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Fuzzy Inference Technique in the Task of Sludge Batching Management

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Abstract: The study described the methodology of application of the fuzzy logic methods and fuzzy control theory for solution of tasks of the sludge feeding to the cement kiln. The research procedure presented in the study consists in modeling the human behavior by operating a complex production facility with the use of the fuzzy inference system. On the basis of this technique, the trend of designing the relevant system providing the state estimation of sludge feeder based on analysis of its processing parameters is considered. In the study an example of calculation of the quantitative value of a control action is provided, namely that of the angle of bend rotation for the automated control system based on fuzzy logic equations. The obtained results of the studies allow evaluating the benefits of fuzzy systems as compared to other kinds of control systems as well as using the fuzzy logic equations derived one may synthesize the fuzzy inference system for the regulator of the sludge feeding to a cement kiln.

Key words: Sludge feeding control, fuzzy logic methods, the monitoring system, fuzzy inference system, quantitative value

INTRODUCTION

Automation of control of the process of sludge feeding to cement kilns is a rather complex research and engineering task. This is due to the fact that the raw mixture has a relatively high viscosity for pumping through piping; in order to reduce it water is added to sludge which in its turn increases the energy consumption by burning of cement while water is vaporized in the kiln. Thus, for example, sludge may contain over 40% of water from its total volume. At the same time the sludge humidity may vary as the result of water loss and deposition of solid particles by storing in sludge pools (Besedin *et al*., 2011a, 2013; Trubayev and Besedin, 2005).

In Fig. 1, the control chart for feeding sludge to a cement kiln is presented that will be used for design of a fuzzy. In order to control the sludge feeding a great number of processing parameters against limited number of controlling actions shall be monitored (Besedin *et al*., 2011b).

In order to synthesize a fuzzy controller that shall perform control of the sludge feeding it is needed to design the fuzzy inference system on the basis of production rules and membership functions (Besedin *et al*., 2014). This task consists in application of accepted algorithms of the fuzzy inference system design (Rubanov and Filatov, 2010).

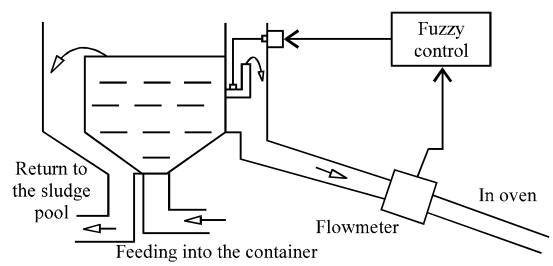

Fig. 1: Control chart for feeding sludge to a cement kiln

The concept of fuzzy inference holds the central position in the fuzzy logic and in the fuzzy control theory. Speaking of fuzzy logic in control systems the following definition of fuzzy inference may be given.

A fuzzy inference system is the process of drawing fuzzy conclusions concerning the required object management on the basis of fuzzy conditions or pre-requisites providing information about the current state of an object.

This process combines the principal concepts of the fuzzy-set theory: membership functions, linguistic variables, methods of fuzzy implication, etc. (Leonenkov, 2005; Shtovba, 2007). The design and application of the fuzzy inference system includes a number of stages implemented on the basis of the above mentioned provisions of the fuzzy logic (Fig. 2).

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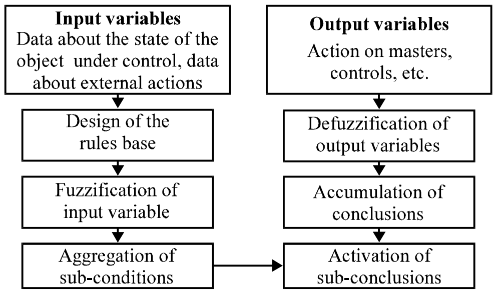

Fig. 2: The diagram of the fuzzy inference proess in the fuzzy control system

The objective of the study: Development of the methods of analysis and control of the process of sludge feeding in the adviser mode and automated control on the basis of the fuzzy logic theory. Step-by-step design of the fuzzy inference system according to the Mamdani algorithm on the basis of the membership functions obtained in the study and production rules (Besedin *et al*., 2014).

MATERIALS AND METHODS

Design procedure: Let's define the input variables in the system under consideration: volumetric flow rate, density and moisture content in the sludge, the command variable sludge consumption by weight of the solid material contained in it and the output variable of the angle of rotation of the tube bend regulating the sludge consumption. For evaluation of the input and output variables, we take the qualitative terms from the term set consisting of three values: (low, average, high) and for the command variable: (very low, low, average, high, very high).

The rule base of the fuzzy inference systems is designed for formal representation of empirical knowledge of experts in some or other domain areas in the form of fuzzy production rules. Therefore, the base of fuzzy production rules of a fuzzy inference system is the system of fuzzy production rules representing the experts' knowledge concerning the methods of the object control in different situations, nature of its operation in different conditions, i.e., containing the formalized human knowledge (Zadeh, 1976).

The following statement is an example of the expert rule from the fuzzy knowledge database in the task of the sludge feeding: IF the consumption of sludge by the weight of solid material contained in it is low AND the volume flow rate of sludge is low AND the sludge density is low AND moisture content in sludge is low, THEN the angle of the bend rotation is average.

Table 1: Rule-base of the fuzzy inference system for the sludge feeding control task

Consumption	Density	Moisture content	Consumption by the weight of solid material	Angle of the tube bend rotation
H	H	H	OH	C
C	H	H	OH	H
B	H	H	OH	H
H	C	H	OH	H
H	B	H	OH	C
H	H	C	OH	H

Table 2: Values of membership functions of linguistic terms

Values	Very low	Low	Average	High	Very high
Consumption	-	0.72	0.30	0.00	-
Density	-	0.00	0.87	0.17	-
Moisture content	-	0.10	0.83	0.00	-
Consumption by weight of the solid material	0.76	0.45	0.00	0.00	0

Using the symbols H "low", C "average", B "high", etc., this base of fuzzy production rules may be represented in the tabular form (Table 1), in the nodes of which the corresponding conclusions as to required angle of the bend rotation may be found. The table contains only part of the rules, the total number of which = 135; however, the presented rules suffice to describe the essence of the procedure applied and solution of the task set.

Fuzzification (introduction of fuzziness) is establishment of correlation between the numerical value of the input variable of the fuzzy inference system and value of the membership function of the relevant linguistics variable term. At the fuzzification stage, the values of all input variables of fuzzy inference system obtained with the use of a method that is external in respect of the fuzzy inference system for example by means of sensors are assigned the specific values of the membership functions of the corresponding linguistic terms used in the conditions (antecedents) of cores of fuzzy production rules constituting the basis of the fuzzy production rules of the fuzzy inference system.

By the example of the sludge transportation system if the current consumption, density and moisture content are 35 t h^{-1}, 1620 kg m^{-3} and 37.15% and consumption by weight of the solid material is 40 t h^{-1}, respectively, then by fuzzification we obtain the degrees of truth of elementary fuzzy statements (Table 2). Searching for degrees of truth of elementary fuzzy statements is presented in graphical form in Fig. 3.

Aggregation is the procedure of determining, the degree of the truth of conditions by each of the fuzzy inference system rules. In the case at the fuzzification stage, the values of the membership functions of the linguistic variables terms are used that constitute the above-mentioned conditions (antecedents) of cores of fuzzy production rules.

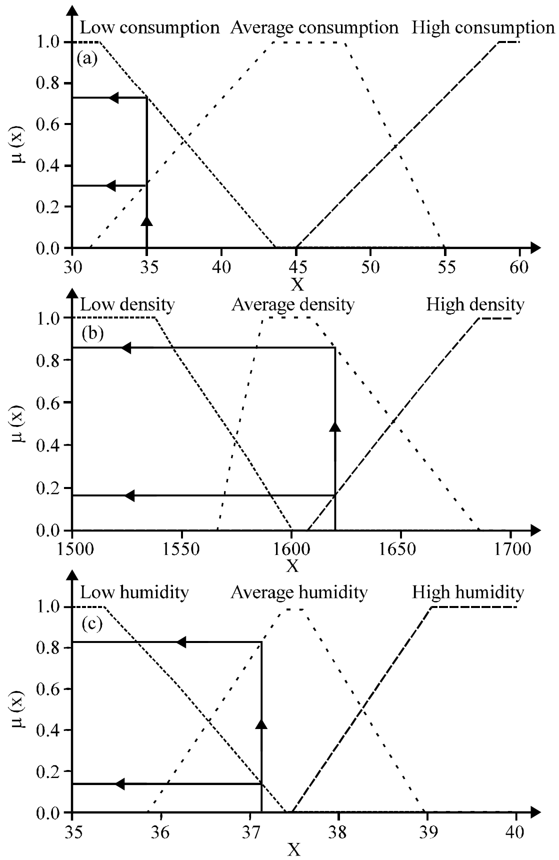

Fig. 3: Determining the degree of truth of the input elementary fuzzy statement by membership functions of the linguistic variables

RESULTS AND DISCUSSION

Taking into account the values of truth of elementary statements obtained as the result of fuzzification the degree of truth of conditions for each aggregated rule of the fuzzy inference system for sludge feeding control according to the definition by Zadeh of the fuzzy logical 'AND' of a few elementary statements A and B will be as follows:

$$T(A \cap B) = \min\{T(A); T(B)\} \quad (1)$$

Rule 1: Antecedent "low sludge consumption" AND "low sludge density" AND "low moisture content in sludge" AND "very low consumption by weight of solid material"; the degree of the antecedent truth min (0.72; 0; 0.1; 0.76) = 0.

Rule 2: Antecedent "average sludge consumption" AND "low sludge density" AND "low moisture content in sludge" AND "very low consumption by weight of solid material"; the degree of the antecedent truth min (0.3; 0; 0.1; 0.76) = 0.

Rule 3: Antecedent "high sludge consumption" AND "low sludge density" AND "low moisture content in sludge" AND "very low consumption by weight of solid material"; the degree of the antecedent truth min (0; 0; 0.1; 0.76} = 0.

Rule 4: Antecedent "low sludge consumption" AND "average sludge density" AND "low moisture content in sludge" AND "very low consumption by weight of solid material"; the degree of the antecedent truth min (0.72; 0.87; 0.1; 0.76) = 0.1.

Rule 5: Antecedent "low sludge consumption" AND "high sludge density" AND "low moisture content in sludge" AND "very low consumption by weight of solid material"; the degree of the antecedent truth min (0.72; 0.17; 0.1; 0.76) = 0.1.

Rule 6: Antecedent "low sludge consumption" AND "low sludge density" AND "average moisture content in sludge" AND "very low consumption by weight of solid material"; the degree of the antecedent truth min (0.72; 0; 0.83; 0.76) = 0.

Activation in the fuzzy inference systems is the procedure or process of finding the degree of truth of each elementary logical statement (sub-conclusion) constituting the consequents of cores of all fuzzy production rules. Since, conclusions are drawn in respect of the output linguistic variables the degrees of truth of elementary sub-conclusions by activation are placed in correspondence with elementary membership functions.

The functions of membership $\mu(y)$ of each elementary sub-conclusion of consequents of all production rules are found with the use of one of the fuzzy composition methods:

- Min-activation $\mu(y) = \min(c; \mu(x))$
- Prod-activation $\mu(y) = c\,\mu(x)$
- Average-activation $\mu(y) = 0.5\,(c+\mu(x))$

where, μ (x) and c, respectively are the membership functions of the linguistic variables terms and degree of truth of fuzzy statement constituting the relevant consequences (consequents) of cores of fuzzy production rules.

As the example of activation for the sludge feeding system let's consider the membership functions for the sub-conclusion according to the rule 5 upon min-activation (Fig. 4).

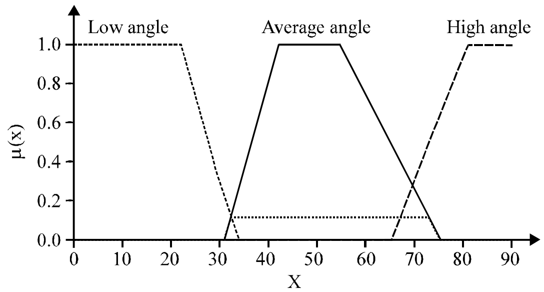

Fig. 4: The membership functions for the output linguistic variable and graphical illustration of min-activation (highlighted with green color) for the rule 5

Accumulation in the fuzzy inference systems is the process of finding the membership function for each of the output linguistic variables. The purpose of accumulation consists in combining all degrees of the sub-conclusions truth in order to obtain the membership function for each of the output variables. The result of accumulation for each of the output linguistic variables is defined as combination of all fuzzy sets of sub-conclusions in the fuzzy rule-base with respect to the relevant linguistic variable.

Aggregation of membership functions for all sub-conclusions is usually performed with the use of the max-aggregation according to Eq. 2:

$$\forall x \in X \; \mu_{A \cup B}(x) = \max\{\mu_A(x); \mu_B(x)\} \quad (2)$$

Figure 5 presents the obtained membership function of the output linguistic variable highlighted with green color.

Defuzzification in the fuzzy inference systems is the process of transition from the membership function of the output linguistic variable to its exact (numerical) value. The purpose of defuzzification consists in using the results of all output linguistic variables in order to obtain the quantitative values for each output variable that is used by the external to the fuzzy inference system devices (control system actuators).

Transition from the membership function μ(x) of an output linguistic variable obtained as the result of accumulation to the numerical value y of the output variable is performed with the use of one of the following methods (Blyumin *et al*., 2002). Method centre of gravity consists in calculation of the centroid.

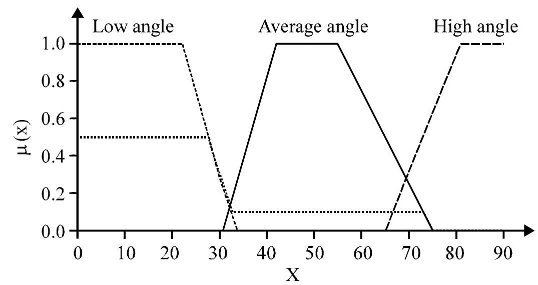

Fig. 5: Membership function of the linguistic variable 'angle of bend rotation'

$$y = \frac{\int_{x_{min}}^{x_{max}} x\mu(x)dx}{\int_{x_{min}}^{x_{max}} \mu(x)dx} \quad (3)$$

where, $(x_{min}; x_{max})$ the carrier of the fuzzy set of the output linguistic variable. Method of centre of area consists in calculating the abscissa y dividing the area limited by the curve of the membership function μ(x), the so-called bisector of the area:

$$\int_{x_{min}}^{y} \mu(x)dx = \int_{y}^{x_{max}} \mu(x)dx \quad (4)$$

Method of the left modal value $y = x_{min}$. Method of the right modal value $y = x_{max}$. With regard to the production rules of the fuzzy inference system for sludge feeding control by means of changing the angle of rotation of the tube bend defuzzification of the membership function of the linguistic variable "angle of bend rotation" (Fig. 5) provides the following results:

- Method of center of gravity y = 34°
- Method of center of area y = 37°
- Method of the left modal value y = 0°
- Method of the right modal value y = 75°

Summary: The procedure of design calculation of the controlling action within the sludge feeding task will allow designing a fuzzy controller that will stabilizing the sludge feeding to a cement kiln or other processing unit to which non-Newtonian fluids are fed.

CONCLUSION

The approach to solving the task of operating the complex non-linear production facilities from the perspective of fuzzy logic is not the single one. However, the use of the theory of the fuzzy control of sludge feeding allows modeling behavior of a human expert that does not master information about the mathematical model of the object under control.

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