Optimization of Pneumatic Control Mode of Bulk Matirials Flow

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***Abstract*— Innovation methods and facilities of bulk materials flow control optimization are considering. The results of continuous and discrete feedback control systems of hard phase flow in two-phase stream "fluid – bulk material" are given. Methodology for structure and parametric a priori synthesis of control devices is proposed.**

***Keywords*— bulk materials; pneumatic control; discrete dosing device; best performance; multicriteria optimization**

I. Introduction

The need to control the variable flow of bulk materials (BM) is characteristic for the technological processes of the chemical, food, pharmaceutical and metallurgical industries, in the production of building materials. The problem of taking into account the integral amount of SM arises often. If the variable supply of BM to technological devices performs the function of control, then it becomes necessary to control its flow. Dispensers are used as systems that enable the integration of flow measurement, quantity accounting and flow control functions. Further, the dispenser will be considered as a system designed for measuring and issuing a given amount of material with an error not exceeding a certain value [1]. Structurally, the dispenser is a closed-loop control system with feedback on the quantity of material and consists of at least two elements – the actuator and the control device. There are volumetric [2] and weight (mass) [3] dosing methods, and the issuance of material in both cases can be carried out in a continuous [4, 5] or discrete [1, 6] form. By changing the task to continuous feeders, continuous flow control can be ensured. In the discrete dispensing mode, the flow can be controlled by changing the frequency and / or the duration of the dose delivery. The latter method is applied less often. Information on the current consumption of the material is obtained directly from the value of the task to the dispenser. The amount of material passing through the dosing system is judged by the integral of the flow rate over time.

The requirements for automatic dispensers are determined by the conditions of a particular manufacture, but among them the most common ones can be identified. These include: providing a specified flow range, the minimum error in the amount (flow) of the material to be weighed; reliability of functioning; non-inertial termination of supply; possibility of repeated switching on under load; fulfillment of environmental and technical safety conditions; providing comfortable conditions for production personnel. The effectiveness of the application of dosing systems also depends on their energy intensity and capital costs. An important condition for the reliable operation of automatic BM metering devices is also the way to create a moving force. On this basis, the equipment can be divided into gravitational, mechanical and pneumatic. The first group includes free-flow devices and devices with aeration and / or vibrational action on the material in order to reduce the friction between the particles. Only the force of gravity contributes to particle motion. According to the data of [7], continuous dosing with gravitational flow is practically not effective. To control the flow, mechanical automatic feeders and dispensers are traditionally used as actuators, the principle of which is based on a weight or, more rarely, a volumetric measurement of the amount of material. The technical implementation of mechanical methods and systems of continuous dosing and control of BM consumption [4, 5, 8], practically unchanged during the previous decades, largely does not meet modern requirements in terms of accuracy, reliability, speed, environmental and technical safety. The reasons for this are incomplete tightness and, most importantly, the presence of a significant number of kinematic pairs operating in dusty conditions and clogging with small fractions of BM. The shortcomings of the mechanical control systems for the consumption of BM should include their high metal content and cost.

II. Materials and Methods

As a promising alternative of the mechanical AD for BM, pneumatic systems have been developed, the advantages of which are complete tightness and the fundamental absence of the moving elements in contact with BM. The principle of operation of the proposed dispensers is based on the pneumatic transportation of the solid phase particles in the gas flow, i.e., the driving force is created due to the pressure difference on the particle layer [9]. As a basis, the unrestricted movement of BM with a volumetric concentration of solid particles σ_V <0,05 along a short vertical pipeline is chosen. The advantage of vertical displacement of a two-phase mixture under such conditions is the possibility of instantaneous termination of the feed and its renewal without additional regime changes. The minimum concentration of solid particles in the flow allows a wide range of flow control to be provided. The phenomenological equation for determining the volume flow of a solid phase in a two-phase flow [10] can be written as

$$Q_M = u_M \cdot S_{TP} \cdot \sigma_V$$

where u_M – average velocity of the particles of the solid phase; S_{TP} – cross-sectional area of the discharge pipeline; σ_v – volume concentration of the solid phase. Given the difference between the velocity of the carrier gas υ_B and the velocity of the particles $\Delta\upsilon = \upsilon_B - u_M$, relative to the carrier gas flow Q_B the design expression for the BM flow has the form:

$$Q_M = \left[Q_B - S_{TP} \cdot \Delta\upsilon(Q_B)\right] \cdot \sigma_V(Q_B)$$

According to this expression, it is possible to determine the static dependence of the BM flow rate on the carrier gas flow, which serves as the basis for implementing systems with pneumatic flow control and dosing. The analytical dependences of the velocity difference $\Delta\upsilon$ and the volume concentration of the solid phase on the gas flow rate in the two-phase flow are generally unknown, since they are determined by the specific parameters of the BM particles, gas and the pipeline [11], therefore, in the subsequent calculations, the static characteristics of the feeders and dispensers actuators obtained from the experiments are used.

The basic element of such automatic pneumatic feeders and dosing devices is a vertical continuous pneumatic feeder (VCPF) (Fig. 1). The feeder is a tank 1 to which a charging 2 and a discharge 3 pipes are connected, as well as an air duct 4 connected with an air blower 5. A pressure sensor 6 is connected to the chamber, in the entry area to the discharge pipeline, the output of which is connected to a regulator (R) (PC) 7, which determines the capacity of the air blower. BM, by itself, or under the influence of additional pressure, enters the tank 1 through the charging Circuit diagrams of discrete vacuum dosing device pipeline 2, where it mixes with the gas, for instance, with air coming through the air duct 4. Under the influence of the pressure drop $\Delta P = P_C + P_{EP}$ between the chamber pressure P_C and the external pressure P_{EP} at the outlet of the discharge pipeline, the mixture of material with air is displaced along the discharge pipeline into the technological apparatus or into the tank.

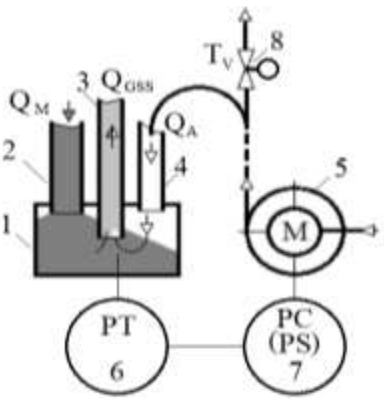

Fig. 1. Circuit diagrams of discrete vacuum dosing device

The flow rate of the solid phase is determined by the current dimension of the pressure in the chamber, that makes it possible to regulate the quantity of the produced material, changing the task to the regulator 7, output signal of which determines the productivity of the air blower 5 [12]. Changing the pressure in the chamber can also be done by connecting the output of the regulator 7 to the throttle valve 8, by means part of the air supplied to the mixing chamber is discharged into the atmosphere. If the pressure in the mixing chamber is less than the pressure, holding the material in the charging pipeline, the chamber is filled continuously as it is emptied. Otherwise, the material is retained in the charging pipeline until the chamber is completely empty.

After that, the pressure in the mixing chamber falls, the pressure regulator (PS) 7 triggers, the air supply stops and the chamber is refilled. Thus, VCPF performs the functions of the discrete volumetric dosing device of BM with a fixed dose rate (FDR) [13]. In this case, the mixing chamber 1 serves as a measuring tank. The control of the average material flow Q_{AF} entering the technological object is carried out according to the equation of frequency-pulse modulation of the dose constant volume sequence $Q_{AF} = V_o f(\mu)$ where V_o = const – the volume of the dose; $f(\mu)$ – law of frequency-pulse modulation of a continuous control signal μ. The control of BM flow rate is carried out when the feed takes place with the help of a discrete vacuum dosing device (DVD) of the volumetric action (Fig. 2). When the air is pumped out from the measuring tank 1, this tank is filled with a material through the charging pipeline 2 under the influence of external pressure. When the material layer reaches the bottom of the filter 10, the vacuum in the air duct 4 increases above the filter that serves as a signal for the operation of the relay-regulator 9, whose output signal interrupts the operation of the air blower 5 from the chamber. The dose is delivered through the discharge pipeline 3 by gravity or by feeding additional pressure to the chamber [14].

Regardless of the pneumatic control scheme used for feeding the BM, in practical implementation arises the problem

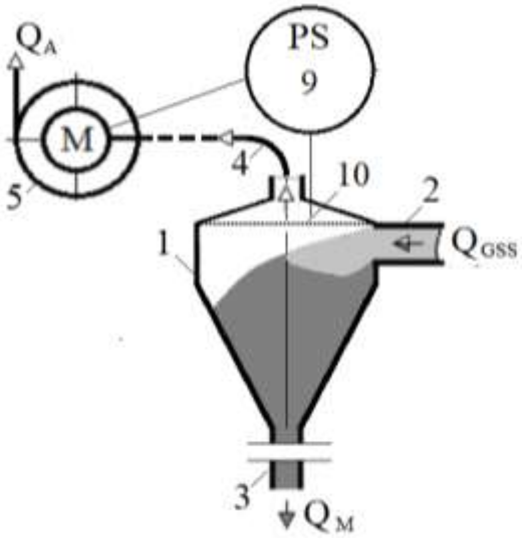

Fig. 2. Normalized criteria characteristics of pneumatic AD

of determining the optimal operating mode of the dispenser in accordance with the achievement of specified requirements for efficiency and operation quality. From the above list in this paper, four basic indicators are distinguished: maximum speed (maximum productivity), high reliability, minimum error in measuring the dose of BM and a minimum of energy costs. If necessary, this list can be expanded.

The basic requirements to the quality of discrete pneumatic AD operation can be formulated as maximum speed (productivity), high reliability, minimum error in measuring the dose of BM and minimum energy costs. In this case, restrictions are set concerning really achievable physical speed values of the two-phase mixture, the carrier air flow rate and the pressure in the tank. To ensure the operation of the AD in the optimal mode, taking into account several different criteria, after starting the working prototype, the dependences of the airflow and the solid phase are experimentally measured depending on the pressure (for pressure AD) or on the pressure drop ΔP between atmospheric pressure and the vacuum created in the inlet manifold of the air blower (for vacuum AD). After that, the problem of choosing the optimal value of the working pressure is solved. As an example of solving problem of the multicriteria optimization, the bearing characteristics of the DVD are given in Fig. 3, which are transformed to the same scale by the relative deviations of the particular criteria from their minimum values $f_k(\Delta P) \in [0,1]$, $k \in [1,4]$.

- $f_1(\Delta P)$ – Consumption characteristic – the dependence of the mass flow rate of the solid phase $F_м$ from the value of the acting pressure drop ΔP during the transfer of the two-phase mixture. It has been experimentally established and confirmed theoretically that this characteristic is essentially nonlinear and it has a maximum of: $f_1(\Delta P) \rightarrow \max$.
- $f_2(\Delta P)$ – Relative air costs for moving the BM in a two-phase flow when changing in the operating range. The characteristic has an extremum $f_2(\Delta P) \rightarrow \min$.

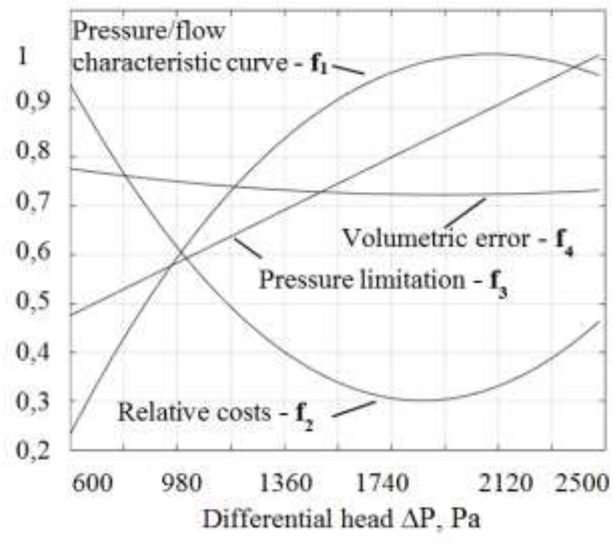

Fig. 3. Calculating results of the optimum pressure

The type of characteristics is determined by the processes occurring in the vertical flow of the two-phase mixture "gas-solid particles": when increasing, after the carrier gas reaches the velocity of the transported particles, their accelerated movement begins, which is slowed down as the internal resistance and frictional resistance of the particles of the outlet shaft walls increase due to the increasing of their true volumetric concentration. In this case, the concentration value depends not only on the speed but also on the air flow rate. With a sufficiently large value of resistance to the two-phase flow, the raise in the air velocity leads not to the increase but to the growing decrease in the flow rate of the solid phase.

- $f_3(\Delta P)$ – a monotonically increasing ratio between ΔP and the amount of pressure $P_к$, that determines the reliable operation of the end-of-dose sensors.
- f_4(ΔP– the dependence between and the relative error in the value of the dose, determined by the weighting method: $f_2(\Delta P) \rightarrow \min$.

All the criteria are transformed to the form $f_k \rightarrow \max$ in advance. In order to take into account the importance of each particular criterion relating to the general conclusion, their ranking with weight coefficients representing C_k expert estimates was used. The physical limitation of the pressure drop from below P_{min} is associated with the creation of the development conditions in the "gas-solid particles" system that exceeds the velocity of particle waving. The upper limit of ΔP is determined by a sharp increase in hydraulic resistance. The problem of multicriteria optimization formulated in general form for the synthesis of DVD operating mode and considering physical constraints has the following form:

$$f_k(\Delta P) = \sum_{i=0}^{n} a_{i+1} \Delta P^{n-i} \rightarrow \max;$$
$$\sum_{k=1}^{4} C_k = 1; \; P_{\min} \le \Delta P \le \max \; f_2(\Delta P).$$

The following multicriteria optimization methods are chosen taking into account the achievement of the required accuracy of the optimal value determination and with the possibility of forming the algorithmic part of the method as part of the DVD application software. Since the a priori calculation of the optimal mode at the design stage is impossible due to the lack of a complete mathematical model of the BM moving system in the gas flow, the tuning will be performed after the first commissioning and it is advisable to implement the calculation procedure as part of the software of the dispenser control device.

The results of complex objective functions calculation are shown in Fig. 4. To determine the compromise optimum of ΔP, the following methods were used: multicriteria optimization on the basis of max-min convolution (u_1 – the objective function generalizing private functionals), the method of comparison with the ideal alternative based on the fuzzy logic apparatus (u_2 – the target function on the basis of the Hamming distance) [15] and the method of fair compromise using the Pareto set (u_{31} и u_{32} – the relative decrease and the quality improvement of the solution when moving from one solution to another) [16].

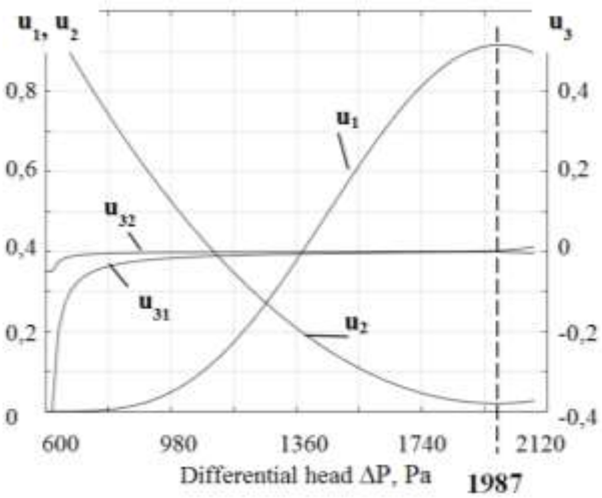

Fig. 4. Calculating results of the optimum pressure

The first criterion for a classical realization gives a rather rough approximation, therefore, within the framework of this paper, an algebraic interpretation of the intersection operation is used. The use of the Hamming distance as a basic function is due to the ease of method expansion and the way in which weights are introduced. Of the set of optimization methods based on the Pareto set, the preference is given to the compromise method, since it works with relative changes in particular criteria and does not require special preliminary normalization. Preliminary rationing of particular criteria in the range [0,1] allows us to identify their values with membership functions for the first and second criteria.

III. Results and Discussion

In the first two cases, the normalized values of the partial criteria are considered as an analog of the function of belonging to the linguistic concept "optimal value of the argument". The criterion restriction $f_2(\Delta P)$ reduces the determination domain of the optimal ΔP. The optimum indicators for the first and the second methods (Fig. 4, curves u_1 and u_2) coincide on the value $\Delta P_{opt} = 1987$ Pa. The result of the method compromise u_3 differs slightly: $\Delta P_{opt} = 1968$ Pa. This discrepancy in practical application can be attributed to the condition of getting into the 5% regulation zone. Considering the minimal complexity of the software implementation for practical applications, it is expediently to use method u_1 or u_2.

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