Aerodynamic study of an ejector in a modernized device for thermal vacuum extrusion of food products

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Abstract. The present study is aimed at the modernization of a device for processing food wet materials using vacuum extrusion. It is proposed to modernize the device by adding an ejector, a chamber for preliminary and final dehydration. Steam is removed from the final dewatering chamber using a vacuum pump. An ejector installed after the vacuum pump allows steam to be removed from the pre-dehydration chamber. The Solidworks FlowSimulation package was used to build and simulate the ejector. The air flows inside the ejector were investigated to obtain data on the required performance of the vacuum pump and to display the distribution of air flows and pressures. The images of the pressure distribution inside the ejector and the pressure at the inlet to the low-pressure nozzle were obtained. A model of an ejector with an initial volumetric flow rate of 4 m$^3$/h and 8 m$^3$/h for an incoming high-pressure flow is considered. The results show that it is sufficient to use a vacuum pump with a capacity of 4 m$^3$/h to remove the generated steam. The modernization of the device increases the energy efficiency of the technology for processing plant raw materials and simplifies technological adjustments.

1. Introduction
The vacuum effect in the technology of extrusion of food raw materials improves the working process and provides the desired coefficient of expansion of the extrudate at lower pressure and temperature [1, 2]. Many studies have reported the effect of different process variables and extruder configurations on the properties of different blends of extrudates [3–6].

The theoretical analysis of the device for thermal vacuum extrusion used in previous studies [7] revealed the following disadvantages:

- heat released during the decompression explosion of water vapor is not useful;
- steam condenses in the process of its contact with the inner side of the wall of the vacuum chamber of the extruder and condensate is formed, which reduces the efficiency of dehydration of the resulting extrudate;
- efficiency of the extruder technological process is significantly reduced when processing raw materials with a moisture content of more than 30%;
- difficulty in adjusting the moisture content of the finished product.

It is proposed to modernize the device by adding an ejector, a chamber for preliminary and final dehydration.

Supersonic ejectors are used in a wide range of applications, such as compressing refrigerants in refrigeration systems, pumping volatile liquids or creating a vacuum [8]. In supersonic ejectors, the main task is to achieve the maximum vacuum level and increase the suction speed. Induced flow or...
secondary flow is air that passes through the second nozzle [9]. Analysis shows that the use of multi-stage vacuum ejectors is more preferable in comparison with single-stage and allows you to create a higher vacuum in a low-pressure nozzle [10].

The aim of the work is aerodynamic study of the ejector with verification of the device's operability and analysis of the degree of steam removal from the chamber for preliminary dehydration of the extrudate.

Figure 1 shows an upgraded thermal vacuum extrusion device. The device consists of a thermal vacuum extruder 1, an air chamber for preliminary dehydration 2, a vacuum chamber for final dehydration 3, sluice gates 4 and 5, a vacuum cylinder 6, a vacuum regulator 7, a vacuum pump 8, pipelines 9, 11, 12 and a gas ejector 10.

Getting from the high-pressure area into the preliminary dehydration chamber, the raw material undergoes a decompression explosion (water into steam). When the liquid evaporates from the surface of the extrudate, its temperature decreases. The resulting hot steam with a temperature of 120-130 °C is sucked off through a pipeline using an ejector 10. The steam from the vacuum chamber of the final dehydration 3 is removed by a vacuum pump. The ejector allows you to remove steam from the preliminary dehydration air chamber 2, using a vacuum pump 8.

2. Materials and methods
Theoretical studies were based on the properties and thermodynamic characteristics of water vapor. For numerical modeling and simulation of air movement, the package of gas-hydrodynamic analysis SolidWorks FlowSimulation was used. Flow functions for a moving medium and other aerodynamic characteristics are determined in FlowSimulation based on the continuity equations [11].

The initial conditions are shown in Table 1.

| Parameter name                  | Value                                           |
|---------------------------------|-------------------------------------------------|
| Thermodynamic parameters       | Static Pressure: 101325.00 Pa                   |
|                                 | Temperature: 293.20 K                           |
| Velocity parameters            | Velocity vector                                 |
|                                 | Velocity in X direction: 0 m/s                  |
|                                 | Velocity in Y direction: 0 m/s                  |
|                                 | Velocity in Z direction: 0 m/s                  |
| Turbulence parameters:         | Intensity: 2.00 %                               |
| Turbulence intensity and length| Length: 4.620e-04 m                             |

The goals for calculating the convergence of calculations were set: global goals - the average value of the total pressure (Pa) and velocity (m/s).
Design data of the ejector model: high-pressure inlet - 12 mm, low-pressure inlet - 30 mm, outlet - 25 mm.

![Ejector Model](image.png)

**Figure 2.** The general view of the ejector model.

The general view of the ejector model is shown in Figure 2. Computational grid: all cells - 2458, cells in a fluid medium - 1435. In the calculation, an ejector model is with initial conditions of volumetric flow rate of 4 m$^3$/h (0.001167 m$^3$/s) and 8 m$^3$/h (0.002333 m$^3$/s) for the incoming high-pressure flow. The inlet mass flow rate of 0.00278 kg/s into the low-pressure opening of the ejector is set as the boundary conditions.

3. Results and discussion

The results of the aerodynamic characteristics of the air flow inside the ejector with an incoming volumetric flow of 4 m$^3$/h (0.001167 m$^3$/s) are presented in Table 2.

**Table 2.** Results of aerodynamic characteristics of the air flow inside the ejector at an incoming volumetric flow of 4 m$^3$/h

| Parameter name                | Minimum   | Maximum    |
|------------------------------|-----------|------------|
| Density (Fluid) [kg/m$^3$]   | 1.18      | 1.38       |
| Pressure [Pa]                | 98250.69  | 115877.06  |
| Velocity [m/s]               | 0         | 137.154    |
| Vorticity [1/s]              | 3.47e-04  | 42838.82   |

The results of modeling the trajectories of air particles and the distribution of pressures inside the ejector are presented in Figures 3 and 4. Figure 3 shows the distribution of air flow velocities in the form of trajectories and the distribution of pressures inside the ejector at a volumetric flow rate of 4 m$^3$/h. The average air speed was in the range of 22.356 m/s.
Figure 3. Distribution of trajectories of air movement and distribution of pressures inside the ejector at a volumetric flow rate of 4 m$^3$/h.

The results of the aerodynamic characteristics of the air flow inside the ejector with an incoming volumetric flow of 8 m$^3$/h (0.002333 m$^3$/s) are presented in Table 3.

Table 3. Results of aerodynamic characteristics of the air flow inside the ejector at an incoming volumetric flow of 4 m$^3$/h

| Parameter name                | Minimum  | Maximum  |
|------------------------------|----------|----------|
| Density (Fluid) [kg/m$^3$]   | 1.18     | 1.38     |
| Pressure [Pa]                | 97765.61 | 116159.59|
| Velocity [m/s]               | 0        | 136,609  |
| Vorticity [1/s]              | 3.18e-04 | 42903.28 |

Figure 4 shows the distribution of air flow velocities in the form of trajectories and the distribution of pressures inside the ejector at a volumetric flow rate of 8 m$^3$/h. The average air speed was in the range of 29.665 m/s.

Figure 4. Distribution of trajectories of air movement and distribution of pressures inside the ejector at a volumetric flow rate of 4 m$^3$/h.
Analyzing the data obtained for different incoming air flows, in general, slight differences are noticeable. The difference in generated pressure for the incoming air flow is 1000 Pa on average. The average flow velocity differs within 7 m/s. The average pressures measured in the section of the incoming low-pressure nozzle are 115755.73 Pa and 116038.23 Pa, respectively. The difference between using a more powerful vacuum pump is 1000 Pa on average. The volumetric flow rate of the low-pressure orifice of the ejector satisfies the speed for removing steam from the pre-dewatering chamber.

4. Conclusion
Analysis of the ejector simulation data allowed obtaining air flow trajectories and pressure maps. The simulation results confirm the possibility of using a vacuum pump with a capacity of 4 m$^3$/h (0.001167 m$^3$/s) to remove moisture from the preliminary dehydration chamber. With the help of the modernization of the device for vacuum extrusion, an increase in the energy efficiency of the technology for processing plant raw materials and the simplification of technological adjustments are observed.

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