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Pneumatic device for lifting a submersible drum for electroplating small parts in bulk

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ABSTRACT

Introduction. The main problems that arise during electroplating processes include, at the design stage of electroplating systems, the challenge of selecting the appropriate type of protective coating from a variety of options, as well as choosing the appropriate equipment from the many different types produced by industry – in particular, installations for the electroplating of small parts in bulk. ***The purpose of the work*** is to increase the economic efficiency of installations for the electroplating of small parts in bulk. **Methodology.** The ***decision*** to create an electronic model (digital twin) of the device at the first stage and then its physical prototype was based on the use of system ***analysis methods***, mathematical modeling, and experimental design. A physical prototype was built based on the created electronic model of the installation using graphic editors. At the design stage, the parameters of a pneumatic lifting device for a submersible drum were determined; the optimal lifting time is ensured by the following key parameters: piston rod stroke: 409–410 mm; required force for lifting the drum with parts: 1.80–1.90 kN; and pressure in the compressor system supplied to the pneumatic cylinder: 5.30–5.40 bar. These values were obtained from an experiment using an orthogonal central composite design for a factorial experiment on a physical prototype of the installation. **Results and discussion.** The proposed design solution differs from other drum lifting mechanisms in that it eliminates manual operation of the lifting mechanism and counterweight. The lifting mechanism is located outside the installation; the main components of the device are manufactured as separate units and assembled into a single structure using bolted connections. The results of the final tests of the physical prototype of the electroplating installation for small parts in bulk using a pneumatic device for lifting a submersible drum demonstrated its high economic efficiency.

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Introduction

Electroplating is a widely used method for improving metal products by providing corrosion resistance, enhancing appearance, and adding other functional properties. One of the main challenges in this field is choosing the right protective coating and the appropriate equipment from the vast range available in modern industry [1–2]. The type and composition of coating significantly affect both production costs and environmental safety, since electrolytes vary considerably in price, toxicity, and handling requirements. Therefore, selecting the optimal plating solution is essential for balancing manufacturing efficiency with the growing demand for specific coating characteristics [3–5].

At present, the processes involved in determining coating types and thicknesses are mostly manual and lack automation, which limits their functionality and makes them labor-intensive [6]. Further progress in this area depends on optimizing and automating these selection procedures, along with upgrading technologies and adopting more advanced equipment [7–8].

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In this context, developing systematic approaches to choosing the most suitable electroplating equipment from a wide range of options is of considerable practical importance. The use of computer technologies and advanced software enables fast and efficient decision-making with minimal time investment [9–10].

A literature review on coating technologies and an analysis of promising electroplating systems for small components show that previous research has largely focused on developing structures based on earlier experimental setups. Less attention has been given to optimizing the design of individual components and units through multi-criteria analysis, taking into account factors such as economic efficiency, reliability, and manufacturability [11–14].

A diverse range of electroplating systems is currently employed for the batch processing of small components. These systems utilize various types of lifting mechanisms, which can be categorized as mechanical, electromechanical, hydraulic, or pneumatic, each offering distinct operational characteristics [15, 16]. A comparative analysis of their respective advantages and limitations is presented below.

1) Mechanical lifting mechanisms (lever- and screw-type). These systems operate through the manual or mechanically assisted movement of a drum trolley along guide rails, facilitated by levers, worm gears, or screw drives. Their application is predominantly confined to small-scale production and experimental environments.

– Advantages: structural simplicity, low initial cost, operational reliability, ease of maintenance, and, in the case of manual variant, independence from external power supplies.

– Disadvantages: low throughput, significant dependence on operator skill, high labor intensity, susceptibility to human error leading to process inconsistency, and limited compatibility with automated production lines.

2) Electromechanical lifting mechanisms (electric motor-driven). In this configuration, an electric motor, coupled with a gearbox, drives a chain, belt, or screw mechanism. Control is typically executed via push-button interfaces or programmable logic controllers, making them a standard choice in serial and large-scale manufacturing.

– Advantages: high positioning accuracy and operational speed, smooth motion profiles, programmable processing trajectories and cycle times, commendable energy efficiency, seamless integration with automated and robotic systems, and excellent process repeatability.

– Disadvantages: a higher capital cost compared to mechanical systems, necessitate robust protection against aggressive chemical environments (e.g., vapors and splashes), and involve more complex repair procedures for electronic components.

3) Hydraulic lifting mechanisms. These mechanisms rely on a hydraulic cylinder, actuated by a pumping station, to generate lifting force. They are typically specified for heavy-duty units where the smooth handling of substantial loads – such as large drums filled with heavy components – is paramount.

– Advantages: high power and an exceptional load-to-actuator-size ratio; provide smooth and precise motion control even under maximum load; can maintain position rigidly without continuous energy input; and exhibit inherent resistance to overload conditions.

– Disadvantages: high system costs, including the pump, cylinder, valving, and cooling apparatus. The risk of hydraulic fluid leakage renders them unsuitable for cleanroom environments. They also demand ongoing maintenance (e.g., filter changes, fluid temperature monitoring), exhibit lower operational speeds compared to pneumatic systems, and can be sensitive to ambient temperature fluctuations.

4) Pneumatic lifting mechanisms. These mechanisms utilize compressed air directed into a pneumatic cylinder. They are primarily deployed in applications involving light to medium loads where high-speed operation is prioritized over extreme positional accuracy.

– Advantages: high-speed and rapid actuation; feature a simple, inherently explosion- and fire-safe construction; involve relatively low component costs; and offer operational cleanliness, as air leaks do not contaminate the surrounding environment. They also function reliably across a broad temperature range.

– Disadvantages: a continuous supply of prepared (i.e., dry and filtered) compressed air, creating a dependency on a centralized compressor station. They are characterized by lower positioning accuracy due to the compressibility of air and face challenges in achieving smooth motion, particularly under fluctuating load conditions.

A comparative overview of the lifting devices used in electroplating systems is presented in Table 1.

It is worth noting that low-capacity units are most commonly used for bulk electroplating of small parts [15–19]. These systems typically employ either mechanical (manual) or pneumatic lifts for the drum or bell containing the components. This paper therefore focuses on developing an efficient pneumatic lifting device for the submersible drum in such units.

Table 1

Comparative characteristics of lifting devices of various types

Criterion	Mechanical	Electromechanical	Hydraulic	Pneumatic
Cost	Low	Average	High	Low / Average
Accuracy	Low	High	High	Average / Low
Smooth running	Low	High	Very high	Average
Performance	Low	High	Average	Very high
Power / Load	Low	High	Very high	Average
Energy efficiency	–	Good	Average	Low
Complexity of maintenance	Low	Average	High	Low
Integration into automated control systems	Impossible	Easy	Possible	Possible

The purpose of this study is to improve the economic efficiency of bulk electroplating systems for small parts. To achieve this objective, the following ***tasks*** were addressed:

– to develop an original design for a pneumatic drum lifting device that is cost-effective, offers high performance, and is easy to maintain;

– to experimentally determine the optimal design parameters for this pneumatic lifting mechanism.

Methods

The proposed design solution aims to automate the lifting of heavy drums loaded with parts for electroplating. The pneumatic lifting mechanism was developed based on a review of research by leading specialists in the field of electroplating system design [9–13]. The development process followed a two-stage approach: first, an electronic model (digital twin) of the device was created; second, a physical prototype was manufactured and used to identify the rational operating parameters of the pneumatic lift [20–22]. Experimental data were processed using *MathCAD* and *Microsoft Excel* software environments [23, 24].

Results and Discussion

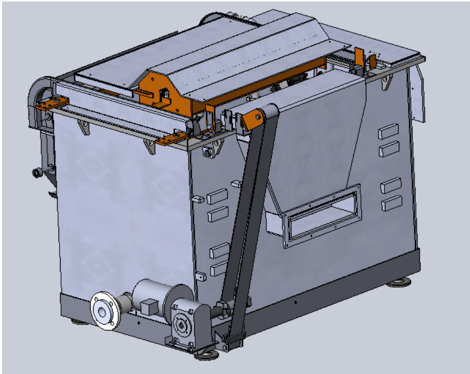
The proposed unit is designed for bulk electroplating of small parts with a minimum size of 3 mm. The system consists of an electroplating bath equipped with a submersible drum, ventilation, a metal frame, and a drum lifting mechanism. As an example, Fig. 1 shows electronic models of units featuring manual (Fig. 1, *a*) and mechanical (Fig. 1, *b*) drum lifting devices.

The authors have developed an original design for a pneumatic drum lifting mechanism intended for bulk electroplating systems. The novelty of this design is protected by a Russian Federation utility model patent [25].

The pneumatic device enables the drum to be raised from the electrolyte solution without requiring personnel to be in close proximity to the unit. This eliminates the risk of chemical electrolyte splashing onto operators' clothing or exposed skin, thereby removing the human error factor associated with manual drum handling.

The pneumatic lifting mechanism for the submersible electroplating drum (Fig. 2) comprises a metal frame (**1**), two rotation mechanisms (**4**), and the pneumatic system itself. The two rotation mechanisms (**4**) are mounted on the side of the bath. They facilitate axial movement of the drum during lifting and lowering

a



b

Fig. 1. Lifting device for a submersible drum:
a – manual; *b* – mechanical

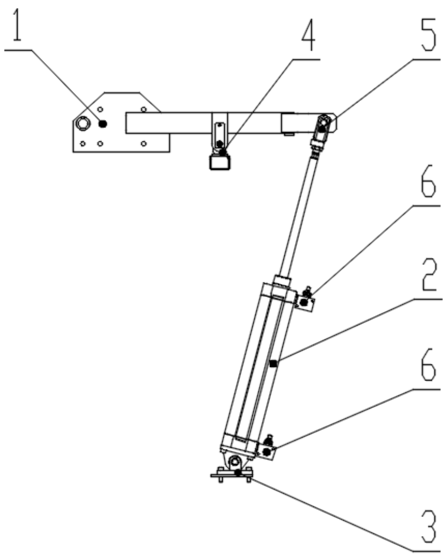


Fig. 2. Submersible drum lifting device: side view

by connecting the drum to the frame (**1**) by means of the pneumatic cylinder stroke (**2**). The rotation mechanism (**4**) consists of a housing containing a rigidly mounted bearing, and the rotating shafts of the frame are attached to the inner race of the bearing.

The frame (**1**) is a metal structure consisting of two parallel plates oriented perpendicular to the floor and connected to each other by a metal framework mounted on the rotating mechanisms attached to the bath rim.

Two guides extend from the frame toward the bath rim. One guide is connected to the rotation mechanism (**4**), while the other is linked via a clevis (**5**) to the pneumatic device (**2**) and also secured to the rotation mechanism.

The pneumatic system comprises a pneumatic cylinder (**2**), a mounting clevis (**5**) that connects the cylinder to the lifting frame, a trunnion (**3**) that secures the cylinder base to a bracket at the lower part of the bath, and flow control valves (**6**) for connecting the air supply lines to the cylinder.

The device is assembled as follows. A pivot trunnion is attached to a bracket on the lower outer side of the bath and connected to the base of the pneumatic cylinder. A mounting clevis is installed on the upper end of the cylinder rod to connect it to the frame. The frame is rigidly mounted on the side of the bath using the rotation mechanisms, extending over the top of the bath and spanning the surface of the electrolyte solution.

Panels that extend downward into the bath are bolted to the side walls of the frame. These panels hold the electroplating drum containing the parts in position at the lower end. Compressed air supply and exhaust lines from the compressor are connected to the pneumatic cylinder via the flow control valves.

During normal operation, the pneumatic cylinder rod is extended, keeping the electroplating drum submerged in the electrolyte solution. When air is supplied to the upper port of the pneumatic cylinder, the rod retracts, creating tension that pivots the frame upward around its mounting axis on the bath rim. This action raises the drum above the solution surface, allowing excess electrolyte to drain and the finished parts to be unloaded.

The pneumatic lifting mechanism enables the drum to be raised from the solution without requiring personnel to be in close proximity to the unit. This eliminates the risk of chemical electrolyte splashing onto operators' clothing or exposed skin, thereby removing the human error factor associated with manual drum handling.

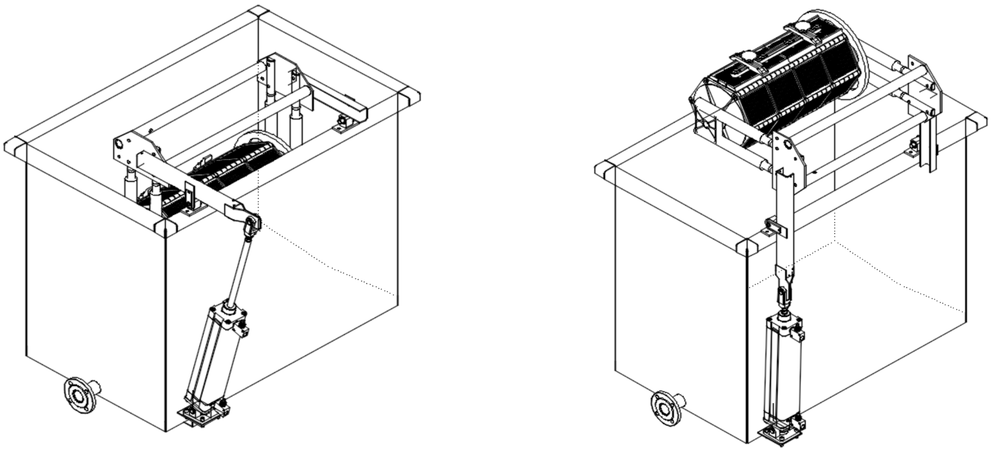
The proposed pneumatic lifting device differs from existing solutions in several respects:

– it eliminates the need for manual operation of the lifting mechanism;

– it prevents splashing of chemical electrolyte onto service personnel;

– the counterweight and all device components are manufactured as separate modular units and assembled into a complete pneumatic lifting system using bolted connections.

Figs. 3, *a*, *b* shows the immersion drum in both lowered and raised positions as operated by the pneumatic lifting mechanism.



a *b*

Fig. 3. Model of the installation with a pneumatic lifting device for a submersible drum:

a – lowered into the bath; *b* – lifted out of the bath

Finding optimal parameters of a pneumatic lifting device

Given that the primary function of the pneumatic lifting mechanism is to raise the drum containing the parts, three key operating parameters were identified for optimization.

Based on the authors' practical experience and expert assessments from electroplating specialists, a drum lifting time of seven seconds was selected as the target value. Lifting times shorter than seven seconds were found to be problematic, as the electrolyte does not drain sufficiently from the parts and drum during rapid ascent. This insufficient drainage leads to several undesirable consequences:

– electrolyte spray contacting personnel;

– spillage of electrolyte outside the unit enclosure;

– potential chemical exposure to operators' skin.

Lifting times exceeding seven seconds increase the overall duration of the plating cycle and should therefore be avoided.

To achieve the optimal seven-second lifting time that ensures maximum electrolyte drainage, three key parameters must be properly balanced: the piston rod stroke, the force required to lift the loaded drum, and the compressed air pressure supplied to the pneumatic cylinder. Fig. 4 presents an electronic model of the lifting mechanism with the submersible drum.

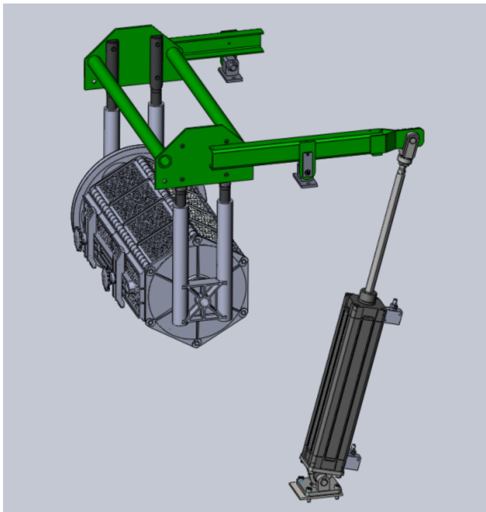


Fig. 4. Electronic model of a pneumatic lifting device with a submersible drum

This section describes the experimental procedure used to determine the rational operating parameters of the pneumatic lifting device. The optimal parameters were identified through experiments conducted on a prototype using an orthogonal central composite design (*OCCD*) [22–24]. The experiments were carried out on the premises of the production facility of *LLC* "Technologiya" in Tambov, Russia.

To identify the optimal factor settings for the batch electroplating system, a composite experimental design was developed. This design extends a standard full factorial experiment by including additional tests at axial points (located at a specified distance from the center point) and at the center of the experimental region. This approach enables the construction of an accurate mathematical model (response surface) and the identification of its optimum.

The optimal parameters of the pneumatic lifting device were determined within the following factor ranges:

- piston rod stroke ($\boldsymbol{p_1}$) – from 370 mm to 450 mm;
- lifting force required for the loaded drum ($\boldsymbol{p_2}$) – from 0.4 kN to 2 kN;
- compressed air pressure at the cylinder inlet ($\boldsymbol{p_3}$) – from 4 bar to 12 bar.

The response function was defined as:

$$f(p_1, p_2, p_3) = \left|T_v - T_{eks,i}\right|,$$

where $\boldsymbol{T_v}$ is the target lifting time (7 seconds); $\boldsymbol{T_{eks,i}}$ is the measured lifting time in the $\boldsymbol{i}$-th experiment, $\boldsymbol{i} = 1, 2, \ldots, 15$.

A central composite design was employed for three factors, with axial arm $\boldsymbol{\alpha} = 1.215$ and quadratic term correction $\boldsymbol{a} = 0.73$. Three parallel experiments were conducted for each trial. Based on the experimental results, a second-order polynomial regression equation was derived to determine the optimal factor values.

The regression equation has the form:

$$f_2(p_1, p_2, p_3) = k_0 + k_1 p_1 + k_2 p_2 + k_3 p_3 + k_{12} p_1 p_2 + k_{13} p_1 p_3 + k_{23} p_2 p_3 + k_{11} p_1^2 + k_{22} p_2^2 + k_{33} p_3^2,$$

where the coefficients $k_0, k_1, k_2, k_3, k_{12}, k_{13}, k_{23}, k_{11}, k_{22}, k_{33}$ are calculated using the method described in [14].

Factor levels are presented in Table 2, and the results of the first experimental series are summarized in Table 3.

The *Student's* t-test value t_m for 15 experiments at a significance level of 0.05 is 2.13. Since the condition was satisfied for all experiments ($\boldsymbol{t_{1p}} < \boldsymbol{t_m}$ and $\boldsymbol{t_{2p}} < \boldsymbol{t_m}$), no outliers were detected in the experimental data.

Cochran's test was used to verify homogeneity of variances. The calculated *Cochran's* criterion $\boldsymbol{G_p}$ =0.173. The tabular value $\boldsymbol{G_m}$ for a significance level of 0.05, 15 experiments, and 2 degrees of freedom is 0.33, i.e. $\boldsymbol{G_p} < \boldsymbol{G_m}$, the variances are homogeneous, and the experiments are reproducible..

The reproducibility variance was 0.017, with a standard deviation of the regression coefficients of 0.033. The residual variance was 0.035. The calculated *Fisher's* criterion value was 2.109, while the tabular value at a significance level of 0.05 was 2.16; therefore, the regression model is adequate for the object of study.

The final regression equation obtained from the central composite design experiments is:

$$f_2(p_1, p_2, p_3) = 0.254 - 0.25 p_1 - 0.141 p_2 + 0.17 p_3 - 0.279 p_1 p_2 - 0.17 p_1 p_3 +$$
$$+ 0.45 p_2 p_3 + 0.33 p_1^2 + 0.030 p_2^2 + 0.031 p_3^2.$$

The lifting time of the drum is provided by a pneumatic lifting device with the following parameters: piston rod stroke: 409–410 mm; force required to lift the loaded drum: 1.80–1.90 kN; and compressed air pressure at the cylinder inlet: 5.30–5.40 bar.

Table 2

Levels of variation of selected factors

Factor	−−α	−1	0	+1	+−α
$\boldsymbol{p_1}$	370.0	377.08	410.00	442.92	450.00
$\boldsymbol{p_2}$	0.40	0.54	1.20	1.86	2.00
$\boldsymbol{p_3}$	4.00	5.71	8.00	11.29	12.00

Table 3

Experimental results

Factor level p_1	Factor level p_2	Factor level p_3	$\lvert T_v - T_{eks,i} \rvert$
−1	−1	−1	0.4
1	−1	−1	0.3
−1	1	−1	0.4
1	1	−1	−0.4
−1	−1	1	0.7
1	−1	1	0.6
−1	1	1	1.1
1	1	1	−0.6
−α	0	0	0.4
α	0	0	0.3
0	−α	0	0.5
0	α	0	0.4
0	0	−α	0.2
0	0	α	0.3
0	0	0	0.2

As a result, a system incorporating a pneumatic lifting mechanism for the submersible drum was developed. Its three-dimensional model is shown in Fig. 5. A physical prototype was manufactured at the production facility of *LLC* “*Technologiya*” (Tambov, Russia). Trial operation confirmed the system’s high efficiency and demonstrated the advantages outlined above.

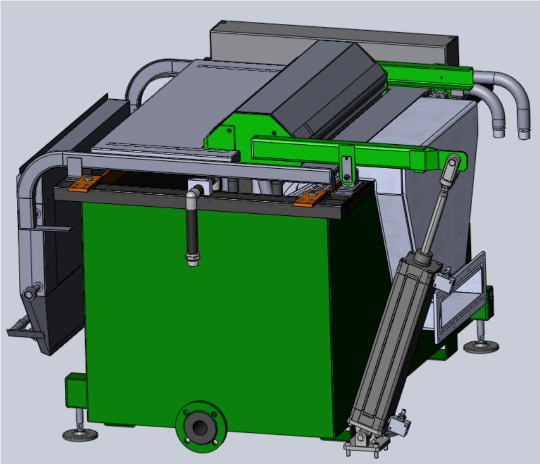


Fig. 5. Model of the installation with a pneumatic lifting device for a submersible drum

Conclusion

As a result of the conducted research:

1) A basic design scheme of the device based on a pneumatic drive has been established for lifting a submersible drum in a galvanic unit for coating small parts in bulk. This scheme is original and provides a new way to solve a technological problem.

2) Empirical dependencies have been identified and obtained, which establish a quantitative relationship between the key parameters of the pneumatic system and the design characteristics of the lifting mechanism.

A key feature of the developed pneumatic device is that it provides remote, automated lifting of the drum from the electroplating bath, which eliminates the need for personnel to be in the immediate vicinity of the unit during this operation. This property gives rise to the following established advantages and benefits:

– elimination of the main occupational safety risk — splashing of chemical electrolyte onto work clothing and exposed skin of personnel;

– creation of the prerequisites for process stabilization through standardization and controllability of the lifting operation, making it independent of the physical effort of the operator.

The novelty of the device's design is confirmed by a Russian Federation patent for a utility model [25].

According to the test results of the physical prototype in the production facility of *LLC* "*Technologiya*" (Tambov, Russia), its economic benefit was confirmed. Analysis shows that the proposed solution has lower operating costs compared to traditional electroplating units for bulk parts that use manual or mechanized (motor-driven) drum lifting.

An important operational advantage is the ability to integrate the device into existing production lines. An inspection of the production facilities showed that the compressor equipment necessary for the operation of the pneumatic lift is usually already present as part of the main workshop infrastructure. This means that the modernization of existing electroplating baths for small parts requires minimal adaptation work, which significantly reduces capital costs and implementation time.

A direct comparison of the capital cost of equipping a single bath demonstrates significant savings. The cost of a pneumatic system for a bath with a volume of 0.5–0.8 m^3, excluding the compressor, is about 60,000 rubles. The cost of a system with a traditional electromechanical drive for the same bath, including turning, is estimated at about 80,000 rubles.

The cumulative economic benefit from the use of a pneumatic solution is derived both from reduced initial investment and from operational efficiency. Calculations indicate that the total cost of implementing this unit is 10–15% lower than that of analogues with motor-driven drum lifting methods. Thus, the modernization proposed by the authors provides a direct economic benefit, which is realized repeatedly throughout the entire life cycle of the equipment.

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Conflicts of Interest

The authors declare no conflict of interest.

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