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Erosion Modelling of Structural Materials in the Working Space of Multistage Convective Dryers

Jan Krmela (0000-0001-9767-9870)[1,2], Kristina Berladir (0000-0002-4287-8204)[3], Oleksandr Pozovnyi (0000-0002-6910-2369)[3], Nadiia Artyukhova (0000-0003-1112-6891)[4]
[1]Faculty of Mechanical Engineering, J. E. Purkyně University in Ustí nad Labem. Pasteurova 3334/7, 400 01 Ustí nad Labem. Czech Republic. E-mail: jan.krmela@ujep.cz
[2]Faculty of Industrial Technologies in Púchov, Alexander Dubček University of Trenčín. I. Krasku 491/30, 02001 Púchov. Slovak Republic. E-mail: jan.krmela@tnuni.sk
[3]Faculty of Technical Systems and Energy Efficient Technologies, Sumy State University. Rymskogo-Korsakova st., 2, 40007, Sumy. Ukraine. E-mail: kr.berladir@pmtkm.sumdu.edu.ua; o.pozovnyi@omdm.sumdu.edu.ua
[4]Academic and Research Institute of Business, Economics and Management, Sumy State University. Rymskogo-Korsakova st., 2, 40007, Sumy. Ukraine. E-mail: a.artyukhov@pohnp.sumdu.edu.ua

The application of different structural materials to manufacture basic parts of drying units of various types was analyzed. It has been established that surface erosion of materials resulting from solid particles' impact is a serious problem for many industrial equipment types using multiphase flow. It is shown that the value of the erosion rate depends on the local particle impact velocity and the impact angle and can be calculated using the software Ansys Fluent 18. The basic principles and criteria for selecting materials for the manufacture of chemical equipment were substantiated. The behavior of steel and polymer material for shelf contact of the convective dryer in the conditions of erosion wear was modeled, the comparative characteristic was made, further research was planned.

Keywords: Convective Dryer, Shelf Contact, Corrosion-Resistant Steel, Polytetrafluoroethylene, Erosion Wear, Ansys Fluent 18, Energy Efficiency

1 Introduction

The introduction of new technologies for drying wet materials (in some cases – moistened at the stages of preliminary preparation to obtain special properties of materials) in the known methods is based on the improvement of technological, environmental, and economic characteristics of the target process and the creation of new designs of dryers and forms of flow organization in the working space of the devices [1].

In the drying process, the vast majority of dispersed (granular) materials of inorganic (e.g., fertilizers) and organic origin (e.g., seeds of cereal, sunflower, etc.) are dehydrated. The drying process of dispersed materials is carried out in devices with different designs depending on the drying method. The choice of strategy and hardware design of the drying process depends on the type of dispersed material to be dried and the temperature and humidity parameters of the dispersed material and the drying agent [2].

Convective drying processes in devices with a weighted layer as a drying method have become widespread in the technology of dehydration of dispersed materials due to the contact of the drying agent (for example, heated to a specific air temperature) with the dispersed material. In addition to the direct interaction between the streams of dispersed material and the drying agent, each of the streams meets the dryer's structural elements. In this case, one of the defining stages of the general algorithm for calculating the dryers is selecting structural materials that will ensure the stability of the dryer in operation and will not affect the properties of the dispersed material, except for changes in moisture content. The dryer's main element with the weighted layer, studied in the paper, is perforated contact shelves (shelf contacts), directly removing moisture [3].

The selection of shelf contacts material of the gravity shelf dryer is the task to be solved using the research presented in this paper. The study is based on a computer simulation of erosion wear of shelf contacts in interaction with dispersed material of plant origin or granular ammonium nitrate with special properties (so-called porous ammonium nitrate).

2 Materials for drying units production

The paper [4] presents the research of modular grain dryers produced by leading foreign and Ukrainian companies. According to the manufacturers and real samples of modular grain dryers, the analytical review and analysis of the design allow stating that for the manufacture of their main parts used stainless steel.

According to the industry standard's general technical requirements, the main parts for dryers with rotating drums must be made of construction carbon steel [5].

The American manufacturer of engineering equipment FEECO International offers various materials for construction shells of rotary dryers. This list includes carbon and stainless steel, Hastelloy, Inconel, and other alloys, depending on the customer's technological requirements. Chinese manufacturer of industrial rotary dryers Hengxing produces equipment for drying minerals and construction materials. As a shell material, they use carbon steel or stainless steel grade 304.

Authors from Nigeria [6] designed and manufactured a tunnel dryer in two modes of operation with an aluminum drying chamber for indoor and outdoor use. The choice of the aluminum sheet was justified by its high corrosion resistance, availability, ductility, lightweight, and average cost.

Weefar H. [7] presents the design, construction, and analysis of a mixed solar dryer's crop characteristics. The choice of material for each part of the dryer was based on the following requirements: functionality, manufacturability, cost, and reliability. Following these requirements, silica, glass, aluminum, and wood were proposed for the drying chamber parts; solar collector parts include low carbon steel, rubber, and organic glass Perpex.

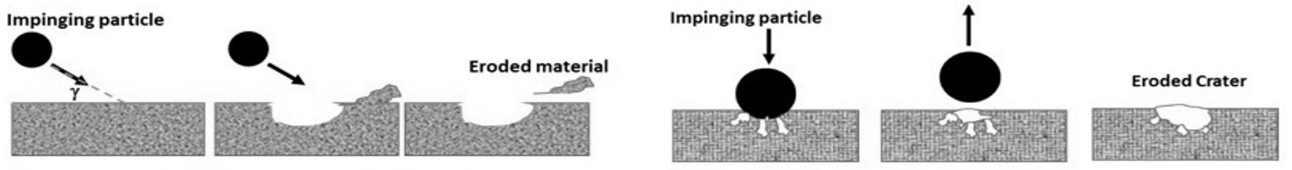
Thus, domestic and foreign companies-manufacturers of dryers traditionally use carbon, structural, and stainless steel to manufacture basic parts, ensuring compliance with the technological requirements (temperature, pressure, durability, etc.).

Instead, scientists are working on a solution to reducing energy and material costs during drying in devices of various designs and improving existing ones. One way to reduce the size of dryers and reduce their price is to use non-ferrous metals and non-metallic materials.

This work aims to select the optimal construction materials for the leading equipment of the drying unit with shelf contacts for drying dispersed materials.

3 Research methodology

Erosion wear is the loss of material due to repeated exposure of solid particles to the surface. This phenomenon causes significant economic losses in various industries, such as oil and gas, hydraulic transportation, and chemical processes. If the surface material is plastic, repeated blows of particles will lead to the formation of craters and platelets; holes will grow with the subsequent impact of particles, and eventually, platelets are easily removed into the stream (Fig. 1, a). Suppose the material is brittle, on the other hand. In that case, it will grow side and radial cracks under the influence of particles that will grow and eventually form small pieces, which are removed by a continuous impact of solid particles (Fig. 1, b) [8].



a) b)

Fig. 1 *Scheme of the mechanism of erosion action: a) for plastic material; b) for brittle material*

Erosion is a complex phenomenon that depends on many parameters. Particle parameters may include the following: shape or angularity of particles (angular particles cause more significant erosion than spherical particles); particle size (erosion rate ER = (dp)n with 0,3 ≤ n ≤ 2); hardness of particles (ER = Hp with Hp < 700 HV).

On the other hand, flow parameters have a more substantial effect on erosion because they determine particle concentration, particle impact angle, and impact velocity. Other parameters that affect erosion are surface hardness and multiphase impact [9].

Progress in understanding erosion due to solid particles has been achieved by using computational fluid dynamics (CFD), which allows to accurately model the flow of fluid and the trajectory of particles through pipelines and bends. After calculating the impact velocity and the angle of the particles in contact with the surface, empirical correlations can be applied to quantify the erosion rate.

The authors [10-12] found that the empirical correlations of erosion include the angle of impact, impact velocity, particle diameter, particle mass, and collision frequency connected to it.

A typical erosion model has the following general form (the default erosion fluid dynamics model in Ansys Fluent):

$$ER = \sum_{p=1}^{N_{trajct}} \frac{\dot{m}_p C\left(d_p\right) f(\alpha) v_p^n}{A_{face}} \tag{1}$$

Where:

$\dot{m}_p$…Mass flow rate of particles,
$f(a)$…Impact angle function,
$C(d_p)$…Particle diameter function,
υ_p…Particle impact velocity,
n…Velocity exponent.

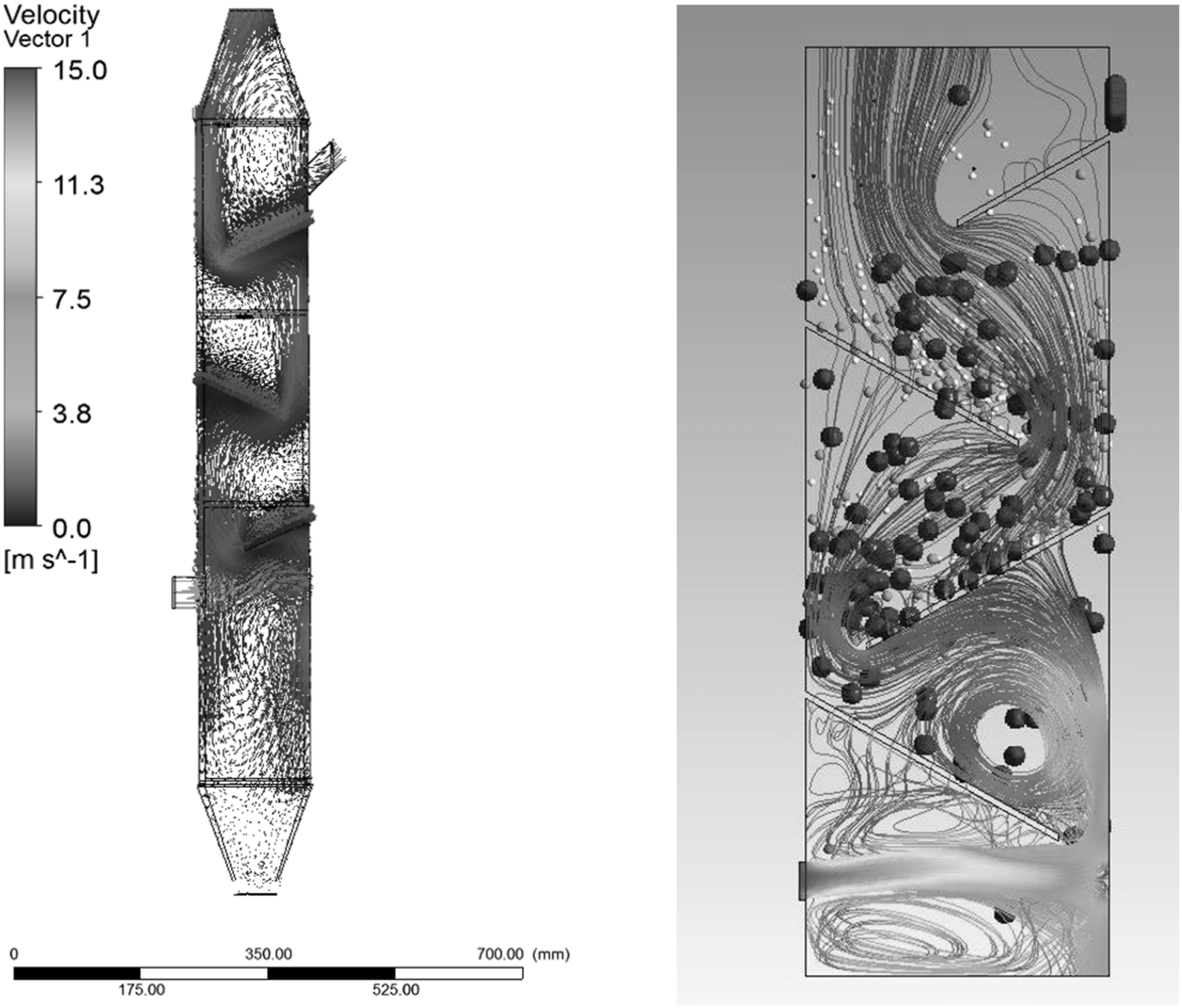
Particle impact angle, impact velocity, and mass flow rate is calculated directly using CFD. However, the impact angle, particle diameter, and velocity index must be supplemented as input to the solver.

In addition to the typical ones, three corresponding erosion correlations have been added to Ansys Fluent in Ansys 18: Finnie [13], Oka [14], and McLaury [15].

The Finnie erosion model is more suitable for plastic materials, where erosion varies depending on the angle of impact and speed. The Oka model provides a more realistic correlation, including the effect of the wall material's hardness. The McLaury erosion model was designed to predict the rate of erosion of solids in water; it was mainly used in sludge streams.

Thus, each erosion model must be calibrated empirically for a particular flow scenario, so the appropriate flow conditions for each model should be considered before using any erosion model.

Modelling the shelves erosion is possible with a known value of the velocities of the gas flow and the mode of movement of particles in the dryer. Using the model shown in Fig. 2, the authors obtained the values of the gas flow rates in the working space of the dryer. In the area where the shelf is installed (over the shelf space), an increased velocity of the gas flow is observed due to its passage through the openings of the shelf. That is why the shelf is subjected to additional force and, along with the action of particles of dispersed material on the shelf, this can lead to its erosion.



a) **b)**

Fig. 2 *Results of modeling the hydrodynamic characteristics of single-phase and two-phase flows in the working space of a gravitational shelf dryer: a) an example of a gas flow velocity distribution field; b) an example of the mode of motion of particles of dispersed material*

The movement of particles along the shelf requires a separate description due to the significant effect of this process on shelf erosion. Particles can move along the shelf in different modes. In this case, the main type of particle motion is translational pulsating, which (depending on the gas flow velocity and the angle of inclination of the shelf) can take on a completely translational motion ("gravitational falling layer" mode). The rolling of particles along the shelf, especially with a high degree of flow restriction, is accompanied by intense friction of the lower layer of particles against the shelf. The pulsating movement of particles is the cause of their mechanical impact (shock) on the shelf.

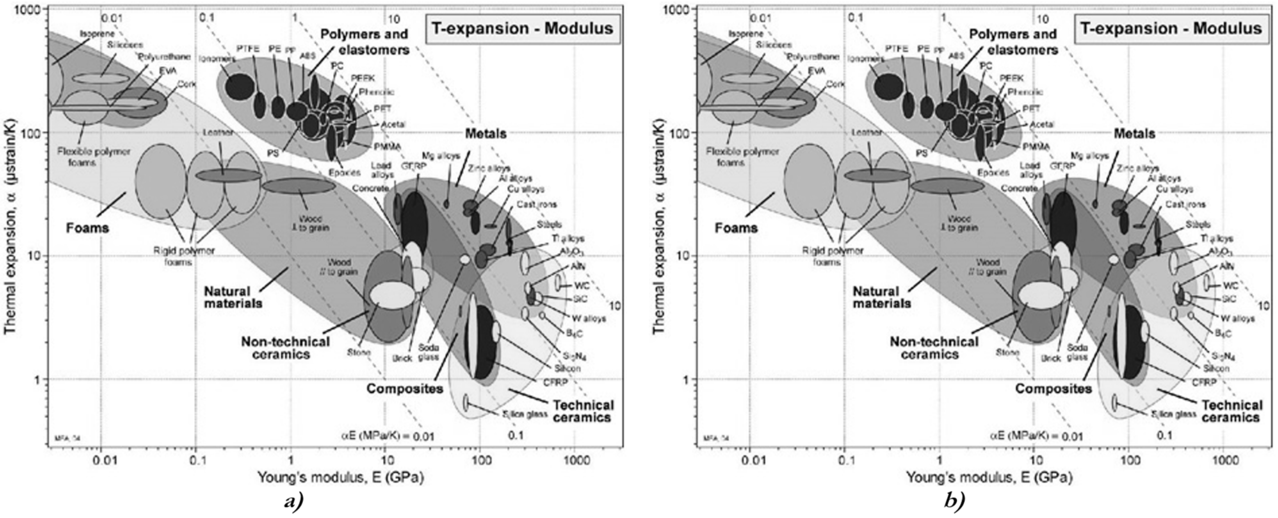
4 Criteria for choosing structural materials for chemical equipment

The choice of a structural materials for the manufacture of chemical equipment should be based, first, on the specifics of their operation [16]. The indicators of working conditions of materials include operating temperature, pressure, environment, and concentration.

Secondly, it is essential to consider the following main properties of the material: physical (thermal expansion, thermal conductivity), mechanical (strength, elastic properties), chemical (corrosion resistance, chemical inertness), technological (weldability, etc.) [17].

Third, the physicochemical properties of materials can change under the influence of operating conditions [18]. Among the main factors of influence are pressure (from deep vacuum to excess values), temperature regime (from liquid nitrogen temperature to melting of iron ore), types of corrosion (chemical, thermal, atmospheric), high mechanical loads in aggressive environments.

As the temperature rises, the material may creep, which limits its ability to withstand the load. The phenomenon of creep can lead to oxidation, destruction or decomposition of the material with a change in its chemical composition, making it unsuitable for further use [19]. Fig. 3 shows the dependence of strength on the maximum service temperature at which each class of materials can be used.



a) *b)*

Fig. 3 *Ashby Diagrams: a) dependence of strength σf on the maximum service temperature Tmax for different classes of materials [18]; b) dependence of linear thermal expansion a on the Young's modulus E for different classes of materials [20]*

The most crucial characteristic of steels and alloys is the change in yield strength under static loads or elastic properties (modulus E and Poisson's ratio μ) on the service temperature. Fig. 3, b shows the linear thermal expansion α from Young's modulus E for different classes of materials. The regions' contours show the temperature stress caused by the change in temperature (°C) in a constrained sample. They determine the characteristic αE = C [MPa/K] (constant thermal stress, °K). The value of the constant C increases towards the upper right.

Therefore, structural materials for chemical industrial equipment must meet the following requirements:

- enough corrosion resistance in an aggressive environment [20] at a certain technological process concentration of reactive compounds, temperature range, pressure level;
- enough mechanical strength under the same conditions, considering additional loads from its weight, wind, method of installation, support area;
- the possibility of obtaining strong welds resistant to breakage and mechanical loads in extreme conditions;
- availability of the material in terms of cost and prevalence;

- safe and easy disposal after service life or recyclability.

Polymers have attractive properties (excellent corrosion resistance, lightweight, ease of manufacture and installation), making them competitive materials for use in various chemical processes [22]. Also, polymer structures require less maintenance than metal structures [23].

The following thermoplastics have been used as corrosion-resistant: fluorocarbon polymers, acrylics, nylon, chlorinated polyester, polyethylene, polypropylene, polystyrene, and polyvinyl(chloride). Fluorocarbon polymers have extraordinary chemical resistance and show good elastic properties in a wide range of temperatures (Fig. 4). Therefore, they are used to manufacture various parts (sealer, linings, tubing, hose, belting, fabrics, caulks, adhesives, dampeners, etc.).

When choosing a structural material, it is necessary to anticipate the extreme conditions and apply them to all components. Material composition and temperature deviations can have a significant effect on the corrosion rate [24].

Although carbon and stainless steel are commonly used structural materials, non-metallic and lined or plastic process equipment is increasingly used. A wide range of plastics is available for use as structural materials and can be used in areas such as treating inorganic salt solutions where metals are unsuitable. The use of plastic pads is widespread in chemical equipment – tanks, pipes, and drums. However, their use is limited to moderate temperatures, and they are generally unsuitable for use in abrasive working conditions. The most used plastics include PVC, PTFE, and polypropylene [25].

Thus, plastics soften at high temperatures and swell under prolonged exposure to the environment; from this point of view, metals are superior. One of the ways to effectively use the high corrosion resistance of plastics is to combine them with metal structures in the form of protective coatings, pads, etc. [26].

5 Computer modelling results

The research was carried out for a multistage convective shelf dryer with vertical partitioning of the working space in the technology of obtaining porous ammonium nitrate [27-29]. This drying unit is an apparatus of continuous action. The drying of materials is carried out in a constant temperature mode: from initial temperature and on the achievement of the maximum temperature, it remains invariable. The drying agent reduces its temperature and the device's height after contact with the dispersed material at each dryer stage.

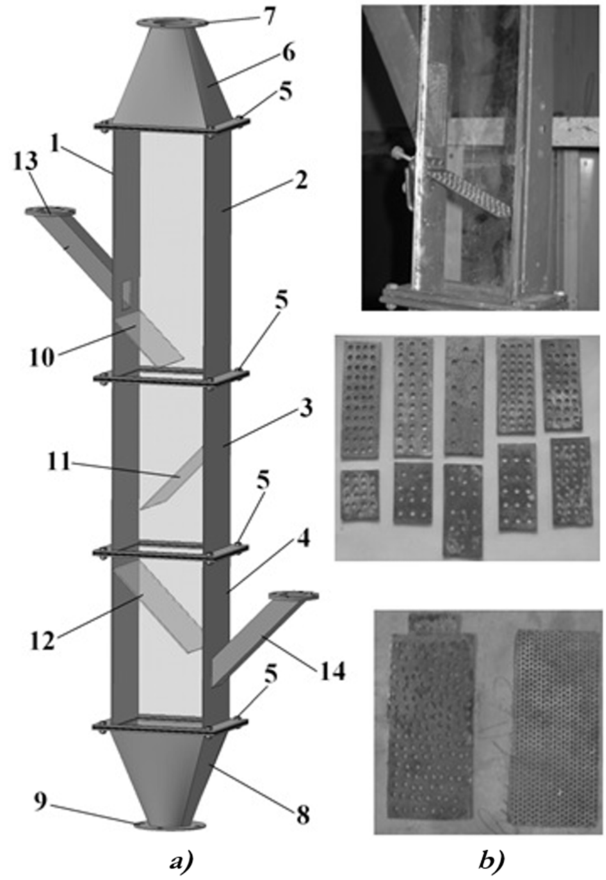
The optimal materials selection was carried out for internal devices – perforated shelves, which can perform the functions of a heat exchange surface and provide conductive drying of dispersed materials (Tab. 1).

Tab. 1 *Materials and conditions for drying*

Material for drying	Type of material	Drying temperature, °C	Drying conditions
Granular and encapsulated fertilizers, granules with special properties	Granular ammonium nitrate	110-130	Corrosive active environment
Seedy materials of plant origin	Wheat	60-70	Chemical inertness; cannot be overdried

After analysing the above review of the use of classes of construction materials for the manufacture of fundamental parts of drying units of different types, the basic principles and criteria for selecting materials for chemical equipment, two research materials were chosen for the experiment - traditionally used corrosion-resistant steel AISI 321 and chemically inert polymer PTFE, the properties of which are described in detail in the papers [30-32].

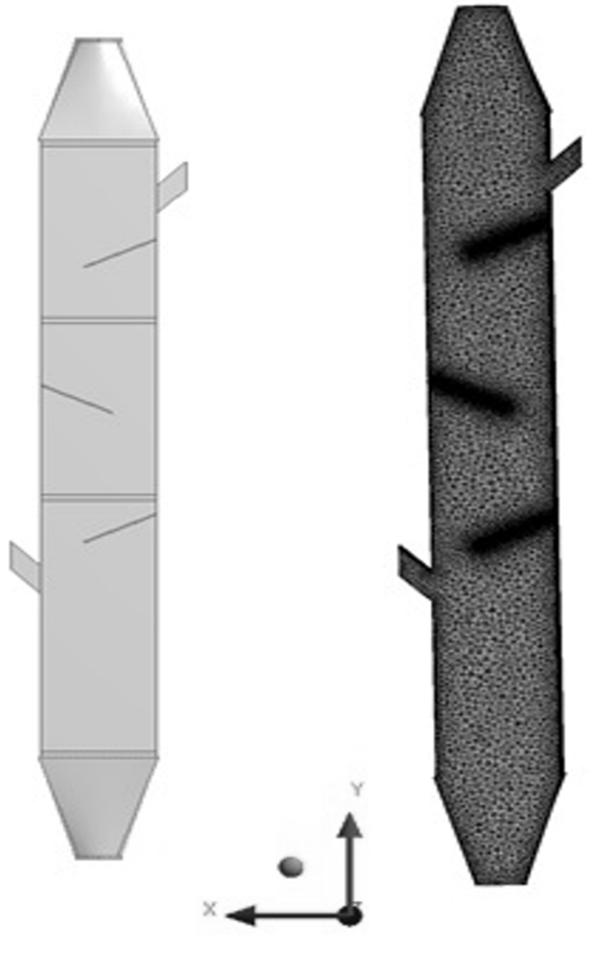
Design and principle of working of the gravity shelf dryer. The dryer consists of a body 1 of rectangular shape with a cross-section of 100x50 mm and a working height of about 1 m, that contains the separate frames 2, 3, 4 – upper, middle, and lower, respectively, which are interconnected by fasteners 5 (Fig. 4, a). To the upper frame 2 by fasteners 5 is connected to a conical frame 6, which is equipped with a branch pipe 7 to remove the drying agent. To the lower frame 4 by fasteners 5 is connected to a conical frame 8, which is equipped with a branch pipe 9 to remove dried material. Inside the body 1 are fixed at least three inclined contact shelves 10, 11, 12 (Fig. 4, b), upper, middle, and lower, respectively, with the same angle of inclination, which is 10-15° higher than the angle of the natural slope of the material. The upper inclined contact shelf 10 is installed in the upper frame 2 with a gap in the horizontal plane between the free end of the shelf and the wall of body 1, equal to 0,5 of the width of body 1. The middle-inclined contact shelf 11 is installed in the middle frame 3 with a gap in the horizontal plane between the free end of the shelf and the wall of body 1, which is equal to 0,3 of the width of body 1. The lower inclined contact shelf 12 is installed in the lower frame 4 with a gap in the horizontal plane between the free end of the shelf and the wall of body 1, which is equal to 0,15 of the width of body 1. The device is also equipped with a rectangular branch pipe 13 for entering the material to be dried and a rectangular branch pipe 14 for entering a drying agent. The dryer works as follows. In the lower frame 4 through a rectangular branch pipe 14 to the body 1 of the device is supplied drying agent, which due to the location of the rectangular branch pipe 14 is first evenly distributed across the cross section of the body 1, and then rises. As the drying agent moves up the body 1, it successively passes through the sections of the lower frame 4, the middle frame 3 and the upper frame 2, the conical frame 6 and is removing from the device through the branch pipe 7.



a) b)

Fig. 4 *Experimental sample of gravity shelf dryer*

Simultaneously with the entering of the drying agent into the body 1 of the device through the rectangular branch pipe 13 in the upper frame 2 on the upper inclined contact shelf 10 is entered a dispersed material for drying. On the upper inclined contact shelf 10 during the upstream interaction with the flow of drying agent is heating the dispersed material and removing the fine fraction in order to equalize the value of the porosity of the weighted layer. The length of the upper inclined contact shelf 10 provides a residence time of the dispersed material, which promotes complete heating of the material, separation of finely dispersed particles, and removal of unbound moisture from the surface layer of the dispersed material during a constant drying rate. The dispersed material during drying by the flow of drying agent gradually moves along the upper inclined contact shelf 10, is removed through its free end and enters the middle-inclined contact shelf 11 in the middle frame 3. As the dispersed material is moved along the middle inclined contact shelf 11, there is a further intensive removal of unbound moisture from the surface layer of the dispersed material during a period of constant drying speed as a result of upstream interaction with the flow of the drying agent. The dispersed material during drying by the flow of drying agent gradually moves along the middle-inclined contact shelf 11, is removed through its free end and enters the lower inclined contact shelf 12 in the lower frame 4. As the dispersed material moves along the lower inclined contact shelf, as a result of upstream interaction with the flow of drying agent the bound moisture from the depth of the material is removed during the period of decreasing drying speed. The dispersed material during drying by the flow of the drying agent gradually moves along the lower inclined contact shelf 12, is removed through its free end and enters the brach pipe 9 of the dried material, which is in the conical frame 8.



a) b)

Fig. 5 *Creation of 3D-model (a) and calculation grid (b) of the dryer*

Calculating parameters of erosion wear in ANSYS. The drying process of ammonium nitrate and wheat using different shelf materials (steel and PTFE) considering gravity was simulated in the ANSYS software complex. Initially, a three-dimensional dryer model (Fig. 5, a) was created based on the discrete phase model (DPM) in Ansys Fluent software to detect the rate of erosion on walls caused by fine solids. A complete model of a gravity shelf dryer was considered. The calculated grid of the compaction model is created in the program ANSYS Meshing (Fig. 6, b). As a result, the estimated grid has approximately 7,5 million elements. The calculation grid in the wall layers was condensed. The grid quality was controlled by the dimensionless parameter y+ on the walls of the shelf dryer, which varied in the range from 20 to 50 for the k-ε model of turbulence; growth rate; the coefficient of proportionality and orthogonality of the model grid. The problem was considered in a static formulation considering gravity. The model uses two inputs and two outputs (13, 14); ammonium nitrate, wheat 15 kg/h are fed to the inlet 13; hot air (O_2) is supplied to the rectangular pipe 14 for drying nitrate 130 °C and for wheat at 70 °C at a speed of 0,2 m/sec. For a branch pipe 7 for removing the drying agent and the connected conical frame 8, which is equipped with a branch pipe 9 for removing the dried material, the limit conditions of atmospheric pressure (1 atm) were set.

The calculation of particle trajectories is conditional. The program simulates the track from the center of each element on the injection surface. The way is the most probable trajectory not of one particle but of the whole group of particles, which entered the calculation zone through the area of the face of the corresponding cell. If there are ~ 100 cells at the input boundary, then only ~ 100 trajectories will be calculated and constructed. The number of particles that will be physically «injected» every second into the calculation zone can be found by the formula:

$$N_{\Sigma} = \frac{\dot{m}}{\rho_p - V_p} \tag{2}$$

Where:

$\dot{m}$…Consumption of particles for a certain time period,

$V_p = 4/3\pi r^3$ – particle volume,

ϱ_p…Density of particle material (ammonium nitrate, wheat).

The effect of particles on the inclined contact shelf 10 for different materials was considered during the calculation.

Conducting an experiment and discussion. As a result of the simulation, the problem of drying of dispersed material in the Ansys Fluent software package was solved:

- «Discrete Particle Model» from the model tree was enabled, and the Erosion/Accretion model on the «Physical Models» tab was activated.
- Particle injections, particle diameter, injection rate, and flow rate were determined.
- The coefficients of normal and tangential reflection of particles on the wall were established.
- Models of erosion on the wall with the DPM tab were selected: Generic Fluent, Finnie, McLaury, Oka.

After starting the flow during one iteration, particles were isolated and the erosion rate on the participating surface was calculated.

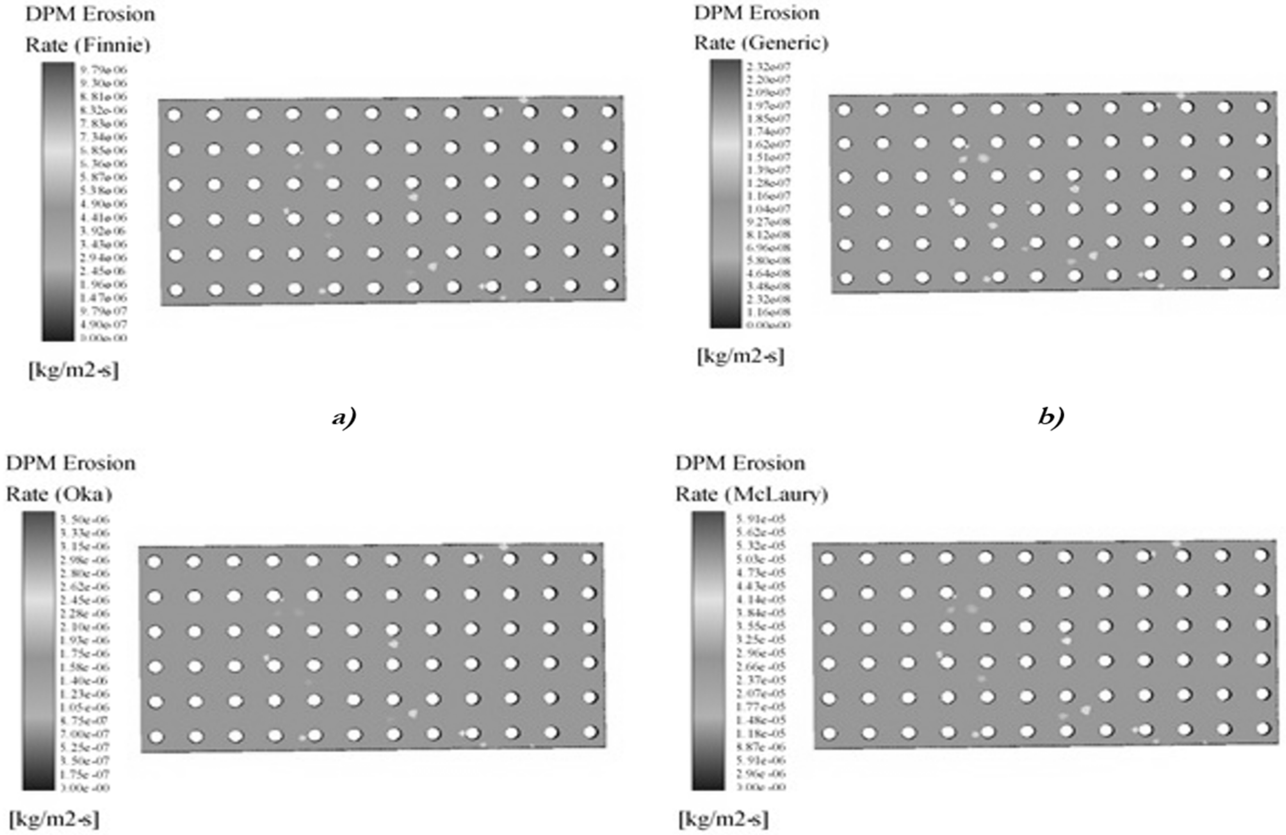
The contours of the erosion rate on one of the shelves of the dryer for different wall materials (PTFE and steel) for different drying materials (ammonium nitrate and wheat) were displayed (Fig. 7-10).

Analysis of Fig. 7 and 8 showed that PTFE is superior to steel for drying ammonium nitrate in terms of erosion resistance. In general, there is a much smaller amount of eroded polymer material in the shelf plane (Fig. 7, 8, a).

The localization of traces of erosion near the holes is noted, which is a predictable phenomenon. The calculation of additional erosion correlations (Figs. 7, 8, b-d) confirmed the proportional distributions of the impact areas of the nitrate erosion particles on the surface of the experimental materials.

The speed of erosion particles has a powerful effect on the wear process: when the rate is low, the stress on the impact of the particle is insufficient to cause plastic deformation and erosion wear, which is associated with surface fatigue; when the speed increases, the eroded material can be plastically deformed by the impact of the particle [33]. The morphology of eroded surfaces determines the wear mechanisms and the presence of micro-cutting, microcracks, and other characteristics of plastic deformation of the polymer [34].

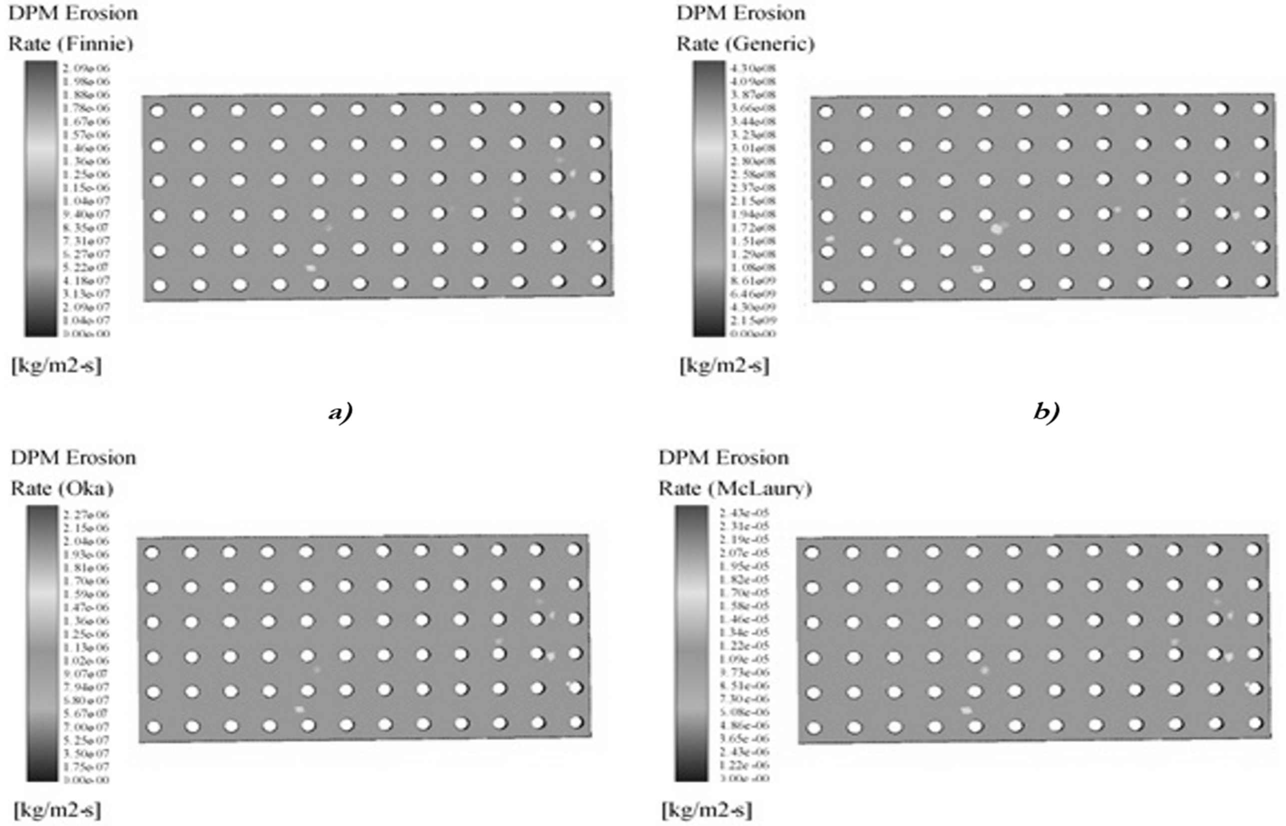
From the comparative analysis of Figs. 9 and 10, it can be concluded that the value of the erosion rate is almost the same for both experimental materials.



a) b)

c) d)

***Fig. 7** Contour graphs of DPM erosion rate in Ansys Fluent, shelf material – steel, drying material – ammonium nitrate*



a) b)

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***Fig. 8** Contour graphs of DPM erosion rate in Ansys Fluent, shelf material – PTFE, drying material – ammonium nitrate*

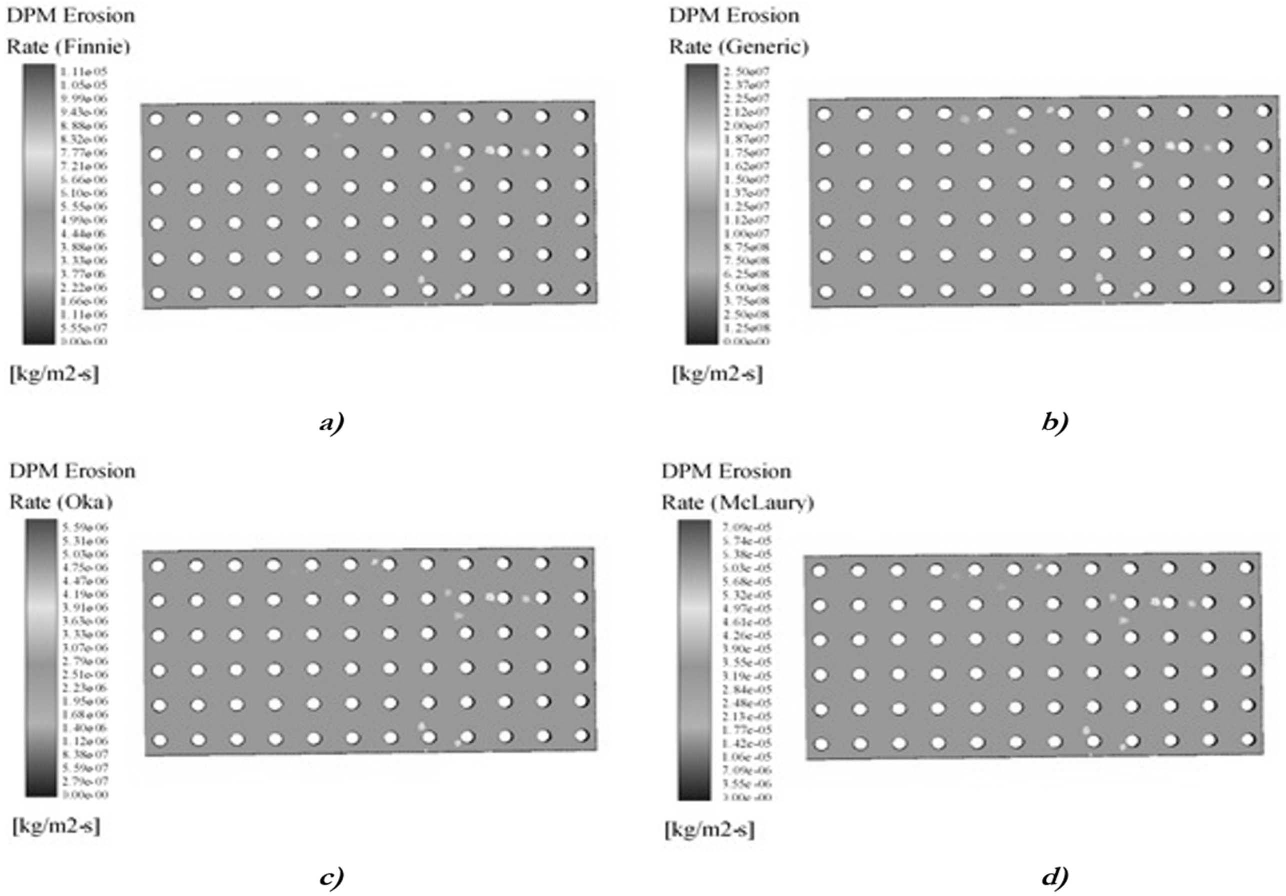

Fig. 9 *Contour graphs of DPM erosion rate in Ansys Fluent, shelf material – steel, drying material – wheat*

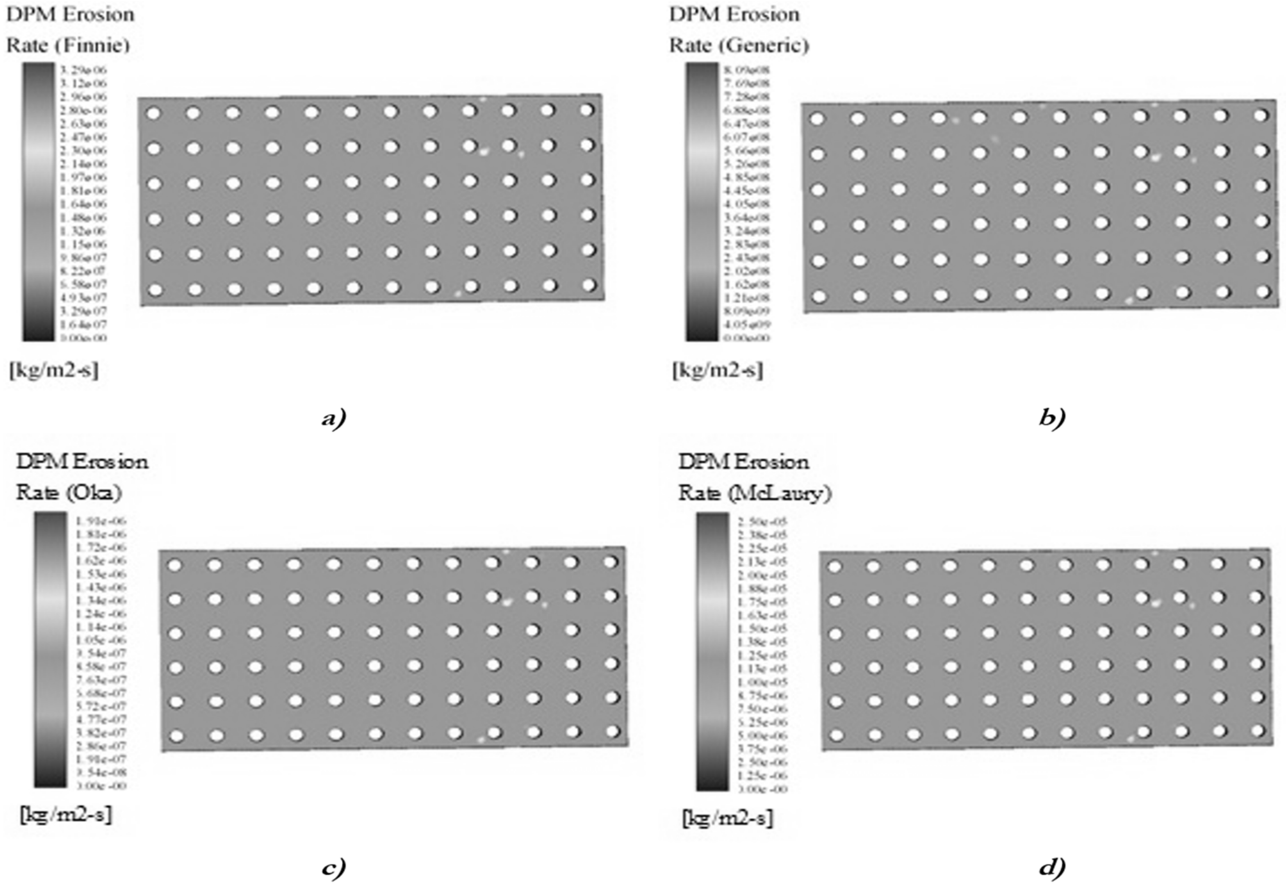

Fig. 10 *Contour graphs of DPM erosion rate in Ansys Fluent, shelf material – PTFE, drying material – wheat*

The temperature range of the drying process does not allow an objective comparison of the experimental materials. In the case of drying wheat, when the temperature is an order of magnitude lower and the process conditions are different from ammonium nitrate, the determining factor is the chemical inertness and stability of the shelf material.

A further direction of the research is to conduct laboratory tests to verify the theoretically calculated values morphology of erosion surfaces of materials using scanning electron microscopy and to determine possible erosion mechanisms by influencing factors.

6 Conclusions

The analysis of the used structural materials to manufacture basic parts of drying units of different types shows that companies-manufacturers of dryers traditionally use carbon, construction, and stainless steel. While scientists are working on the problem of reducing metal and energy consumption, testing different non-ferrous metals and non-metallic materials.

Surface erosion of materials due to the impact of solid particles is a severe problem for many types of industrial equipment using multiphase flow. Erosion causes point corrosion, which leads to functional failure of the part, although the rest of the equipment may not be damaged. Since the erosion rate is considered a function of the local particle impact velocity and the impact angle, these parameters are widely studied and vary for different classes of materials.

When choosing structural materials for chemical industrial equipment, the following properties should be considered: high corrosion resistance and sufficient mechanical strength in aggressive environments, material availability in terms of cost and prevalence, safe and easy disposal or recycling.

Computer simulation of the behavior of materials in the conditions of erosion wears in the software package Ansys Fluent 18 makes it possible to predict the results of laboratory tests. The obtained research results indicate the prospects for the use of PTFE in the construction of convective dryers as an alternative to construction steels for reducing the metal consumption of equipment. A further area of research is related to experimental work based on computer simulation data.

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