SAT-ONLINE-P-2-BFT(R)-09

SCIENTIFIC SUBSTANTIATION OF THE PROCESS OF MANAGING CRITICAL MODES OF PNEUMATIC TRANSPORTATION FOR FOOD PRODUCTS

Liudmyla Kryvoplias-Volodina, DcS
Department of Mechatronics and Packaging Technology
National University of Food Technologies, Kyiv, Ukraine
E-mail: kryvopliasvolodina@camozzi.ua

Prof. Oleksandr Gavva, DcS
Department of Machines and Apparatus for Food and Pharmaceutical Industries,
National University of Food Technologies, Kyiv, Ukraine
E-mail: gavvaoleksandr@gmail.com

Oleksandr Volodin, master
Department of Mechatronics and Packaging Technology,
National University of Food Technologies, Kyiv, Ukraine
E-mail: sashavolodin11@gmail.com

Abstract: *The mathematical and physical models for critical modes of pneumatic conveying has been developed to ensure calculations and design of the main pneumatic product pipelines with a continuous mode of operation. The model takes into account the technological conditions of the gas suspension movement; the laws of motion of individual small-piece particles, taking into account their impact interaction and decompression, as well as real boundary conditions for the movement of a food product. The parameters of the zone of dynamic destruction of the layer of small-piece food product by the air shock wave were experimentally investigated and the comparison of the calculation results with the experiment was performed. The process of controlling the critical modes of pneumatic conveying based on proportional elements and feedback (current loop 4–20 mA) was theoretically described; investigation of the process of destruction of a cluster of products using an air wave and controlled decompression. An approach to modelling pneumatic conveying systems as a whole is proposed. The total pressure loss in the pneumatic conveying pipeline is investigated, it consists of: pressure losses arising from the movement of clean air; additional pressure losses arising from the movement of material; pressure losses to maintain the transported material in suspension in a vertical section; pressure loss for acceleration of transported particles when they are drawn into the transport pipeline; which are directly proportional to the volumetric mass of air, the speed of its movement and the weight concentration of the material in the mixture.*

Keywords: pneumatic conveying, small-piece, model, modes, boundary conditions, control, layer.

INTRODUCTION

The current controlling and mathematical models describing the dynamics of the pneumatic conveying process of food products are simplified; most often their description does not correspond to the real phenomena arising in technological equipment. (Hasan Ghafori , 2018). Therefore, to consider the operation of a pneumatic line in a dynamic mode, it is necessary to investigate and develop mathematical models based on physical modeling. Accordingly, promising issues today are the development and application of technically advanced designs of pneumatic product pipelines for different types of storing facilities, technological areas for dosing bulk, small-piece food products. (Rajan, K.S., 2008). The challenge is to build flexible pneumatic conveying automation systems to improve productivity by three to five times and reduce actual costs by 30 to 50 %. Issues are also tackled to develop and implement the principles of transporting bulk, small-piece materials through pipelines with compressed air in a dense layer without congestion. (Gavva, O., 2018). The use of pneumatic conveying for delivering small-piece food products to the area of technological processing has a series of advantages: environmental friendliness, cleanliness, changing modes of operation during the continuous transportation process, the introduction of proportional monitoring systems in management.

EXPOSITION

The aim and objectives of the study

The aim of this study is to mathematically and physically model the process of the pneumatic conveying of small-piece products, as well as critical modes to ensure the calculation and design of product pipelines with a continuous supply.

To accomplish the aim, the following tasks have been set:

– to investigate the process of transporting small-piece products in a working pneumatic pipeline;

– to develop a control system, as well as real boundary conditions for the geometric, kinematic, and dynamic parameters;

The study materials and methods

Studying the process of transporting small-piece products in a working pneumatic pipeline

Our experimental and theoretical studies are based on the application of the fundamental laws of theoretical mechanics, the hydrodynamics of multiphase environments, the theory of solving ordinary differential equations. As well as taking into consideration equations in private derivatives, numerical methods; the mechanics of the deformable body; our own findings from experimental research of pneumatic conveying processes.

The study materials and methods

Studying the process of transporting small-piece products in a working pneumatic pipeline

Our experimental and theoretical studies are based on the application of the fundamental laws of theoretical mechanics, the hydrodynamics of multiphase environments, the theory of solving ordinary differential equations. As well as taking into consideration equations in private derivatives, numerical methods; the mechanics of the deformable body; our own findings from experimental research of pneumatic conveying processes. According to, the proportion of solid particles in a flow β is the volume concentration in the range of 0.01 to 0.04 (up to 4 %).

Control system

A combination of the feedback control system (the current loop format is 4…20 mA) was chosen as a system for controlling the flow of compressed air in the vertical channel. The possibility of regulating the control signal for current on a control solenoid of 0…5 s was taken into consideration.(Fig. 1).

The kinematic and dynamic characteristics of pneumatic conveying of certain types of products have been investigated in the course of experiments on individual pneumatic conveying modes.

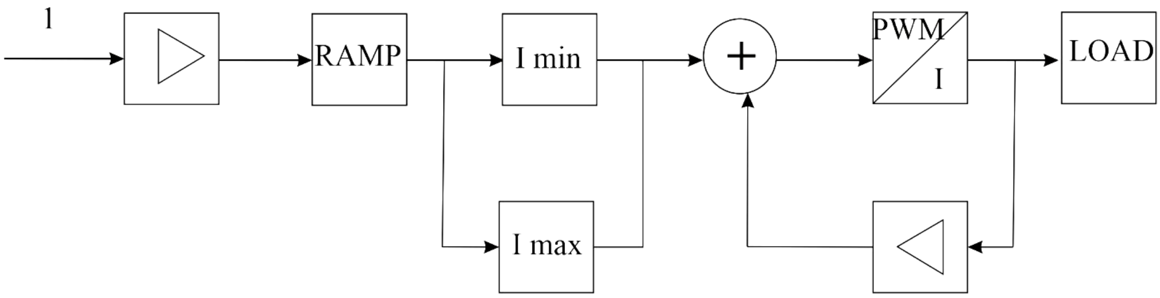

Fig. 1 Control signal transmission scheme for the pulsed supply of compressed air in a vertical pipeline: 1 – standard signal; RAMP – calibration of acceleration time; *I*min, *I*max – current load (mA); PWM – power management by the method of pulsating enabling/disabling the device; *I* – current calibration (mA) that sets the maximum value of the current fed to the valve with a support signal of 100 %; LOAD – a load in the control circuit

The mechanism of the pneumatic conveying process, characteristic of most technological processes, is illustrated by a photograph of the experimental bench, when using different types of small-piece products (for a better representation of the transportation process, a frame-by-frame formation of the stabilization area is shown in Fig. 2).

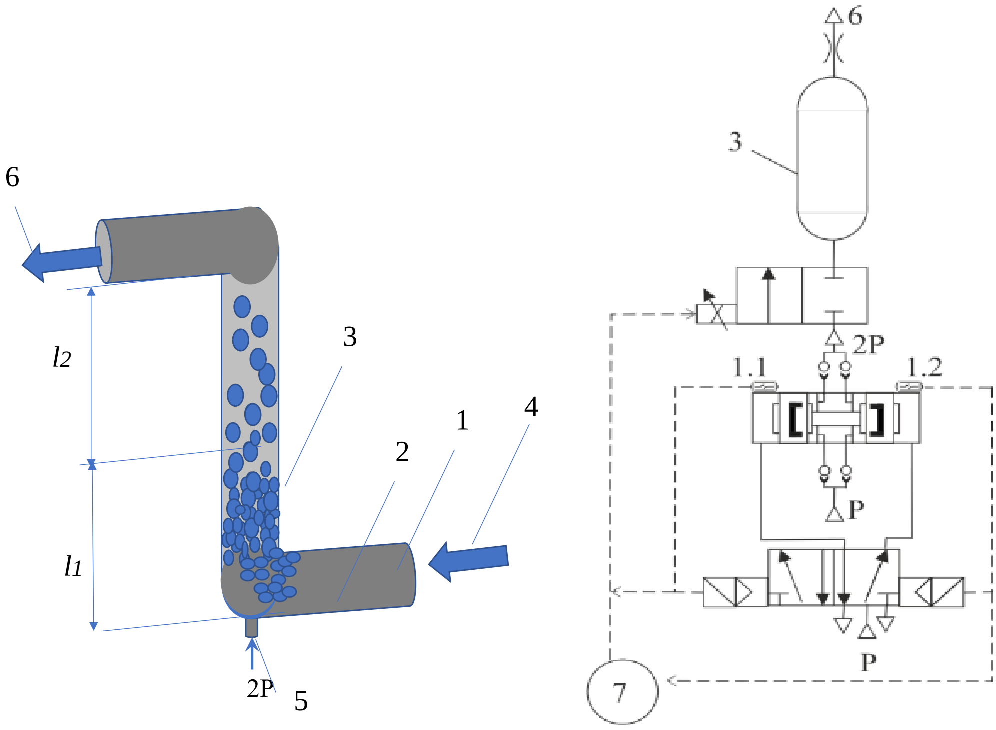

Fig. 2 Schematic transportation of small-piece products in the pneumatic conveying technological module: 1 – loading bunker, 2 – supply zone of a product by an auger feeder, 3 – vertical transporting channel; 4 – product, 5 – compressed air; 6 – gas suspension (air, small-piece product), 7 – electro-pneumatic control unit; P – main pressure of compressed air (MPa), 2P – double pressure at the outlet of the booster; 1.1., 1.2. – reed sensors; l1, l2 – the length of the acceleration and stabilization sections (m)

The control system in Fig. 2 employs CAMOZZI elements: series 130 drivers to control the proportional valve dispensers, type AP (2/2), electronic sensor/pressure relay, SWCN series, booster 40M2L100A120MC02. The PWM signal, formed by the driver, generates, in the closed circuit of current regulation of 4.20 mA, a signal with a frequency of up to 500 Hz to the coil of the solenoid of the electromagnetic valve of compressed air supply to the system of the vertical channel of the product pipeline. The power voltage in the control circuit is 24 VDC (±10 %) in accordance with the chosen proportional distributor AP. The flow rate of compressed air will depend on the value of the incoming mainline pressure P (0.1...0.3 MPa), and, according to data from [17, 18], are 80...160 (Nl/min). The use of pneumatic conveying automation methods is based on a model that represents the integrated ideas about particle movement in an inseparable flow in a dense phase. To combine the main characteristics for a dispersed environment (flow rate, density, mass, pressure), it is necessary to take into consideration the kinematic and dynamic characteristics that are created in the flow of the material.

Let us consider the process of the pneumatic conveying of a small-piece product in the experimental bench system. The process of rotation of particles in the gas flow is associated with the absence of spherical form, the presence of impact interaction between the particles and wall of a product pipeline, as well as the presence of the effect of spinning the particles by individual small turbulent vortexes.

Consider the process of pneumatic conveying, controlled by compressed air pulses that cause working modes.

The airflow is formed at the inlet to the channel with the product, by using a pneumatic valve, which is controlled by the generation of current in line with the Heaviside function (a single step function). The measured current value in mA (at a resolution of 0.001 mA) relative to the standard scale Imax, Imin=4…20 mA, was registered in the ranges of 4.1 mA...19.9 mA; 12

mA...19.9 mA. The flow rate characteristic of the pneumatic valve in the installation is 180 Nl/min. The function period duration was accepted by up to 0.3 s.

Mathematical Model

By stating the problem of mathematical modeling, consider the movement of the spherical particle of radius *r′*, density ρ′ in the turbulent gas flow. Provided: the flow is stationary, the gas is incompressible, the kinematic viscosity ν=μ/ρ. μ is the dynamic viscosity of the gas (compressed air), ρ is the air density. Since the flow of compressed air is turbulent, the resistance to the movement of the particle relative to the gas is subject to a non-linear law. Therefore, the particle is affected by the gravity *G*=ρ’·*g*’, (*H*); *g*’ – is the vector of the acceleration of gravity. The input parameters of the mathematical model: the radius of the particle is $r`=3\cdot10^{-3}$ (m); the density of a single particle of a small-piece product is $\rho`=1.24\cdot10^{-3}$ ($kg\cdot m^{-3}$); the air density is $\rho`=1.24\cdot10^{-3}$ ($kg\cdot m^{-3}$); the acceleration of free fall is g=9.81 ($m\cdot s^{-2}$); the maximum compressed air flow rate is v_m=20 ($m\cdot s^{-1}$); the dynamic viscosity is $\mu=1.82\cdot10^{-5}$ kg/(m·s); the pipe radius is *b*=0.05 m. In the compressed air flow, the particle is set into a rotational motion, which predetermines the motion equations (Fig. 4):

$$\frac{\pi}{6}(2\cdot r')^3\rho'\frac{\mathrm{d}u_i}{\mathrm{d}t}=D'(v_i-u_i)+G_i+F_s, \qquad (1)$$

$i=x, y, z$; v_i is the projection of the vector of the velocity $\bar{v}$ of compressed air, u_i is the projection of the particle velocity vector $\bar{u}$ relative to the stationary count system *x, y, z*. F_i is the projection of the Rubinov-Keller force vector onto the spherical surface of a particle on the side of compressed air when rotated. G_i is the projection of the gravity vector onto a particle, where

$$D'=6\pi\mu r'\left(1+0.065\left(\frac{2}{\mu}r'\rho'\left(\sqrt{\bar{u}-\bar{v}}\right)\right)\right)^{\frac{3}{2}}. \qquad (2)$$

Represent the equation of the rotational motion of particles together with motion equation (1)

$$\begin{cases}\frac{4}{3}\pi\cdot r'^3\cdot\rho'\cdot\frac{\mathrm{d}u_x}{\mathrm{d}t}=D'(v_x-u_x)+G_x+F_x,\\ \frac{4}{3}\pi\cdot r'^3\cdot\rho'\cdot\frac{\mathrm{d}u_y}{\mathrm{d}t}=D'(v_y-u_y)+G_y+F_y,\\ J\cdot\frac{\mathrm{d}\omega}{\mathrm{d}t}=-\pi\mu(2\cdot r')^3\cdot\left(\frac{1}{2}\cdot\frac{\partial v_x}{\partial y}-\omega\right).\end{cases} \qquad (3)$$

where ω=ω*z* is the projection onto the vector's *z* axis of the angular velocity when the particle rotates; *J* is the moment of particle inertia relative to the central axis, which is parallel to the *Oz* axis: $J=\left\{\pi\cdot(2\cdot r')^5\rho'\right\}/60$.

Rewrite the system of equations (3) taking into consideration the transforms described above:

$$\frac{4}{3}\pi\cdot r'^3\rho'\frac{\mathrm{d}^2x}{\mathrm{d}t^2}=6\cdot\pi\mu r'\times$$
$$\times\left(1+0.065\cdot\left(\frac{2}{\mu}r'\rho'\cdot\sqrt{\left(\frac{\mathrm{d}x}{\mathrm{d}t}-v_x\right)^2+\left(\frac{\mathrm{d}y}{\mathrm{d}t}\right)^2}\right)^{\frac{2}{3}}\right)^{\frac{3}{2}}\times... \qquad (4)$$
$$...\times\left(v_y-\frac{\mathrm{d}x}{\mathrm{d}t}\right)-\pi\rho'(r')^3\omega(2\cdot r')^3\cdot\left(\frac{\mathrm{d}y}{\mathrm{d}t}\right),$$

$$\frac{4}{3}\pi\cdot r'^3\rho'\frac{d^2y}{dt^2}=-6\cdot\pi\mu r'\times$$
$$\times\left(1+0.065\cdot\left(\frac{2}{\mu}r'\rho'\cdot\sqrt{\left(\frac{dx}{dt}-v_x\right)^2+\left(\frac{dy}{dt}\right)^2}\right)^{\frac{2}{3}}\right)^{\frac{3}{2}}\frac{dy}{dt}-... \tag{5}$$
$$...-\frac{4}{3}\pi\cdot\rho'(r')^3-\pi\cdot\rho'(r')^3\cdot\omega\cdot\left(v_x-\frac{dx}{dt}\right),$$
$$J\cdot\frac{d\omega}{dt}=-\pi\mu(2\cdot r)^3\cdot\left(\frac{1}{2}\cdot\frac{\partial v_x}{\partial y}-\omega\right). \tag{6}$$

Initial conditions for finding five arbitrary *const* of the integration:
– at the initial moment of movement t=0; $x(0)=x_0$; $y(0)=y_0$;
– to determine the projections of the velocity vector at the initial point in time:

$$\left.\frac{dx}{dt}\right|_{t=0}=u_{x_0},\quad \left.\frac{dy}{dt}\right|_{t=0}=u_{y_0};$$

– at the initial point in time, the angular velocity of the particle's rotation:
$\omega(0)=\omega_0$;
– the estimation scheme of particle kinematic characteristics for the established mode of transportation (Fig. 3).

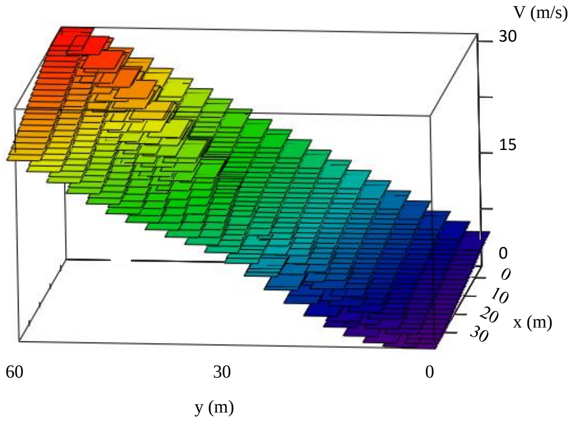

Fig. 3 Kinematic parameters of transporting a small-piece product in a product pipeline at different values of structural parameters: a change in the linear speed of movement of a small-piece product *v* when moving in the channel of the product pipeline under pressure

The purpose of physical modeling is to determine the pressure in the pneumatic conveying channel under the condition of the pulsed supply of compressed air, as well as the assessment of energy costs. Physical simulation of the pneumatic conveying process was carried out for small-piece products with the above-described working conditions and product properties.

The analysis of our simulation results has shown that the following conclusion is fair – the total loss of pressure in the pipeline of pneumatic conveying consists of:
– the loss of pressure caused by the movement of clean air;
– additional pressure losses arising from the movement of the material;
– the loss of pressure to maintain the transported material in a suspended state on a vertical section;
– the loss of pressure to accelerate the transported particles when they are involved in the transport pipeline. The loss of pressure is directly proportional to the volume mass of air, the speed of its movement, and the weight concentration of the material in a mixture.

CONCLUSION

1. A control signal transmission scheme has been developed for the pulsed supply of

compressed air in the vertical pipeline, taking into consideration the introduction of elements of the proportional pneumatic equipment (analog signal, 4.20 mA).

2. The rational parameters have been determined for both the control process and the process of transporting a product in general. The particle radius is r`=$3\cdot10^{-3}$ (m); the density of a single particle of a small-piece product is ρ`=$1.25\cdot10^{-3}$ ($kg\cdot m^{-3}$); the air density is ρ`=$1.24\cdot10^{-3}$ ($kg\cdot m^{-3}$); the acceleration of free fall is g=9.81 ($m\cdot s^{-2}$); the maximum compressed air flow rate is v_m=20 ($m\cdot s^{-1}$); the dynamic viscosity is $\mu=1.82\cdot10^{-5}$ kg/(m·s); the radius of the pipe is b=0.05 m.

3. A mathematical model of the pneumatic conveying process of small-piece products has been developed. The model includes the differential motion equations for individual particles in the flow, as well as their behavior after colliding, with corresponding initial and boundary conditions. The boundary conditions take into consideration the influence of pneumatic conveying modes and the geometry of a product pipeline. The measured current value in mA (at a resolution of 0.001 mA) relative to the standard scale Imax, *I*min=4..20 mA is registered in the ranges of 4.1 mA...19.9 mA; 12 mA...19.9 mA. The flow rate characteristic of the pneumatic valve in the installation is 180 Nl/min. The accepted function period duration is up to 0.3 s.

REFERENCES

Hasan Ghafori (2018). Numerical and experimental study of an innovative pipeline design in a granular pneumatic–conveying system *Particuology, Volume 38,* June 2018, 196–203.

Rajan, K.S. (2008). Experimental study of thermal effectiveness in pneumatic conveying heat exchanger. Applied Thermal Engineering. Volume 28, Issues 14–15, October 2008, 1932–1941.

Gavva, O. Kryvoplias-Volodina, L. Volodin, S. Hnativ, T. Dynamics of mechatronic function modules drives of flow technological lines in food production. Ukrainian Food Journal, 2018, Volume 7, Issue 4 - P.726 – 738.

Raheman, Hifjur & Jindal, V. (2001). Pressure drop gradient and solid friction factor in horizontal pneumatic conveying of agricultural grains. Applied Engineering in Agriculture, 2, 4–8.

Raheman, Hifjur & Jindal, V. (2001). Solid velocity estimation in vertical pneumatic conveying of agricultural grains. Applied Engineering in Agriculture,7, 233–245. doi: 10.13031/2013.6903

Cui, Heping & Grace, John. (2006). Pneumatic conveying of biomass particles: A review. China, 4, 183–188. doi: 10.1007/s10556–015–9990–6.

Timoshenko, V.I. (2013). Pnevmotransport syipuchih materialov s povyishennyim davleniem nesuschego gaza. Nauka ta innovatsii, T.9, №1, 5–17.

Kril, S.I., Chaltsev, M.N. (2010). K voprosu o metodikah rascheta osnovnyih parametrov pnevmotransporta syipuchih materialov po gorizontalnyim trubam. Prikladnaya gidromehanika. T. 12, №4, 36–44.

Dixon, G. (1981). Chapter “Pneumatic conveying”. In: Butters, G. (ed.) Plastics Pneumatic Conveying and Bulk Storage. Applied Sciences Publisher, Reading, 343. doi: https://doi.org/10.1007/978–90–481–3609–4

Gyenis, J., Arva, J., (1994). Steady state particle flow in mixer tubes equipped with motionless mixer elements. In: Tatterson, G.B., Calabrese, R.V., Penney, W.R. (eds.) Industrial Mixing Technology, AIChE Symposium, Series 90, 144–156.

Orozovica, A., Lavrineca, A. (2020). Transport boundaries and prediction of the slug velocity and layer fraction in horizontal slug flow pneumatic conveying. Chemical Engineering Science, Volume 227, 247—257. doi: https://doi.org/10.1016/j.ces.2020.115916

Zhang, P., Roberts, R. M. & Bénard, A. (2012), Computational guidelines and an empirical model for particle deposition in curved pipes using an eulerian–lagrangian approach. Journal of Aerosol Science 53(Supplement C), 1–20. URL: http://www.sciencedirect.com/science/article/pii/S0021850212000997

Rohrig, R., Jakirlic, S. & Tropea, C. (2015). Comparative computational study of turbulent flow in a 90pipe elbow. International Journal of Heat and Fluid Flow 55, 120–131. doi:10.1016/j.ijheatfluidflow.2015.07.011