Fuzzy economic and mathematical model of a heat-technological system for pelletizing in non-ferrous metallurgy

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An economic and mathematical problem of increasing energy efficiency of a heat-technological system (HTS) of pelletizing in non-ferrous metallurgy was stated. The problem is to determine the values of controlling parameters in order to minimize the total cost of electric and thermal power of pelletizing taking into account technological, organizational and other limitations imposed on these processes. Justified is the conclusion that in the present context of pelletizing in non-ferrous metallurgy, usage of a fuzzy logical approach is worthwhile for modeling and estimating electrical and thermal energy costs in order to increase energy efficiency of the heat technology system of pelletizing. A cascade multicomponent fuzzy economic and mathematical model of a heat-technological system of pelletizing in non-ferrous metallurgy has been developed. It includes: fuzzy component models for analyzing the pelletizing processes; fuzzy productional models for estimating cost of electrical and thermal energy at all stages for all the processes of pelletizing; fuzzy productional models for estimating cost of electrical and thermal energy for all the processes of pelletizing; fuzzy productional models for estimating total electrical and thermal energy costs. The article describes the suggested approach to solving an economic and mathematical problem of increasing the energy efficiency of HTS of pelletizing using the proposed cascade multicomponent fuzzy model, which is to set various combinations of control parameters for each stage of all the processes, taking into account technological, organizational and other limitations imposed on these processes followed by modeling and in the determination of such combinations of these parameters, which provide minimization of electric and thermal energy total costs during pelletizing.

Key words: heat-technological system, roasting conveyor machine, pelletizing, electrical and thermal energy, energy efficiency, fuzzy economic and mathematical model, fuzzy logical deduction.

DOI: 10.17580/nfm.2018.02.10

Introduction

Stable growing trend of demand for beneficiated ore raw materials in non-ferrous metallurgy stipulates the necessity of its quality increasing and lessening manufacturing costs [1]. Industrial processing of the complex heterogeneous ore mineral raw material requires a preliminary thermal treatment. The beneficiated feedstock should meet the engineering requirements in a qualitative and quantitative sense, grain size distribution, have no moisture, contain minimum of carbonate inclusions, volatile gases, and useless impurities [2]. Besides, about half of the raw material of non-ferrous metallurgy is lost during extraction, transportation and preliminary processing of ore [3].

Permanent tendency towards deterioration of the ore raw material quality in the absence of the energy efficient methods of its thermal pretreatment leads to deterioration of performance characteristics of the thermal-electric method of production of non-ferrous metals [4].

Thereupon, development of a theory and working out the technical and engineering solutions meant for improvement of the energy efficient roasting heat-technological systems (HTS) and processes (HTP) is the topical research and practical problem [5].

An ore-dressing in non-ferrous metallurgy is quite power-consuming process [6]. The electricity charges during pelletizing are, on the average, two times greater than that of a thermal energy. At this, electric energy is consumed by exhausters in order to form the heat carrier gas flow with required parameters, while thermal energy of firing provides an initial temperature of the heat carrier gas in HTS — a roasting conveyor machine [7].

The main pelletizing processes are drying, heating, hard firing, recuperation, cooling [8].

These processes are carried out in a roasting conveyor machine in the order named and differ by values of the following control parameters on each stage of them (in every vacuum chamber):

— the heat carrier gas temperature at the point of entry into a layer of pellets;

— the heat carrier gas temperature after moving through the different layers of pellets;

— rate of movement of the heat carrier gas.

Target setting

Setting up an economic and mathematical problem of increasing the pelletizing energy efficiency is as follows. It is necessary to determine the values of controlling parameters with the purpose of minimization of electrical and thermal energy costs of pelletizing, taking into account technological, organizational and other limitations imposed on these processes:

$$S = s_E E + s_H H$$
$$E = FE (E_1, ..., E_k, ..., E_K),$$
$$E_k = FE_k (E_1^k, ..., E_j^k, ..., E_{J_k}^k), k = 1, ..., K,$$
$$H = FH (H_1, ..., H_k, ..., H_K),$$
$$H_k = FH_k (H_1^k, ..., H_j^k, ..., H_{J_k}^k), k = 1, ..., K,$$
$$S \xrightarrow{\quad Tg_0^{jk}, Tg_n^{jk}, Wg^{jk}, j = 1, ..., J_k, k = 1, ..., K \quad} \min,$$

where S is total electrical and thermal energy cost; E and H are general costs of electrical and thermal energy, correspondingly; s_E and s_H is the specific costs of electrical and thermal energy, correspondingly; E_k and H_k are electrical and thermal energy costs for the k-th pelletizing process, respectively; FE is a relationship between the spendings on electrical energy for separate processes and general costs of that; FH is a relationship between the spendings on heat energy for separate processes and general costs of that; E_j^k and H_j^k are electrical and thermal energy costs for the j-th stage (in the j-th vacuum chamber) of the k-th pelletizing process, respectively; FE_k is dependence between electrical energy costs for the j-th stage of the k-th pelletizing process and that through the entire k-th process; FH_k is dependence between thermal energy costs for the j-th stage of the k-th pelletizing process and that through the entire k-th process; Tg_0^{jk} is the heat carrier gas temperature at the point of entry into the layer of pellets for the j-th stage of the k-th process; Tg_n^{jk} is the heat carrier gas temperature after passing through all n layers of pellets for the j-th stage of the k-th process; Wg^{jk} is a rate of movement of the heat carrier gas for the j-th stage of the k-th pelletizing process.

Commentary. The problem is stated for the roasting conveyor machine under investigation and the processes $k = 1 ... K$, $K = 5$, which are realized in it. At the same time:
— for drying the pellets — $k = 1$, $J_1 = 11$;
— for heating the pellets — $k = 2$, $J_2 = 2$;
— for hard firing — $k = 3$, $J_3 = 8$;
— for recuperation of the pellets — $k = 4$, $J_4 = 2$;
— for cooling the pellets — $k = 5$, $J_5 = 10$.

The structure and description of a cascade multicomponent fuzzy economic and mathematical model of a heat-technological pelletizing system

Since the dependences FE and FH as well as FE_k and FH_k ($k = 1, ..., K$) are essentially nonlinear and depend in large measure on the features of the processes under consideration, originality of the HTS equipment as well as environment processes variation, then applying a fuzzy logic approach for formalization and approximation of these dependences would be appropriate to estimate electrical and thermal energy costs (both general and for each single process) [9–10].

According to the aforesaid, a cascade multicomponent fuzzy economic and mathematical model of a heat-technological system of pelletizing is suggested. Its structure is illustrated in Fig. 1.

The cascade multicomponent fuzzy economic and mathematical model of a heat-technological system of pelletizing involves the following models:

— *Cascade 1*: aggregates of the fuzzy component models $M_{comp_i}^{jk}$ ($i = 1, ..., n, j = 1, ..., J_k, k = 1, ..., K$) for analysis of corresponding pelletizing processes (drying, heating, hard firing, recuperation, cooling), equal to results of decomposition of these processes;

— *Cascade 2*: aggregates of the fuzzy productional models $\{ME_1^1, ..., ME_j^k, ..., ME_{J_k}^k\}, \{MH_1^1, ..., MH_j^k, ..., MH_{J_k}^k\}$, meant for estimating electrical and thermal energy expenses at the j-th stages ($j = 1, ..., J_k$) for the k-th ($k = 1, ..., K$) pelletizing processes ($E_1^k, ..., E_j^k, ..., E_{J_k}^k$), ($H_1^k, ..., H_j^k, ..., H_{J_k}^k$), correspondingly;

— *Cascade 3*: aggregates of the fuzzy productional models $\{MFE_1, ..., MFE_k, ..., MFE_K\}, \{MFH_1, ..., MFH_k, ..., MFH_K\}$, meant for estimating energy expenses of electrical and thermal energy for the k-th ($k = 1, ..., K$) pelletizing processes ($E_1, ..., E_k, ..., E_K$), ($H_1, ..., H_k, ..., H_K$), respectively;

— *Cascade 4*: fuzzy productional models MFE and MFH, meant for estimating general costs of electrical and thermal energy E and H, correspondingly.

In Fig. 2 an interaction of the models of the 1st and 2nd cascades for the k-th pelletizing process, $k = 1, ..., K$, is illustrated in more detail.

Fuzzy component models of the 1st cascade $M_{comp_i}^{jk}$ ($i = 1, ..., n, j = 1, ..., J_k$) for analysis of the k-th ($k = 1, ..., K$) pelletizing process corresponds to the results of decomposition of this process. Each of these models permits to solve an inner thermal conductivity problem in conditions of uncertainty of thermophysical characteristics and fuzzy temperature distribution of the pellets. At the same time the analysis starts form the systems of differential equations with uncertain thermophysical characteristics of the pellets (volumetric heat capacity, thermal conductivity, coefficient of heat-transfer from the surface) [11], as well as from the approach to investigation of thermally activated chemical-energotechnological processes by fuzzy numerical methods, suggested by the authors in [12].

A fuzzy logic approach is used as a base for constructing the models on cascades from 2 to 4.

Let us consider in more detail the procedures of definition, adjustment and application of the suggested models of the 2nd cascade by the example of a ME_j^k fuzzy productional model for estimation of electrical energy costs at the j-th stage for the k-th pelletizing process E_j^k.

Stage 1. Assignment of the input and output variables of the fuzzy productional model.

The following fuzzy variables serve as the input variables for a ME_j^k model:

— Tg_0^{jk} — the heat carrier gas temperature at the point of entry into vertical laying of pellets;

— Tg_n^{jk} — the heat carrier gas temperature after moving through the whole of n layers of vertical stacking of pellets;

— Wg^{jk} — rate of movement of the heat carrier gas.

The expenses E_j^k serve as a fuzzy output variable.

Stage 2. Construction of linguistic scales for the input and output fuzzy variables of the model, for which the
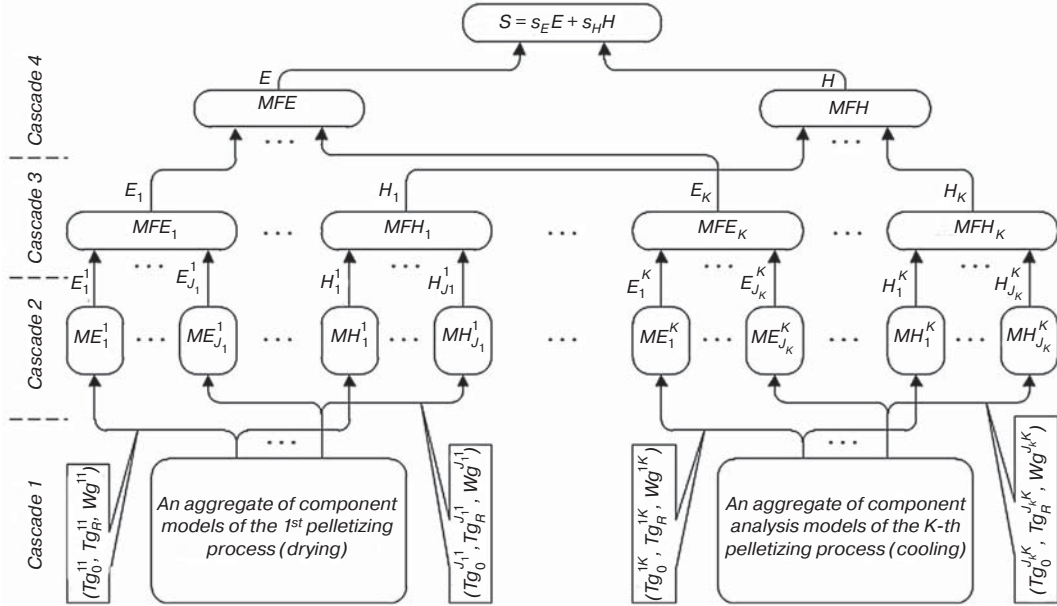

Fig. 1. Structure of a cascade multicomponent fuzzy model economic and mathematical model of a heat-technological systems of pelletizing
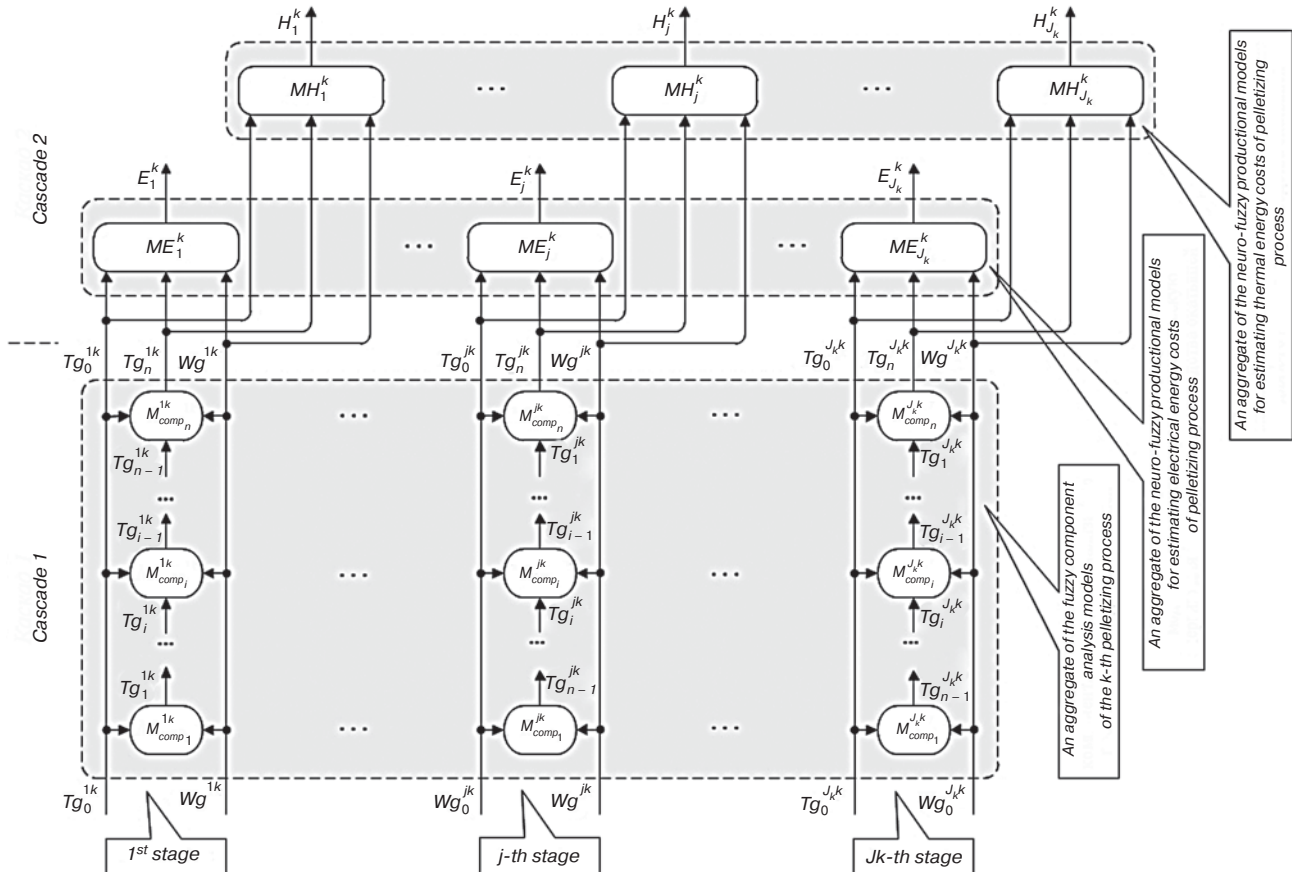

Fig. 2. An example of organization of interaction between the models of the 1st and 2nd cascades for the k-th pelletizing process

L-R-functions (such as Gaussian, triangular, trapeziform) may be used. For more illustrative description of all mentioned fuzzy variables of the model we use similar therms $\{L$ — minor, M — middle, H — large$\}$ [13].

Stage 3. Making the fuzzy productional rule database of the model.

Below a rule database fragment of the model is represented:

R_1:   **If** Tg_0^{jk} is L **AND** Tg_n^{jk} is L **AND** Wg^{jk} is L, **Then** E_j^k is L;

...

R_y: **If** Tg_0^{jk} is M **AND** Tg_n^{jk} is M **AND** Wg^{jk} is M, **Then** E_j^k is M;

...

R_Y: **If** Tg_0^{jk} is H **AND** Tg_n^{jk} is H **AND** Wg^{jk} is H, **Then** E_j^k is H.

For adjustment of the made fuzzy productional model ME_j^k, one can use the method based on applying a learning sample, which is formed as a result of calculations according to the previously described fuzzy component models $M_{comp_i}^{jk}$ $(i = 1, ..., n)$ [11].

Procedure of utilization of the made ME_j^k fuzzy productional model is run on the base of the known fuzzy logical deduction algorithms [13].

Definition, adjustment and application of all fuzzy productional models $\{ME_1^1, ..., ME_j^k, ..., ME_{J_k}^k\}$, $\{MH_1^1, ..., ME_j^k, ..., ME_{J_k}^k\}$, designed for estimation of electrical and heating energy spendings $(E_1^k, ..., E_j^k, ..., E_{J_k}^k)$,

Table 1

A fragment of the fuzzy productional rule database structure of a *MFE_k* model for estimating electrical energy spendings *E_k* for the *k*-th pelletizing process

The rule number	Fuzzy input variables					Fuzzy output variable
	E_1^k	...	E_j^k	...	E_{Jk}^k	E_k
R_1	L	...	L	...	L	L
...	...	...	...	...	...	...
R_g	M	...	M	...	M	M
...	...	...	....	...	...	...
R_Q	H	...	H	...	H	H

Table 2

A fragment of the fuzzy productional rule database structure of a *MFE* model for estimating electrical energy general costs *E* for pelletizing

The rule number	Fuzzy input variables					Fuzzy output variable
	E_1	...	E_k	...	E_K	E
R_1	L	...	L	...	L	L
...	...	...	...	...	...	...
R_u	M	...	M	...	M	M
...	...	...	....	...	...	...
R_U	H	...	H	...	H	H

$(H_1^k, ..., H_j^k, ..., H_{J_k}^k)$, correspondingly, at the j-th stages $(j = 1, ..., J_k)$ for the k-th $(k = 1, ..., K)$ pelletizing processes are implemented in an analogous way.

Construction of the models of the 3rd cascade we will illustrate by the example of assigning the structure of a fuzzy productional model MFE_k for estimating energy expenses E_k for the k-th pelletizing process. Fuzzy output variables $(E_1^k, ..., E_j^k, ..., E_{J_k}^k)$ of the models of the 2nd cascade $\{ME_1^1, ..., ME_j^k, ..., ME_{J_k}^k\}$ serve as the input fuzzy variables of this model. Expenses E_k are the fuzzy output variable.

A fragment of the fuzzy rule database structure of a MFE_k model is represented in Table 1.

Procedures of adjustment and estimating electrical energy costs E_k for the k-th pelletizing process using the MFE_k model is realized similarly to the above examined ME_j^k model.

Definition, adjustment and application of all fuzzy productional models $\{MFE_1, ..., MFE_k, ..., MFE_K\}$, $\{MFH_1, ..., MFH_k, ..., MFH_K\}$, designed for estimation of electrical and heating energy spendings $(E_1, ..., E_k, .., E_K)$, $(H_1, ..., H_k, ..., H_K)$, respectively, for the k-th $(k = 1, ..., K)$ pelletizing processes are implemented in an analogous way.

Definition of the models of the 4th cascade is exemplified by the example of assigning the structure of a fuzzy productional model MFE for estimating electrical energy general costs E for pelletizing. Fuzzy output variables $(E_1, ..., E_k, ..., E_K)$ of the models of the 3rd cascade $\{MFE_1, ..., MFE_k, ..., MFE_K\}$ serve as the input fuzzy variables of this model, and general expenses E are a fuzzy output variable.

A fragment of the fuzzy rule database structure of a MFE model is represented in Table 2.

Procedures of adjustment and estimating electrical energy general costs E for pelletizing process using the MFE model is fulfilled similarly to the above examined models.

Definition, adjustment and application of the MFH fuzzy productional model for estimating the pelletizing heating energy general costs H are implemented in an analogous way [14—15].

Hence, a solution of an economic and mathematical problem of increasing the HTS energy efficiency of pelletizing using the suggested cascade multicomponent fuzzy model consists, in a general view, in setting various combinations of control parameters for each stage of all the processes, taking into account technological, organizational and other limitations imposed on these processes followed by modeling and determining such combinations of these parameters, which provide minimization of electric and thermal energy total costs during pelletizing [16—18].

Conclusion

An economic and mathematical problem of increasing energy efficiency of heat-technological systems (HTS) of pelletizing was stated in the paper.

Justified is the conclusion that in the present context of pelletizing in non-ferrous metallurgy (firstly, in conditions

of essential non-linear dependences between electrical and thermal energy costs both for different processes and separate stages of these processes and the general ones; secondly, taking into account the HTS equipment originality; thirdly, under material effect of environmental parameters), usage of a fuzzy logical approach is worthwhile for modeling and assessing electrical and thermal energy costs (both general and for each process taken separately) in order to increase energy efficiency of pelletizing HTS.

Suggested is a cascade multicomponent fuzzy economic and mathematical model of a heat-technological system of pelletizing, which includes:

— aggregates of the fuzzy component models for analyzing the pelletizing processes (drying, heating, hard firing, recuperation, cooling);

— aggregates of the fuzzy productional models for estimating cost of electric and heat energy at all stages for all the processes of pelletizing;

— aggregates of the fuzzy productional models for estimating cost of electric and heat energy for all the processes of pelletizing;

— the fuzzy productional models for estimating total electrical and thermal energy costs.

The article describes the suggested approach to solving an economic and mathematical problem of increasing of the pelletizing HTS energy efficiency using the proposed cascade multicomponent fuzzy model, which is to set various combinations of control parameters for each stage of all the processes, taking into account technological, organizational and other limitations imposed on these processes followed by modeling and in the determination of such combinations of these parameters, which provide minimization of electric and thermal energy total costs during pelletizing.

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