SECTION 6. FOOD TECHNOLOGY

6.1 Determining the influence of the coolant velocity on the parameters of the formation of the spray torch in the drying chamber

The spraying process is characterized by a set of forces acting on the jet or pellicle of liquid coming out of the spray. These include surface tension forces and forces of normal pressure of the gaseous medium that counteract them; forces of inertia and viscosity; friction forces in the interaction of jets with the environment. The interaction of these forces determines the dynamics of the process of spraying liquid jets or pellicles into droplets.

Studies of the hydrodynamics of spraying make it possible to obtain a ratio for calculating the dispersion of the spray, the diameter and shape of the spray torch, as well as the density of the spray torch along its radius. These studies are important for solving a practical problem in choosing a rational scheme of supply and movement of liquid or gas.

The efficiency of spray dryers is largely determined by the rational organization of the process of interaction of dispersed droplets with the coolant in the area of the spray torch.

When studying the process of coolant distribution, the most important thing is to establish the dependences of the dispersed characteristics of the spray torch on the parameters of the spray, its design and coolant supply rates.

The aim is to increase the efficiency of the spray drying method of whey and other liquid foods, reduce energy consumption and improve the quality of the finished product by improving existing drying methods and developing new equipment based on theoretical and experimental studies of spray drying.

Determination of the geometric dimensions and elements of chamber drying

The depth location of the spray disk in the drying chamber (H_R)

Defined [248] that the minimum ratio between the distance from the camera cover to spray disk *(H_R)* in diameter chamber drying *D*,in which the motion of the spray stream will not "stick" to the cover of the drying chamber is:

$$\frac{H_p}{D} = 0{,}1 \quad (\mathbf{1})$$

For the existing chamber H_P = 60 cm.

In the range of linear speeds of a spray disk 60 ÷ 120 m / s at size of departure of a disk under an arch of the device $\frac{\mathrm{H}p}{D}$<0.1 creates a board jet mode. The spray torch is pressed against the cover of the device, leading to intensive fouling of the surfaces of the device by the undried product.

At values of $\frac{Hp}{D}$ > 0.1 two-phase jet propagates as a free flooded jet, inducing the movement of the surrounding gas volumes in the direction of the spray torch. [248]

Geometric ratios in centrifugal spray dryers ($\frac{Hc}{D}$; $\frac{Hp}{D}$ Fig. 1) are established as a result of influence of the following factors:

- design features of the spraying mechanisms (the drive device, length of a high-speed shaft).
- spraying method, characterized by the horizontal direction of the main forces and, accordingly, the shape of the "spray torch" close to the horizontal.

Based on the experience of practical development of these devices [248], taking into account the specified conditions for drying chambers with the upper location of the sprayer, the following size ratios are established:

$$\frac{Hc}{D} = 0.5 - 1.0; \quad \frac{Hp}{D} = 0.1 \quad (\mathbf{2})$$

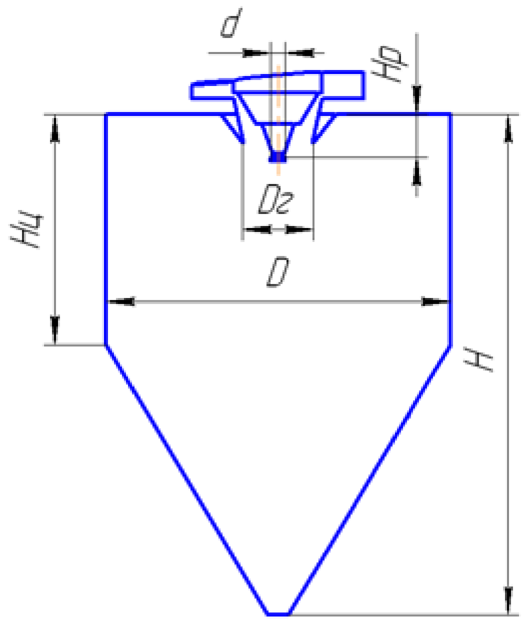


Fig. 1 Scheme of a drying chamber with a centrifugal spray.

As can be seen, the tower cover is located at a short distance from the disk, and the height of the cylindrical shell under the disk may be comparable to or less than the radius of the device.

Under these conditions, the operation of the dryer is possible only with a horizontal, or close to it shape of spray torch.

A similar effect of a sharp rise in the initial section of the spray torch was observed during the launch of a number of industrial facilities in the production of milk powder, feed yeast, dyes and other materials [228]. In these cases, even when using forced values of temperature and velocity of the coolant, the dryer was inoperable, not providing a dry bulk powder and leading to intensive overgrowing of the inner surfaces of the drying chamber with undried product.

Based on these assumptions and design parameters of the spray system, it is clear that there is a need to change the operating parameters, namely to increase the flow rate of the coolant to change the aerodynamic vortices inside the tower of the spray complex, optimize the spray process and reduce energy consumption.

In order to increase flow rates, geometric narrowing of the conditional passage of devices for liquids and gases in the form of nozzles and caps is widely used in scientific research and technology.

In these devices, for a given inlet pressure, the mass flow rate through the constricted device will reach a maximum value when the downstream pressure decreases to a critical value. The flow under these conditions is called the critical flow [236].

After reaching this mode, any further decrease in flow pressure does not increase the flow rate of the mass, and it is said that the Venturi nozzle has critical value [237] or acquires a critical flow regime [235,238].

This flow mechanism allows you to accurately monitor and measure the dynamic parameters of the device. The critical flow can be used where it is necessary to maintain a constant mass flow rate.

The mechanism regulating the transition for single-phase gas is well defined. To achieve the critical mode, the gas flow must be accelerated to a local sound velocity at the Venturi nozzle to prevent pressure waves that moving upstream. Conditions and standards for the use of Venturi critical injectors are clearly defined by ISO 9300 [239].

When air enters the Venturi nozzle, the velocity increases and the pressure in the area decreases due to a decrease in the cross-sectional area available for flow. This maximum fluid velocity is also called the critical flow velocity, which is a function of the pressure emanating from the nozzle geometry and the physical properties of the fluid [228]. This type of flow is specifically referred to as the critical cavitation flow [244].

According to the laws governing the dynamics of the flow of liquids and gases, the velocity must increase as the air passes through the constriction to satisfy the principle of continuity, while its pressure must decrease to satisfy the principle of conservation of mechanical energy. Thus, the pressure drop denies any increase in kinetic energy that can be accumulated by a liquid or gas due to an increase in velocity due to constriction. The equation of pressure drop due to the Venturi effect can be obtained from a combination of the Bernoulli principle and the continuity equation. It usually has a resistance factor of about 0.85 [244].

Using the Bernoulli equation for incompressible flows (for example, the flow of water or other liquid, or low gas flow rate v), the theoretical pressure drop p1-p2 at narrowing is given [247]:

$$p_1 - p_2 = \frac{\rho}{2}(v_2^2 - v_1^2) \quad \textbf{(3)}$$

Where ρ is the flow density.
The volumetric flow rate Q is given:

$$Q = v_1 A_1 = v_2 A_2 \quad \textbf{(4)}$$

where: A is the Venturi cross-sectional area at any point; $v$is the flow rate at this point.

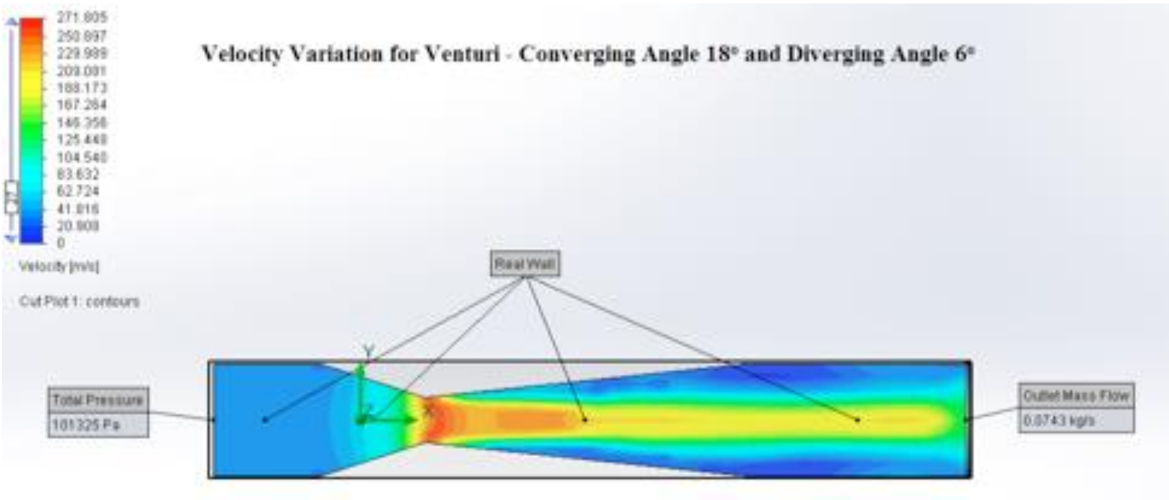


Fig. 2 Distribution of velocities in the cross section of the Venturi nozzle.

Another method of accelerating the flow due to design parameters is the technique used in Laval nozzles. In the following analysis of the gas flow in the Laval nozzle, the following assumptions are made:

- the gas is considered ideal;
- the gas flow is isotropic (i.e. it has a constant entropy, friction forces and dissipative losses are not taken into account) and adiabatic (i.e. heat is not supplied or removed);
- the gas flow is stationary and one-dimensional, i.e. at any fixed point of the nozzle all flow parameters are constant in time and change only along the nozzle axis, and at all points of the selected cross section the flow parameters are the same and the gas velocity vector is parallel to the nozzle axis;
- the mass flow of gas is the same in all cross sections of the flow;

- the axis of symmetry of the nozzle is the spatial coordinate.

The ratio of the local speed *v* to the local speed of sound *C* is denoted by the Mach number [249], which is also considered local, i.e. dependent on the coordinate x:

$$M = v \cdot C \quad \textbf{(5)}$$

From the equation of state of an ideal gas we obtain:

$$dpd\rho = C2 \ \textbf{(6)}$$

where ρ is the local density of the gas, *p* is the local pressure.

With this in mind, as well as taking into account the stationary and uniformity of the flow, the Euler equation takes the form:

$$vdvdx = -1\rho \cdot dpdx = -1\rho \cdot dpd\rho \cdot d\rho dx = -C2\rho \cdot d\rho dx, \ \textbf{(7)}$$

Given equation (3), we obtain:

$$1\rho \cdot d\rho dx = -M2 \cdot 1v \cdot dvdx. \ \textbf{(8)}$$

Equation (4) is key. Consider it as follows:

$$\frac{1\rho d\rho dx}{1vdvdx} = -M2 \textbf{(9)}$$

The values of *1ρdρdx* and *1vdvdx* characterize the relative degree of variability in the coordinate of x the gas density and its velocity, respectively.

Moreover, equation (9) shows that the ratio between these quantities is equal to the square of the Mach number (minus sign means the opposite direction of change: with increasing speed, the density decreases).

Thus, at subsonic velocities (M <1) the density changes to a lesser extent than the velocity, and at supersonic (M> 1) - on the contrary. As will be seen later, this determines the narrowing - expanding shape of the nozzle.

Since the mass flow of gas is constant:

$$\rho \cdot v \cdot A = const \ \textbf{(10)}$$

A is the area of the local section of the nozzle,

$$ln\rho + lnv + lnA = ln\,(const) \ \textbf{(11)}$$

differentiating both parts of this equation by *x*, we obtain:

$$1\rho \cdot d\rho dx + 1v \cdot dvdx + 1A \cdot dAdx = 0 \ \textbf{(12)}$$

After substitution with (4) in this equation, we obtain finally:

$dAdx = Av \cdot dvdx \cdot (M2 - 1)$ **(13)**

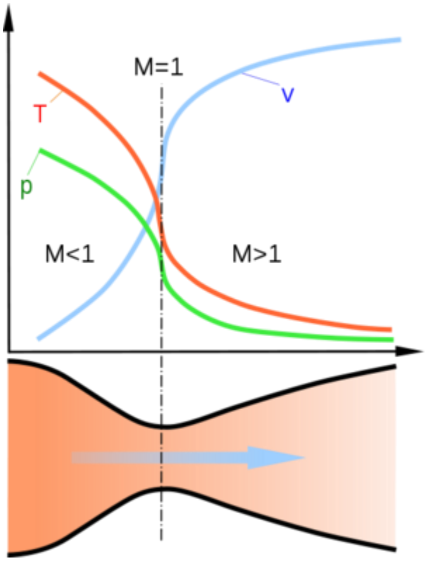


Fig. 3 Characteristics of the Laval nozzle. As the gas moves through the nozzle, its absolute temperature T and pressure P decrease, and the velocity V increases.

From the above we can draw the following conclusions:

- at the subsonic velocity of the gas (M <1), the derivative *dAdx* <0 - the nozzle narrows;
- at the supersonic velocity of the gas (M> 1), the derivative *dAdx*> 0 - the nozzle expands;
- when the gas moves at the speed of sound (M = 1), the derivative *dAdx* = 0 - the cross-sectional area reaches an extreme, i.e. there is the narrowest section of the nozzle, called the critical.

Therefore, in the narrowed, subcritical section of the nozzle, the gas moves at subsonic speeds. In the narrowest, critical section of the nozzle, the local gas velocity reaches supersonic. The flow accelerates to supersonic speed in an extended, supercritical section. This acceleration is due to the fact that the wave of pressure drop from the expanded portion of the gas in the supersonic flow does not have time to spread to other parts of the nozzle. Bernoulli's law is not fulfilled in these conditions. [249]

Hydrodynamic CFD modeling of drying agent supply modes in the drying complex

The use of the basic, above, provisions and methods of changing the physical parameters of the output flow of the coolant in order to adapt the organization of drying agent supply to the installation chamber requires additional modeling.

For this purpose, the simulation of the air supply to the spray tube and the basic CFD calculations were performed using the Ansys software package with the establishment of double the accuracy of the calculation based on the pressure in ANSYS FLUENT.

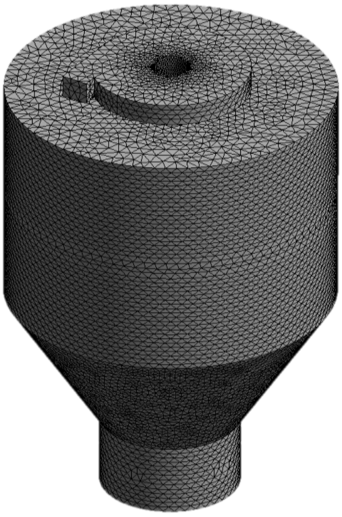


Figure 4. 3d-Model of the drying complex.

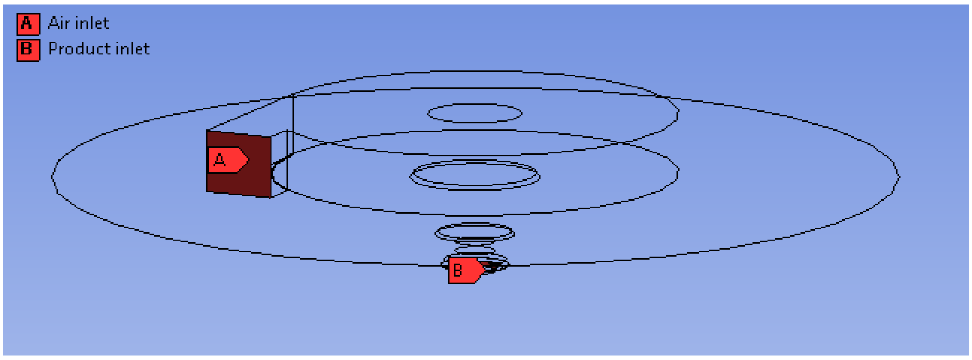


Figure 5. A - coolant supply zone; B - the area of product supply to the tower.

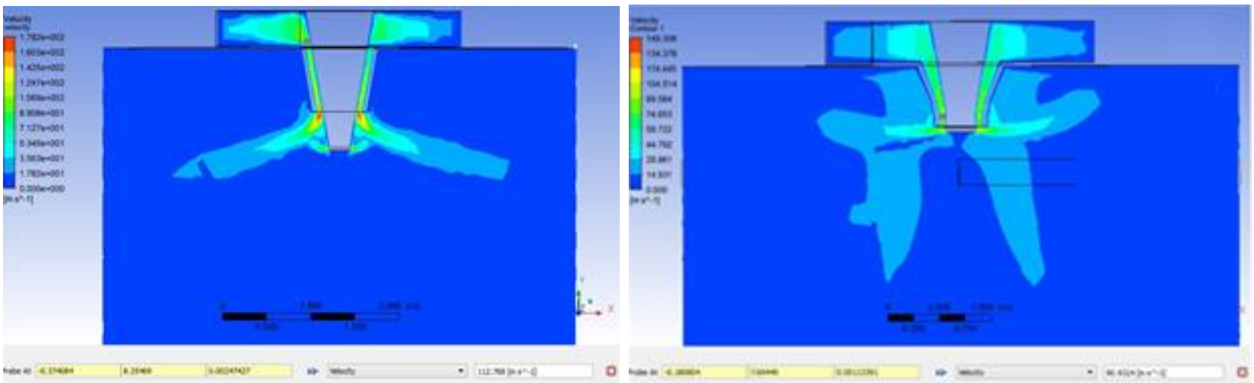
When creating the calculation area and mathematical model in the Ansys Fluent space, to calculate the air velocities in the spray torch, all equations were spatially discretized according to the scheme of the second order. The "PRESTO!" Scheme was used for spatial pressure sampling.

The following assumptions were accepted as boundary conditions:

- the transitional formulation followed an implicit second-order scheme;
- communication "pressure - speed" was carried out according to the COUPLED scheme;
- turbulence modeling was achieved by the method using the SST turbulence model, for which a detailed justification can be found elsewhere [228];
- for boundary conditions of the wall used the so-called "enhanced wall treatment", which solves the zone of "wall zone", which affects the viscosity to the viscous sublayer and automatically switches based on the laminar sublayer to the function of the wall depending on the grid [229];

- the discrete phase (particles) was combined with the continuous phase by means of two-way turbulence communication when applying the boundary condition of the "reflecting" wall with a reduction factor of 1, which was considered justified in the work of Y. Jin, XD Chen [230].

The aim of the research was to establish the hydrodynamic modes of supply of the drying agent and to determine their influence on the parameters of the formation of the product spray torch (Fig. 6).



a ***b***

Fig. 6 Speed modes in the flare zones in the radial intersection of the drying chamber:

a) speed in the design without modification of the Venturi nozzle;

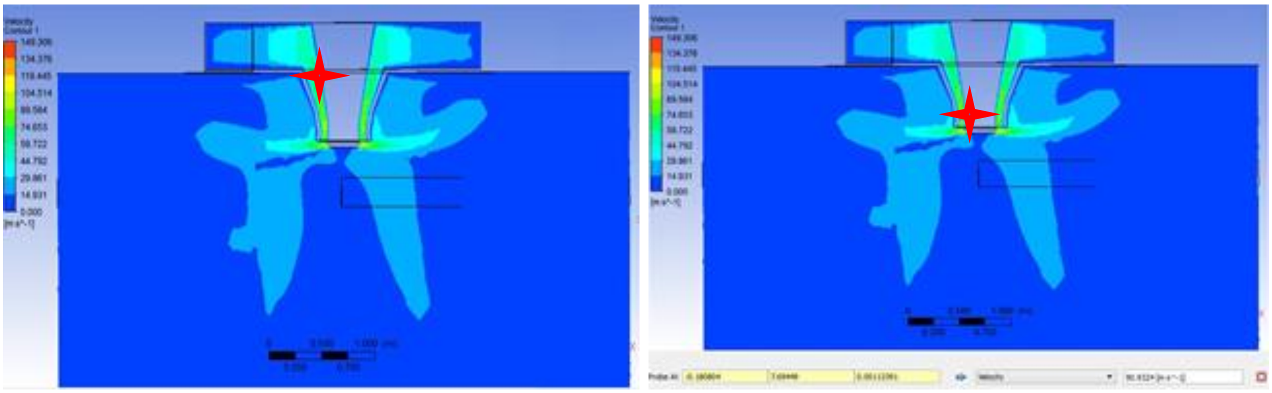
b) speed in the design with a modification of the Venturi nozzle at the entrance to the vertical part of the timing device.

At small values of the diameter of the conical part, the air flow knocks down the torch of the product spray, as a result it begins to oscillate in the vertical plane and goes into unstable mode, resulting in premature contact of undried serum particles with the surface of the chamber lid and product particles stick to its surface. (Fig.4)

Also, the diameter of the lower part of the cone of the gas distribution device should be such that the speed of the coolant supplied to the chamber is sufficient to balance the recirculation flows. Therefore, the diameter of the lower part of the cone can not be very large.

The smaller the depth of the cone in the drying chamber, the higher the spray torch rises, which goes into board mode. The removal of the spray disk from the edge of the cone gas distribution device must be such that the jet of the spray torch does not touch the edge of the cone and it does not stick wet particles of the product.

Based on this, the experiment selected the following parameters: air velocity in the vertical part of the gas distribution device 15 m / s, which allowed at the beginning of the Venturi nozzle to reach a speed of 63 m / s (left), and at the outlet of the nozzle, near the spray disk (right), speed 90 m / s (Fig. 7), which accelerates the flow of air to the spray torch 6 times without additional energy consumption, but only due to the design solution.



a ***b***

Fig. 7. Modes of coolant velocities in the drying chamber:

a) Coolant velocity at the entrance to the vertical part = 63 m / s.

b) The velocity of the coolant near the spray disk.

The motion of a particle in a gas flow depends on the action of various forces - hydrodynamic resistance, gravity, centrifugal, Coriolis, etc. In addition, the motion of the particle is significantly affected by a number of difficult to predict factors (change in mass, shape and particle size, unevenness and turbulent pulsations gas velocity through the section of the device, changes in gas temperature, etc.), so when deriving the ratios suitable for engineering calculations, the analyzed system is usually simplified by introducing assumptions. Thus, it is assumed that the particle has a spherical shape of equivalent diameter; the mass and particle size are averaged over the initial and final values. It is believed that the movement of gas in the device occurs at a constant speed in the considered cross section of the device; turbulent pulsations and mixing is not taken into account. The gas temperature is also averaged, or set constant at the entrance to the drying complex. When calculating the trajectory of the particle, the decomposition of the velocity vector into coordinate axes is allowed. Of all the variety of forces acting on the particle during its motion, only the force of gravity and the force of hydrodynamic resistance are taken into account. In some cases, the forces of inertia are also taken into account when the particles move along a curvilinear trajectory (flow twist). Empirical coefficients are usually introduced to account for other forces.

The following parameters were used as a basis for subsequent studies.

Parameters of research of process of spray drying

Boundary conditions and physical parameters:

Temperature of drying agent - 175 °C

Velocity of giving of a spray product - 150 m / s

Acceleration of free falling in the drying chamber - 9.81 m / s^2

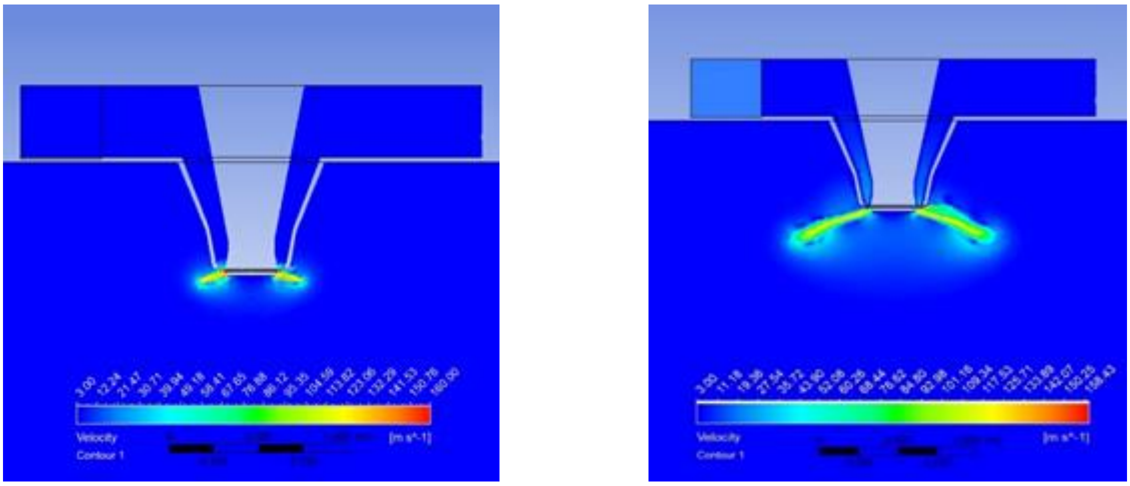
Mass expense of a product - 0,3 kg / s

Thermal conductivity of the wall of the drying chamber - 3 W · m^{-1}· K^{-1}

Pressure in the tower during drying - 0.8 bar

Volume flow of the blower - 560 m^3/ min.

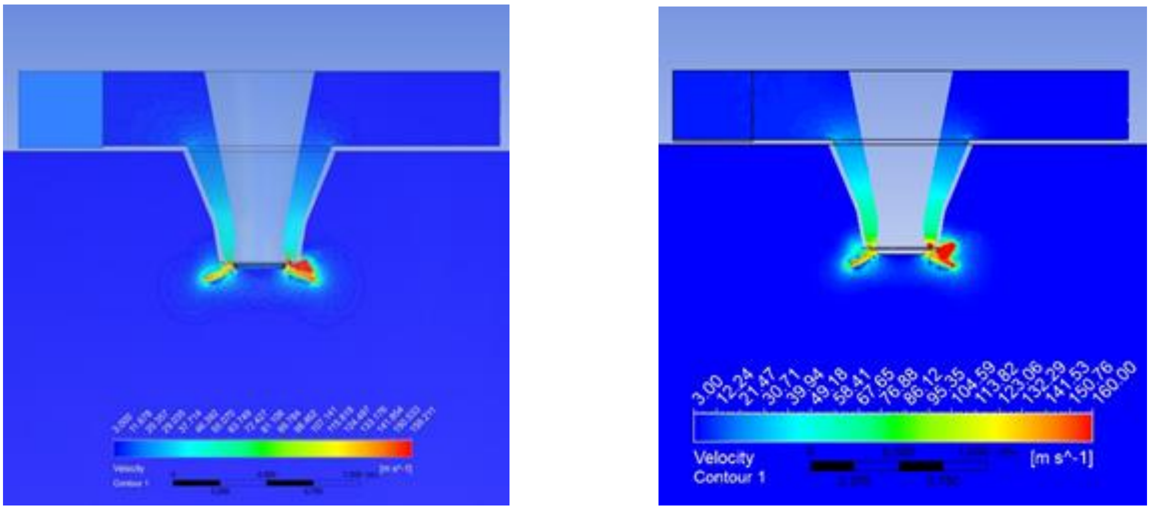
Changing the feed rate of the coolant, a number of simulations were performed in the prototype of the narrowed part of the tube of the spray dryer.



a ***b***

Fig. 8. The result of product distribution at the feed rate of the coolant**:**
a) = 0 m / s *b)* 10 m / s

At feed rates (Fig. 8) the deviation of the torch of the product spray does not differ significantly.



a ***b***

Fig. 9. The result of product distribution at the flow rate of the coolant**:**

a) = 20 m / s *b)* 25 m / s

At the feed rates (Fig. 9) is formed externally on the opposite side of the coolant supply tube.

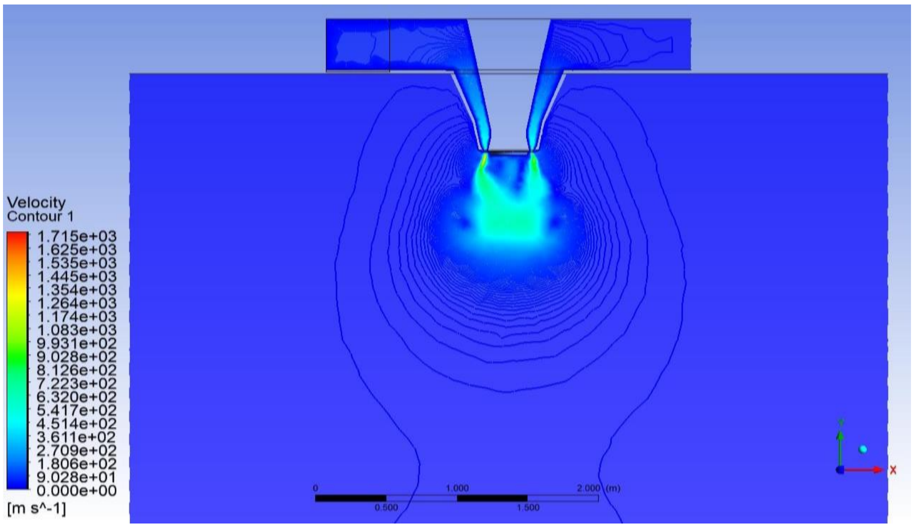


Fig. 10. Distribution of the product at the feed rate of the coolant = 50 m / s. Particle concentration.

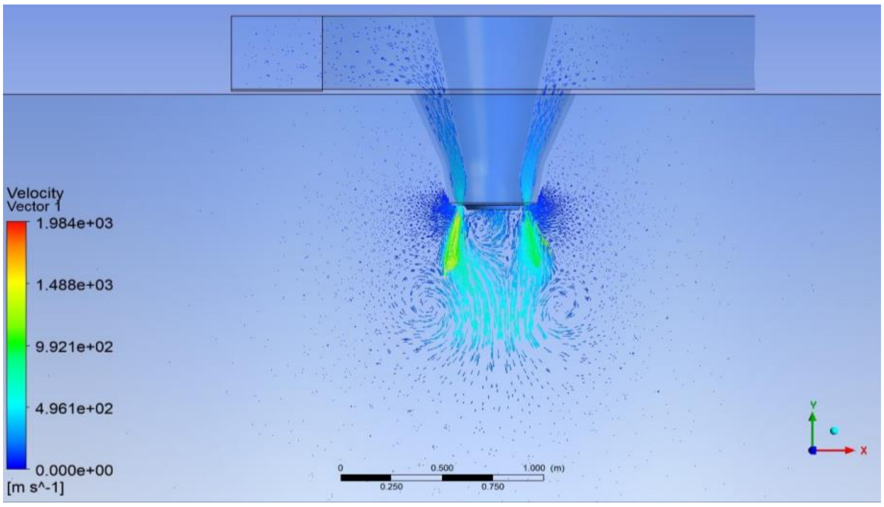


Fig. 11. Distribution of the product at the flow rate of the coolant = 50 m / s. Velocity vectors.

Analysis of the spray drying process in a disk spray complex.

Based on the simulation results, it can be seen that when the coolant (Fig. 8) is characterized by 0 and 10 m / s, the product spray torch is practically indistinguishable. When increasing the velocity characteristic to 20 and 25 m / s (Fig. 9), the so-called extremes are formed on the opposite side of the coolant supply, which can negatively affect the distribution of the product in the drying chamber. The optimal value of the coolant supply to the spray complex = 50 m / s (Fig. 10). With this parameter of air supply to the spray torch, there is an effective distribution of the spray product, and an effective process of evaporation of moisture from it.

As a result of researches the following dependencies are received:

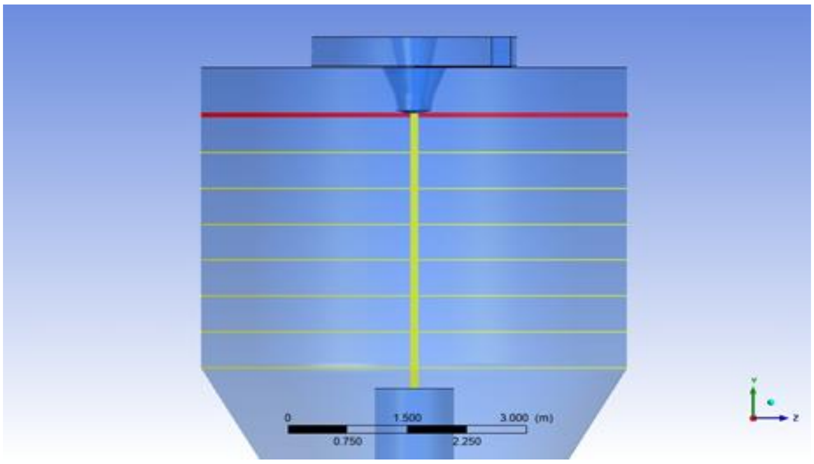


Fig. 12. Distribution lines of 3d-model on which graphs are received.

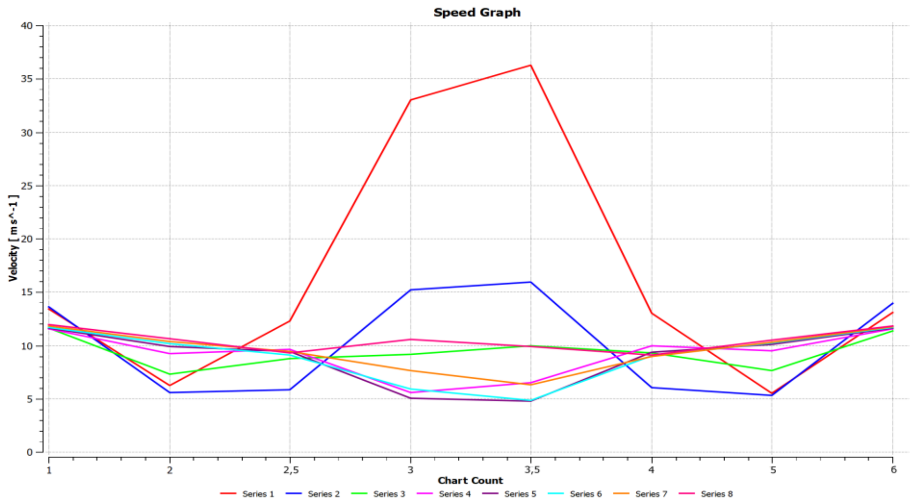


Fig.13. The dependence of the flow rate along the diameter line under the spray disk to the bottom.

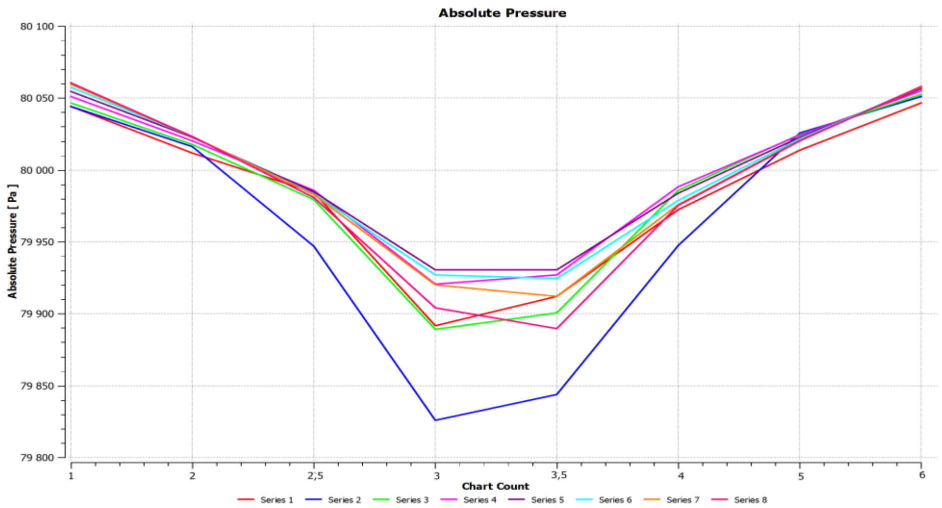


Fig. 14. Dependence of absolute pressure in the tower, along the diameter line under the spray disk to the bottom.

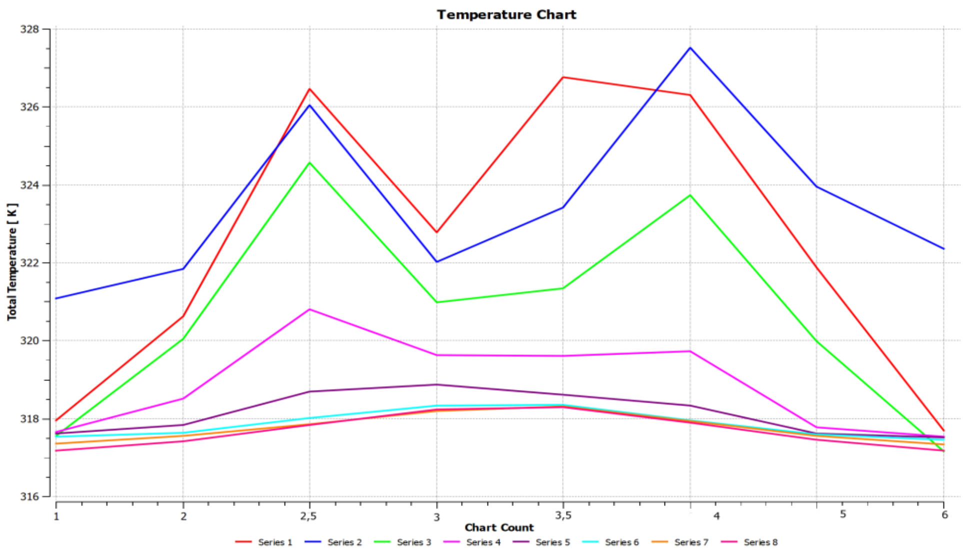


Fig. 15. Dependence of temperature on the line under the spray disk to the bottom.

Conclusions

The article considers and defines the following goals:

● The aerodynamic parameters of the flight of product particles in the drying complex depending on the supply parameters of the drying agent are determined.

The optimal parameters are:

Drying agent temperature - 175°C, Spray product feed rate - 150 m / s, Free fall acceleration in the drying chamber - 9.81 m / s^2, Mass product consumption - 0.3 kg / s, Thermal conductivity of the drying chamber wall - 3 W · m^{-1} · K^{-1}, Pressure in the tower during drying - 0.8 bar, Volume flow of the blower – 560 m^3 / min.

● At a coolant supply rate of 50 m / s, the particle flow distribution of the product is formed in the middle of the drying complex.

● The dependence of the operating mode of the spray equipment and the parameters of the whey drying process on the design solutions of the dryer is determined, namely the design solution in the form of geometric narrowing of the distribution tube that accelerates the air flow to the spray disk.

● The scientific substantiation of methods of spray drying of whey from sour-milk cheese by increase of efficiency of the process of giving of the heat carrier and use of high temperatures is given.