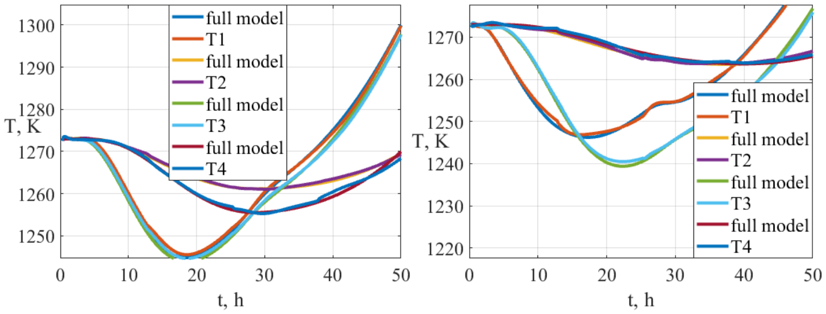
Fig. 2. Temperature curves with control points of the reduced and full cooling models in the time interval: *a* – 50 h, *b* – 6 h



a *b*

Fig. 3. Temperature curves with control points of the reduced and full flue gas heating models in the time interval: *a* – 50 h, *b* – 13.3 h

Special attention is drawn to the reduced model of the under fire chamber mode (Fig. 4). Despite the rather complex temperature dynamics in this mode, the reduced mathematical model monitors all current changes rather accurately.



a *b*

Fig. 4. Temperature curves with control points of the reduced and full "under fire" chamber models: *a* — workpiece No. 1; *b* — workpiece No. 2

Temperature curves with control points of the reduced mathematical models show good results despite the complex processes taking place at this stage. It can be seen that the curves of the reduced and full models are almost identical and partly overlap.

6. Discussion of the results of reduction of the mathematical model of the process of burning carbon products

The obtained results of the accuracy of the reduced mathematical model can be characterized by the choice of the permissible error of reproduction $e_{\max}$=0.1, and then both the possible number of first basis vectors and structure of the model. In this case, these parameters were taken from the author's considerations.

One of the advantages of the proposed solution is the possibility to choose the necessary model structure directly when developing the reduced model.

The proposed solution has no shortcomings of the methods that use reduction of the number of equations, since this solution approximates the solution of the system with all equations. Also, when developing the model, methods of structural-parameter identification are used, which are well-known and well-described in the literature. So, this solution is devoid of ambiguity in the choice of parameters.

In the development of complex mathematical models, consisting of a group of reduced models, one can face the problem of combining them. In this case, the reduced model of the baking process consists of three reduced models of the main process stages, having different numbers of state variables. Accordingly, the described reduction algorithm is complicated by solving the problem of combining reduced models.

7. Conclusions

1. Using the initial complex models, temperature fields for three main stages of the process of baking carbon products were obtained. By means of singular value decomposition, the values of the basis vectors were obtained. As a result of the estimation of approximation quality, it was found that the use of more than 15 basis vectors in this work was impractical.

2. For each of the baking process stages, identification of optimal model structures was carried out. The results of the influence of the number of first basis vectors on the accuracy of reproduction of temperature images are given. It was found that for all the key stages of the baking process, structures No. 15 coped with the task best of all.

3. The study of the accuracy and adequacy of the developed models was conducted. The results of the study of the models showed their high efficiency. The mean absolute error is about 10 °C, the mean relative error is 2–3 %, and the normalized mean absolute error ranges from 0.8 to 1.1 %.

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ASSESSMENT OF EFFICIENCY OF DRYING GRAIN MATERIALS USING MICROWAVE HEATING

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Наведено результати експериментальних робіт з дослідження сушіння щільного шару зерна із застосуванням мікрохвильового нагрівання. Для оцінки ефективності використання енергії мікрохвильового поля вивчався ряд способів підведення теплоти до зерна. Досліджені мікрохвильовий, мікрохвильовий пульсуючий, микрохвильово-конвективний циклічний із продувкою шару нагрітим потоком повітря й повітрям без попереднього підігріву, одночасний микрохвильово-конвективний способи сушіння.

Дослідження кінетики сушіння в мікрохвильовому полі показало, що процес можна розділити на періоди прогріву (нульовий), постійної (перший) і падаючої (другий) швидкості сушіння. Ці періоди характерні для сушіння колоїдних капілярно-пористих тіл при інших способах підведення теплоти. На підставі узагальнення експериментальних даних по дослідженню сушки зерна гречки, ячменю, вівса та пшениці отримано емпіричні залежності для швидкості сушіння і середньої температури зерна в першому періоді. Представлені кінетичні залежності в безрозмірному вигляді, узагальнюючі дані по дослідженим зерновим.

Комплексні дослідження різних способів підведення теплоти при сушінні ставили метою визначення оптимального способу й раціональних режимних параметрів, що забезпечують високу інтенсивність процесу й необхідну якість готового продукту при мінімальних енерговитратах. Для забезпечення вірогідності зіставлення всі дослідження проводилися в ідентичних умовах з однієї й тією же зерновою культурою (овес). Визначено, що кращим є одночасний микрохвильово-конвективне підведення енергії, при цьому попередній підігрів повітря не передбачається, завдяки чому мінімізуються питомі витрати енергії. Експериментальні дослідження сушіння із застосуванням мікрохвильового поля дають можливість підібрати необхідні параметри процесу: потужність, темп нагрівання, масу й форму завантаження. На підставі цих даних передбачається розробка технології сушіння зерна із застосуванням енергії мікрохвильового поля

Ключові слова: мікрохвильове нагрівання, микрохвильово-конвективний, вологовміст, температура, швидкість сушіння, оптимальний спосіб

1. Introduction

Convective dryers are the most common for grain drying currently. They have a series of significant disadvantages. However, we can eliminate the disadvantages using microwave-convective heat supply [1, 2]. We obtained convincing evidence of applicability of microwave technology and feasibility of development of microwave dryers. There is success-