Modeling of particle motion in a vortex layer while drying

Anatoliy Pavlenko

Dr. sci, professor,
Poltava National Technical Yuri Kondratyuk University, Poltava

Anna Koshlak

Ph.D., associate professor,
Poltava National Technical Yuri Kondratyuk University, Poltava

Bohdan Usenko

Postgraduate,
Poltava National Technical Yuri Kondratyuk University, Poltava

Abstract
In article experimental data, on the basis of which the mathematical model of movement of a particle in a vortex layer is created at heat treatment, are resulted. Features of movement of a particle in the vortex device are determined, the dependences are received. These dependencies allow to operate duration of thermal processing, on the basis of which it is possible to design the device for drying disperse particles. In the suggested model it is accepted, that the basic power component of process of heat treatment are borders of speed and pressure in a stream and concerning a particle.
Keywords: DRYING, VORTEX DEVICE, TURBULENT FRICTION, MATHEMATICAL MODEL, EQUATIONS OF MOTION

Introduction

At the present level of development of vortex devices, the relevance of research for in-deep study of the processes, improving ofdesign and manufacturing technologies of individual units has increased. The absence of rigorous theory is the most acute in design of systems and installations, where the vortex device is one of the main units. In this regard, the primary task is to develop a theory, which provides a fairly reliable mathematical description of the processes that occur in the vortex chamber.

The purpose of the work

Basing on the research results contained in [1], the aim is to develop a mathematical model of the motion of a particle in vortex layer of heat transfer medium.

The materials and research results

Motion of subsonic different gases at different temperatures [1] represented by the following system of equations of motion, energy, diffusion, continuity and state:

$$\begin{cases} \dfrac{\partial(\overline{\rho u})^2}{\partial x} + \dfrac{\partial}{\partial y}\overline{u}\left(\overline{\rho\upsilon} + \overline{\rho'\upsilon'}\right) = -\dfrac{\partial}{\partial y}\left(\overline{\rho u'\upsilon'}\right), \\ \dfrac{\partial(\overline{\rho u}\overline{h})}{\partial x} + \dfrac{\partial}{\partial y}\overline{h}\left(\overline{\rho\upsilon} + \overline{\rho'\upsilon'}\right) = -\dfrac{\partial}{\partial y}\left(\overline{\rho}\overline{h'\upsilon'}\right), \\ \dfrac{\partial(\overline{\rho u c})}{\partial x} + \dfrac{\partial}{\partial y}\overline{c}\left(\overline{\rho\upsilon} + \overline{\rho'\upsilon'}\right) = -\dfrac{\partial}{\partial y}\left(\overline{\rho c'\upsilon'}\right), \\ \dfrac{\partial(\overline{\rho u})}{\partial x} + \dfrac{\partial}{\partial y}\left(\overline{\rho\upsilon} + \overline{\rho'\upsilon'}\right) = 0. \end{cases} \tag{1}$$

where $\overline{u'}\overline{\upsilon'}$ - function characterizing the turbulent friction; $\overline{h'}\overline{\upsilon'}$ - function of turbulent diffusion of heat; $\overline{c'}\overline{\upsilon'}$ – function of turbulent diffusion of substance.

Patterns of distribution of a swirling jet depend on a large number of different conditions (the design features of the nozzle, swirling intensity) and flow parameters (density and velocity).

The flow in the jet has complicated non-self-similar character, and therefore in [1] it was considered to be appropriate to use for the calculation numerical methods of integrating the equations of motion, similar to those used in [2,3] for the description of non-self-similar character flow in the ordinary jets.

Neglecting the influence of velocity fluctuations on pressure change, the equation of motion for the axisymmetric incompressible turbulent flow in boundary layer approximation and with account of the relation (2) can be written in this form:

$$\frac{P - P_b}{\rho} = \int_b^y \frac{\omega^2}{y}\,dy, \tag{2}$$

$$yu\frac{\partial u}{\partial x} + yv\frac{\partial u}{\partial y} = -y\frac{\partial}{\partial x}\Theta - y\frac{\partial}{\partial y}(\overline{u'}\overline{\upsilon'}) - \overline{u'}\overline{\upsilon'},$$

$$v\frac{\partial u}{\partial y} - uv - yu\frac{\partial v}{\partial y} = -y\frac{\partial}{\partial x}\Theta - y\frac{\partial}{\partial y}(\overline{u'}\overline{\upsilon'}) - \overline{u'}\overline{\upsilon'},$$

$$y^2u\frac{\partial \omega}{\partial x} + y^2\upsilon\frac{\partial \omega}{\partial y} + y\omega\upsilon = -y^2\frac{\partial}{\partial y}(\overline{\omega'}\overline{\upsilon'}) - 2y\overline{\omega'}\overline{\upsilon'},$$

$$yu\frac{\partial c}{\partial x} + y\upsilon\frac{\partial c}{\partial y} = -y\frac{\partial}{\partial y}(\overline{\upsilon'}\overline{c'}) - \overline{\upsilon'}\overline{c'},$$

$$\Theta = \int_0^y \frac{\omega^2}{r}\,dr$$

(3)

In [4], basing on the hypothesis of constancy of analogue of turbulent viscosity coefficient for the stationary swirling flow of compressed gas and considering μ_T and λ_T to be constant for the swirling flow, there provided the following model of vortex flow one-component stream:

$$\rho\left(\upsilon\frac{\partial\upsilon}{\partial r} - \frac{\omega^2}{r} + u\frac{\partial u}{\partial x}\right) = -\frac{\partial p}{\partial r} + \mu_T\left[\frac{4}{3}\left(\frac{\partial^2\upsilon}{\partial r^2} + \frac{1}{r}\frac{\partial\upsilon}{\partial r} - \frac{\upsilon^2}{r}\right) + \frac{\partial^2\upsilon}{\partial x^2} + \frac{\partial^2 u}{\partial r\partial x}\right];$$

$$\rho\left(\upsilon\frac{\partial\omega}{\partial r} + \frac{\upsilon\omega}{r} + u\frac{\partial\omega}{\partial x}\right) = \mu_T\left(\frac{\partial^2\omega}{\partial r^2} + \frac{1}{r}\frac{\partial\omega}{\partial r} - \frac{\omega}{r} + \frac{\partial^2\omega}{\partial x^2}\right);$$

$$\rho\left(\upsilon\frac{\partial u}{\partial r} + u\frac{\partial u}{\partial x}\right) = -\frac{\partial p}{\partial x} + \mu_T\left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r}\frac{\partial u}{\partial r} + \frac{4}{3}\frac{\partial^2 u}{\partial x^2} + \frac{1}{3}\left(\frac{\partial^2\upsilon}{\partial r\partial x} + \frac{1}{r}\frac{\partial\upsilon}{\partial x}\right)\right];$$

$$\frac{\partial}{\partial r}(\rho r\upsilon) + \frac{\partial}{\partial x}(\rho r u) = 0$$

(4)

The disadvantage of these models is that when solving the model of vortex flow becomes laminar flow model. However, many values cannot be determined analytically or experimentally.

When separating the flow into zones: zone of vortex flow and vortex core zone, the error in the calculation of flow hydrodynamics and particles increases significantly, because of the use of different equations of turbulent viscosity coefficient, which is taken for each zone constant. These models are written for continuous medium and therefore are not suitable for multiphase flow. We have compared the data [1] and [4] for the distribution of certain parameters of the vortex flow with the data obtained by experiment.

The experiment was carried out on an apparatus developed by authors, which consists of a vortex chamber 1 (Fig. 1) containing tangentially failed nozzle 5, which through a conduit is connected to the heater 9 and the gas blower 15. By the end surface of the device in order to supply liquid binder there attached pipe 4 with heat exchanger 3 and the pump 2, by which the spray-gun 13 the liquid is distributed by volume. The material through the conduit 8 is supplied into the vortex chamber 1, by means of swirler it diffuses all over the chamber and rotates in vortex layer of gas. Dried material falls into the mold 7.

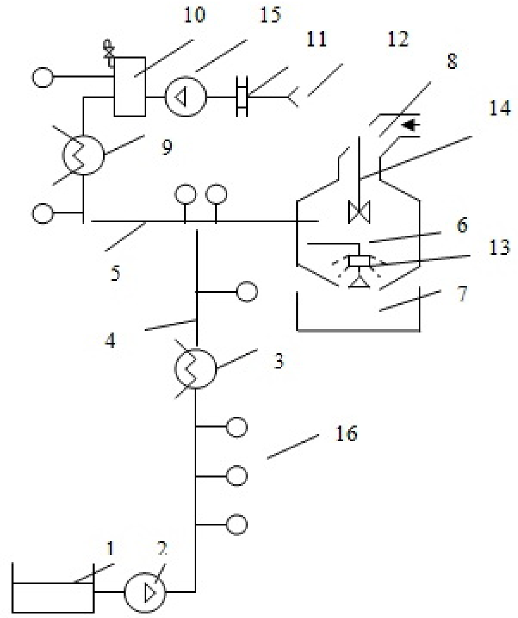

Figure 1. The scheme of the experimental equipment:
1 container with gluing substance; 2- liquid supply pump; 3- liquid heat exchanger; 4- liquid supply; 5 - air supply; 6 - vortex chamber; 7- form; 8 - material fed; 9 - heat exchanger for air; 10 - receiver; 11 - filter; 12 - air intake; 13 - spray gun; 14 - swirler; 15 - pump of gas supply; 16 - pressure, temperature and flow.

On the basis of data, obtained in the course of experiment carried out with the help of above-described equipment, the following dependencies were obtained (Figure 2 and Figure 3).

According to these dependencies one may conclude that the parameters received at the installation, which we developed, characterize vortex motion in the device. Circumferential velocity is lower than in [1], [3] and [4], pressure does not exceed the data [1], [3] and [4].

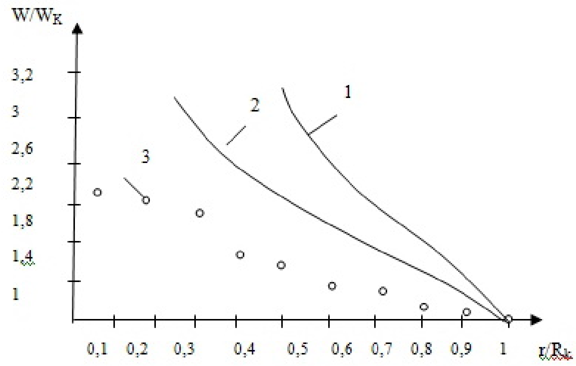

Figure 2. Analysis of the distribution curves of circumferential speed over the radius: 1 - according to Abramovich data [1,3]; 2 - according to Koval data [4]; 3 - the results of the experiment

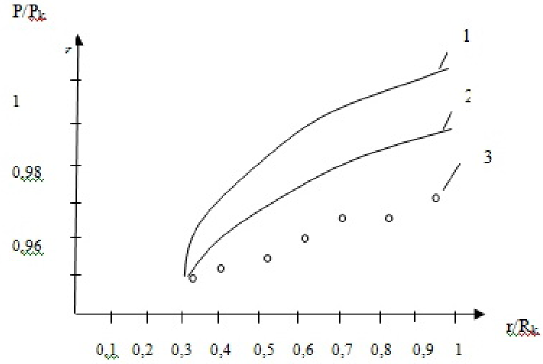

Figure 3. Analysis of the distribution curves of pressure over the radius: 1 - according to Abramovich data [1,3]; 2 - according to Koval data [4]; 3 - the results of the experiment

In [5], [6], [7] there was an attempt to take into account the regularities of the particles motion in a multiphase medium, but there was not developed models of vortex motion. Combining the model of Koval and Abramovich vortex flow, considering Nigmatulin multiphase, we can obtain physical and mathematical model of the motion of a particle in the developed device.

Below there represented mathematical formulation of the problem of hydrodynamics of particles in a centrifugal field of the vortex chamber. As a result of its solution one should define the basic parameters of the flow necessary for the efficient emulsification.

The equation of equilibrium of forces in the flow is as follows:

$$\rho_n \frac{dV_n}{d\tau} = \rho_n F_c(\vec{V} - \vec{V}_n) - gradP + \rho_n g, \qquad (5)$$

where $V_п$ – speed of movement of the dispersed phase; V – velocity of movement of the medium; $P_п$ – the density of the disperse phase; F_c – force of resistance:

$$F_c = F_{a.c} + F_s = \frac{3}{8} C^* \frac{\rho}{\rho_n a} \left| \vec{V} - \vec{V}_{II} \right| + F_s \quad , \qquad (6)$$

where $F_{a.c}$ – aerodynamic force of resistance; F_s – structural strength stability, characterizing free energy of the system (particles).

Theoretically the movement of air drops in a centrifugal field can be represented by a system of equations:

$$\frac{dV}{d\tau} = F_c(V - V_n) - \frac{1}{\rho_n}\frac{\partial P}{\partial r} + \frac{W_n^2}{r} \qquad (7)$$

$$\frac{dW}{d\tau} = F_c(W - W_n) - \frac{V_n W_n}{r} \qquad (8)$$

$$\frac{dU}{d\tau} = F_c(U - U_n) - \frac{1}{\rho_n}\frac{\partial P}{\partial h} + g \qquad (9)$$

where $V_п$, $W_п$, $U_п$ – radial, circumferential and axial components of the velocity of air drops; V,W,U – the same for the flow; $\frac{W^2}{r}$ - centrifugal acceleration; $\frac{V_n W_n}{r}$ - Coriolis acceleration; h – height of the vortex chamber.

Using the system of dimensionless components:

$$\begin{cases} \bar{\tau} = \tau \frac{|V_k|}{R_k}; \\ \bar{\rho}_м = \frac{\rho_м}{\rho}; \\ F_r = \frac{g R_k}{V_k^2}; \\ \bar{P} = \frac{P}{\rho V_k^2}; \\ \chi = g \frac{\mu}{d^2} \frac{1}{\rho_м} \frac{R_k}{|V_k|}. \end{cases} \qquad (10)$$

Then the equations (7) - (9) take the form:

$$\begin{cases} \frac{d\bar{V}}{d\bar{\tau}} = \frac{\bar{W}_n^2}{\bar{r}} + \chi |(\bar{V} - \bar{V}_м)| - \frac{1}{\rho_n}\frac{\partial P}{\partial r} & (11) \\ \frac{d\bar{W}}{d\bar{\tau}} = \frac{\bar{V}_n \bar{W}_n}{\bar{r}} + \chi |(\bar{W} - \bar{W}_n)| & (12) \\ \frac{d\bar{U}}{d\bar{\tau}} = \chi |(\bar{U} - \bar{U}_n)| - \frac{1}{\rho_n}\frac{\partial P}{\partial h} + Fr & (13) \\ \frac{d\bar{r}}{d\bar{\tau}} = \bar{V}_n & (14) \\ \bar{W}_n = \frac{\bar{r} d\varphi}{d\tau} & (15) \\ \bar{U}_n = \frac{dh}{d\tau} & (16) \end{cases}$$

Initial conditions for solving the problem (11) – (16):

$$\{\tau = 0; \quad r = 1, \quad \varphi = 0; \quad h = 0; \quad \bar{V}_n = 1; \quad \bar{W}_n = 1; \quad \bar{U}_n = 0\} \qquad (17)$$

Conclusions

When solving the system (11) - (16) there were obtained the following dependencies of flow velocities and bubble on the radius chamber (Fig.4., Fig. 5). Hence we conclude that the circumferential and radial velocities have maximum up to r = 0.2 and do not exceed the W=9 and V=12 (dimensionless). Calculations performed by the proposed model equations show satisfactory agreement with the experimental data. When estimating the relative velocity of the particle motion, it is evident that the use of equations for laminar flow, which are traditionally used in the calculations, leads to significant errors.

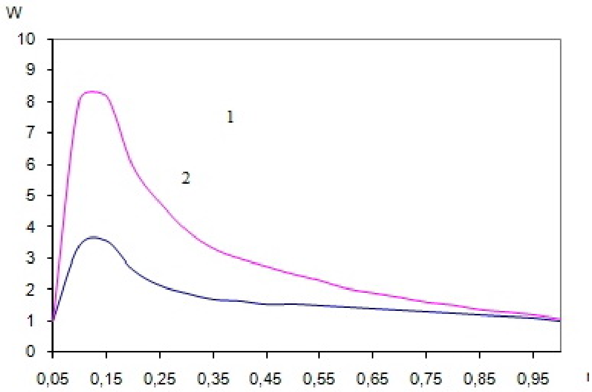

Figure 4. Distribution of the circumferential velocity over the radius: 1- flow rate; 2 - particle velocity

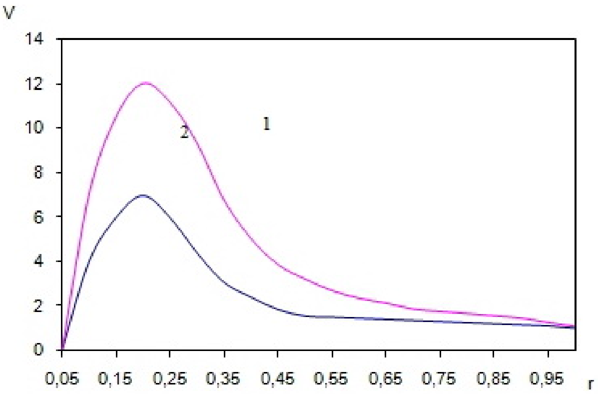

Figure 5. Distribution of radial velocity over the radius: 1 flow rate; 2- particle velocity

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