Lecture Notes in Networks and Systems 305

Daniela Doina Cioboată *Editor*

International Conference on Reliable Systems Engineering (ICoRSE) - 2021

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Editor

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Foreword

During the last two years, we have witnessed unprecedented challenges. But human beings' ingenuity is endless, and we were able to find solutions to all the threats we deal with. In this context, organizing a scientific event is not an easy task. This is why I am very proud to be able to coordinate a conference during the pandemic that seems–hopefully–to be coming to an end.

And it is due to the degree of excellence that science has attained–in terms of medicine–that we can now say that we stand firm against the threat of COVID-19. And, more than ever, the impact that science has–on the long run–on the well-being of society is easier than ever to spot.

The evolution of science and technology, so fast paced, is obvious especially in the fields of electronics and microelectronics, automation and digitization. These have resulted in a shift in focus, from precision mechanics to mechatronics, integronics, adaptronics and currently claytronics and cyber-mix-mechatronics. This is why the National Institute of Research and Development in Mechatronics and Measurement Technique (INCDMTM), which is the main organizer of our conference, and that is an organization that has been writing the history of Mechatronics in Romania for 40 years, has strived to keep up with the trends and developments in the field. Consequently, we have changed the concept and the structure of former International Conference of Mechatronics and Cyber-Mix-Mechatronics (ICOMECYME), and we have established ICoRSE—The International Conference on Reliable Systems Engineering.

As of this year, ICOMECYME, which used to have a rich tradition behind (it derives from MECAHITECH International Symposium too), aims to adapt to the challenges of the field of mechatronics and that of related engineering fields, thus becoming ICoRSE.

The conference that my team and I are coordinating aims to promote scientific research results and technological developments in reliable systems engineering, cyber-physical systems, mechatronics, applied mechanics and complementary fields, by facilitating the interaction and exchange of experience and good practice between experts in universities, research institutes and private companies.

I would like to take the chance to thank all the authors for their valuable contributions. Given the reasons mentioned in the first lines, I appreciate their effort more than ever. This is the first year that I am coordinating an international conference, and it is a great honour to benefit from such valuable works. I am also very proud to say that the papers we have reunited in the form of these proceedings come from all major parts of the world. The collected papers are from Europe, Asia, North and South America, and the fact that the country of origin of the authors of papers is so diverse, along with the rich scientific contents debated in the papers, makes me able to strongly stress out the importance of this event and to express my belief that ICoRSE 2021 is–indeed–a conference that can render the current state of the art of mechatronics.

To conclude, I would like to thank the organizing team members for their support in all areas. An international event is a matter of team work above anything, and it is important to acknowledge the efforts of my colleagues too. Also, the excellent collaboration with Springer is to be pointed out, and I am highly thankful for the support offered by Mr. Holger Schaepe and Mr. Thomas Ditzinger in the development of the work herein.

I genuinely hope that the readers of the proceedings will find the current book interesting and useful.

Doina-Daniela Cioboată

Contents

Study of a Test Stand for Determining the Oil Density in Hydraulic Systems

Mihai Avram[1], Valerian-Emanuel Sârbu[2(✉)], and Mariana-Florentina Ştefănescu[2]

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Abstract. The purpose of this paper is to document the development of a test stand that enables experimentally determining the viscosity of the fluid used in a hydraulic system. This test stand also doubles as a method for determining the influence of the temperature and pressure on this parameter.

The resulting setup allows full control of the system while also measuring and processing the measured data. For the core of this type of system a microcontroller was selected. High performance transducers are used for ensuring accurate measurements, they provide a proportional electrical output. The microcontroller firmware mostly runs as a command processor, a Lab View program is responsible for communicating with it in order to acquire data and control the system variables in a predefined sequence.

Keywords: Hydraulic oil · Density · Hydraulic drive system · The theoretical and experimental analysis

1 Introduction

Hydraulic systems use pressurized fluid to transfer the energy from the pump to the desired system. At first, hydraulics appeared and rapidly evolved in applications that require the control of high power, high inertia and forces with relatively high accuracy; furthermore, they also facilitate full control of the position and speed. The method by which the delivery of hydraulic power is adjusted gives hydraulic transmissions advantages compared to electrical and mechanical transmission systems [1, 2].

In order to determine the performances of this type of system, static or dynamic, there are two methods available depending on the circumstances: theoretical and experimental. In practice we generally encounter two scenarios:

When the real system is available.

When it needs to be designed and then manufactured.

In both cases the system needs to be mathematically defined [6]. Mathematical models of systems that use a liquid transport medium include several equations that describe its movement if the following parameters are known: fluid density - ρ, Elasticity modulus - E, Dynamic viscosity - η and cinematic viscosity - μ.

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Mathematical models are used for describing existing machines and for designing new ones. The first case is used in attempts to determine optimum functional parameters of the system in order to improve its overall performance. Thus, it requires knowing these parameters and the way they vary in time. This can be accomplished with an experimental test stand that is designed specifically for this purpose. In order to ensure that valid values are measured the system must be designed with accuracy in mind, the transducers need to be of high quality along with the acquisition system. Temperature, pressure and flow sensors are necessary in this setup. The control and data acquisition are done with a control unit built around a microcontroller [3–5].

Designing of this system was done with some targets in mind, some are considered general practice while others are application specific:

- Rapid deployment of the equipment and its components
- Being able to measure both static and dynamic variables
- Lightweight, robust and compact design
- The usage of standard and readily available components
- Can adapt to different sensors
- Needs to be designed with current easily available technology
- Be able to easily acquire the components in due time

Following these guidelines results in: high cost for designing and measurements, complex test setups, expensive equipment, and poor time usage.

Up next, the experimental test stand that enables the measurement of the fluid density and the test procedures will be described.

2 Methodology and Experimental Details

To be able to experimentally determine the density of a mineral oil, used as work medium in a hydraulic drive system, a stand has been designed and built with the corresponding functional scheme presented in Fig. 1A.

The proposed stand contains the following equipment:

- the hydraulic power generation group GGE, group containing the fixed flow pump P and safety valve S_{sig};
- proportional valve SP;
- classic hydraulic valve 3/2, with a preferential position and electrical control DHC;
- proportionate butterfly valve DrP;
- flow transducer T_q;
- pressure transducers T_{Pav} și T_{Pam};
- temperature transducer T_T;
- electronic acquisition and control block BEAC.

Observation: The proportionate butterfly valve DrP used is a proportional hydraulic distributor, model 4 WREE 6 EA08-2X/G24K31/A1V, manufactured by Rexroth Bosch, to which the holes A and T are plugged (Fig. 1B).

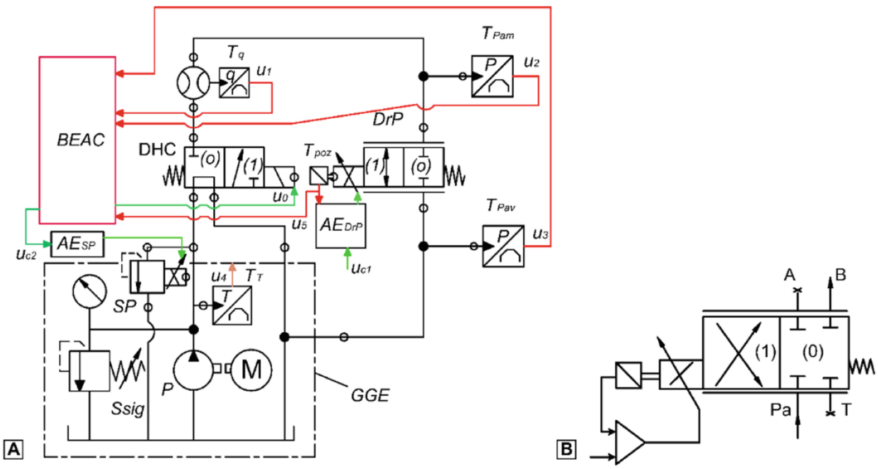

Fig. 1. Functional scheme of the experimental stand (A); Proportional hydraulic valve (B)

Proportional equipment used, proportional valve SP and the proportional butterfly valve DrP are served by proportional amplifiers AE_{SP} and AE_{DrP}.

Figure 2 presents two images of the experimental stand designed and realized by us, where A represents the electronic control block and B represents the hydraulic power generation group.

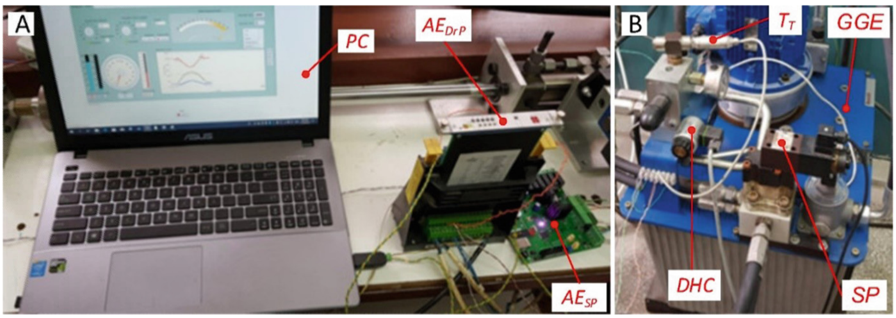

Fig. 2. Main components of experimental setup, with the electronic control block (A) and hydraulic power generation group

The presentation will be clear and concise, and the symbols used therein will be specified in a symbol list (if necessary). In the paper the International System measurement units will be used. There will however be no apparatus or installation descriptions.

The initial condition of the system is defined as follows:

$$u_0 = 0\,V, u_{c1} = 0\,V \text{ and } u_{c2} = 0\,V$$

In this situation the distributor DHC assumes the position (0), the flow section through the proportional hydraulic butterfly valve DrP is zero, and the proportional valve SP is open (no flow resistance).

From this moment experimental determinations can start, which involve the following steps:

Start the hydraulic power generator unit and apply a control voltage ($u_0 = 24$ V) to the GGE, the distributor electromagnet DHP will engage and the distributor will materialize the position (1));

At the input of the amplifier AE_{SPis} a voltage is installed $u_{c2} \in [0,10]$ V which provides the desired hydraulic pressure to the hydraulic system; this pressure will be constantly maintained during the experiment, as in the memory of the microcontroller that is integrated in the electronic acquisition and control block BEAC there is an algorithm specifically designed for this purpose;

First the electronic amplifier AE_{DrP} is supplied with a voltage of $u_{c1} = 1$ V;

Measurement is done using the system transducers: P_{am}, P_{av}, q, x and t;

Finally, there is the increasing of the voltage u_{c1} by Δu_{c1}; previous steps are repeated until target voltage $u_{c1} = 10$ V is reached.

Same pattern but in reverse (from 10 V to 1 V) is then applied;

3 Experimental Determination of Mineral Oil Density

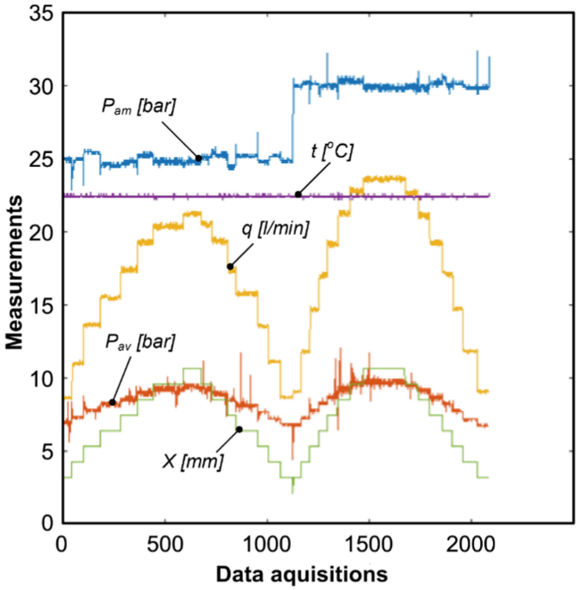

Fig. 3. Experimental results

Figure 3 shows the results obtained for two set feed pressure values P_{am}, i.e.25 bar and 30 bar.

For a set of experimentally determined values, the density of the oil can be calculated with the relationship [6]:

$$\rho = \frac{2}{q^2} \cdot S_c^2(u_c) \cdot (P_{am} - P_{av}) \tag{1}$$

The law of variation of the flow section is not known, the only certain thing is the maximum stroke of the drawer $x_{max} = 1{,}25$ mm as this value is specified by the manufacturer in the catalog tab of this equipment.

For this reason, we have attempted at the theoretical determination of the variation law of the flow section. For the drawer geometry indicated by the manufacturer in the documentation of this equipment, the following expression of the flow section has been determined:

$$S(x) = \mathrm{n} \cdot \left\{ \left(\frac{b}{2}\right)^2 \cdot arccos\left[1 - \frac{2}{b} \cdot (x - l_a)\right] - \left[\frac{b}{2} - (x - l_a)\right] \cdot \sqrt{x - l_a} \cdot \sqrt{b - (x - l_a)} \right\} \tag{2}$$

where:

n – the number of channels processed on the drawer in the control area;

b – the width of the channel;

la – cover length.

This expression is valid for $x \in [l_a, l_a + b/2]$. In the range $[0, l_a)$ the flow section is null.

Figure 4 shows the variation of the flow section according to the spool position for different situations.

Below we consider that the flow section through the butterfly valve corresponds to the variant (*) on the graph (see 4). In this case, the maximum value of the flow section is obtained for $x_{max} = 1.25$ mm and is $S_{c,max} = 5{,}8$ mm^2.

Following the measurements, for a maximum control voltage were obtained the following values:

$$\Delta p = P_{am} - P_{av} = 20,469\, bar$$
$$q = 23,61\, l/\min$$

Oil density can be now calculated with the relation (1) as follows:

$$\rho = 360 \cdot \frac{2}{23,61^2} \cdot 5,8^2 \cdot 20,469 = 889,39\, kg/m^3$$

The stand allows determination of density variance with pressure and temperature. Because the connections between the stand equipment are made with metal inserts rubber hoses, the maximum system pressure must be limited to 80 bar. Within this scope, density variance with pressure is insignificant and most of the times the density is assumed to be constant. Keeping the same stand structure and making couplings of the equipment with metal ducts, the working pressure may be increased to 320 bar a situation where the determination of density variation with temperature makes sense.

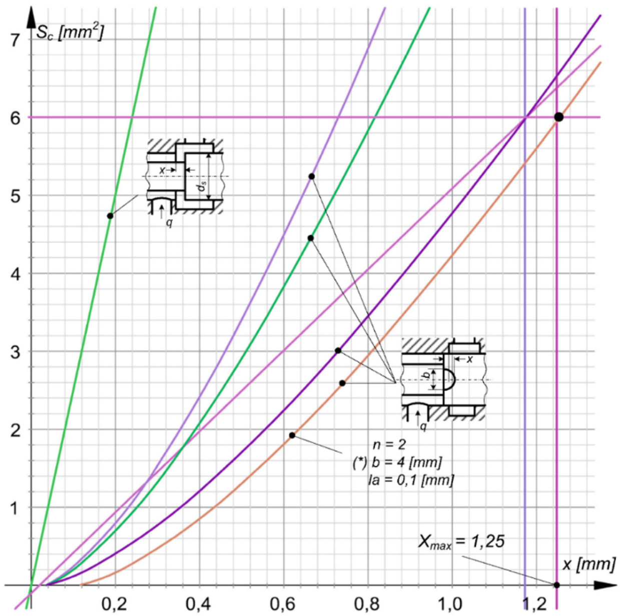

Fig. 4. Variation of flow section depending on the position of the drawer

4 Conclusions

Determination of the density of a mineral oil used as a working medium in a hydraulic drive system under certain working conditions, as well as the dependence of the density with temperature and pressure is an important issue for which a solution is still being sought.

The experimental stand designed and made by the authors is an effective solution to solve the above-mentioned issues. This stand represents, through its hardware and software structure, a complex system of experimentation and testing, where all activities are computer assisted.

One of the advantages of the system consist in that the experimental results obtained can be both directly viewed on the computing system monitor, during the measurement, which is a great advantage in experimental research, and stored in memory in the form of csv files, for further data processing and their printing as test /experimental bulletins, without human operator intervention.

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The Absorbents Nanoporous Structures Regeneration for Industrial Dryers by Microwave Energy

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Abstract. The presented work is devoted to solving the problem of energy conservation in industrial production. Modern industrial equipment and technological processes use compressed air energy. Wherein deep drying of compressed air is often required. The air preparation process is an expensive and energy-intensive process. Reducing useless energy losses, in this case, is possible through the use of innovative technologies that are technically feasible and economically justified. The adsorption air dryer's efficiency feasibly increased by using microwave energy to regenerate the adsorbent by deporising water molecules from its nanoporous structure. This paper explores the application of this regeneration technology in air dryers wich have high throughput. The scientific novelty of this submitted research lies in this study of the regularities of the spatial distribution of thermal and electromagnetic energy and their uniform distribution in the adsorbent volume if the proposed innovative technology is applying. Also, it was establishing the dependence of the intensity of exposure to microwave energy depending on the frequency, voltage level, and design features of the adsorption tower. The practical significance lies in the proposition of a new technological process for the regeneration of the adsorbent in adsorption dryers with high performance.

Keywords: Nanopores · Air dryer · Regeneration · Microwave energy

1 Introduction

Nanotechnology is used intensively in modern industrial [1–4], agricultural [5], and food [6, 7] production. In particular, the use of nanostructures has become widespread in the technological process of drying compressed air using adsorption technologies. Today, adsorption dryers are the main type of equipment that can provide modern technology processes with high-quality compressed air.

The problem of increasing the efficiency of adsorption dryers is to reduce energy costs and increase the intensity of the process of periodic desorption of accumulated moisture from the nanoporous structure of the adsorbent.

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Today the conventional adsorbent regeneration technology uses heated purge air for drying the adsorbent [8–11]. Air dryers with hot regeneration of the adsorbent are currently the most economical means of producing dried air and the development of the design of this type of equipment is the most important direction to improve the energy efficiency of industrial production.

In this case, energy is transferred from the electric heater to the purge air, then from the heated air to the adsorbent material, and only then to the water molecules in the pores. At the same time, at the stages of energy transfer, its non-productive losses occur.

It is possible to qualitatively increase the efficiency of adsorption dehumidifiers by applying new technology for removing moisture from the nanoporous structure of the adsorbent, which will make it possible to act directly on water molecules.

We have proposed a regeneration technology using the energy of microwave radiation. The electromagnetic field created in the cavity of the adsorption column causes accelerated movement of water molecules in micro-pores, which leads to deporization of moisture and its subsequent evaporation from the surface of the adsorbent granules. The impact of microwave energy on an adsorbent saturated with water leads to an increase in its temperature. This makes it possible to purge the adsorbent volume with a stream of unheated air.

Studies show that the use of microwave radiation reduces the energy loss, which is spent during the regeneration of the adsorbent [12, 13]. Microwave energy acts directly on water molecules. This avoids unproductive convective and conductive heat losses, which is inevitable in the case of using classical regeneration technology [14, 15]. Under the influence of microwave radiation, the drying of the adsorbent occurs more intensively, faster [16–29], and at a lower temperature [30]. This makes it possible to reduce the energy consumption for the regeneration of the adsorbent and the consumption of dried air for the subsequent cooling of the adsorbent.

The presented article examines the use of high-frequency exposure to adsorbent adsorption dryers with high throughput.

2 Research Problem

The process of regenerating serves to remove moisture desorbed from the porous structure of the adsorbent.

The completeness of regeneration depends on the uniformity of energy distribution in the volume of the adsorbent [31–37]. All areas of the adsorbent volume must be energized. This eliminates the occurrence of residual zones with high moisture content in the porous structure. Also, the design of the adsorption tower must ensure a uniform laminar flow of purge air through the entire volume of the adsorbent. Stagnant zones with a low flow rate of purge air prevent complete moisture removal, which reduces the quality of regeneration.

Our earlier studies [38–42] have shown the possibility of using a magnetron with a wave-guide system for the action of microwave energy on a small volume of the adsorbent. The low price of this design makes it advisable to use microwave regeneration in dryers with a productivity of 1.5 m^3/min and less [43]. The problem of using one or a group of magnetrons to regenerate a large volume of adsorbent is the limited depth of wave energy penetration into the bulk of the material.

It should be taken into account that silica gel loses its useful properties when it overheats above 200 °C. From this, it follows that an increase in temperature above this limit to intensify the process of regeneration of the adsorbent is unacceptable. Thus, an unlimited increase in the parameter is not possible to increase the intensity of the regeneration process.

In a column with a diameter of 100 mm, it is possible to achieve a uniform distribution of energy without the appearance of peripheral overheating zones due to heat exchange in the horizontal section of the column. In this case, the microwave energy does not intensively affect the inner layers of the adsorbent (Fig. 1, pos.5).

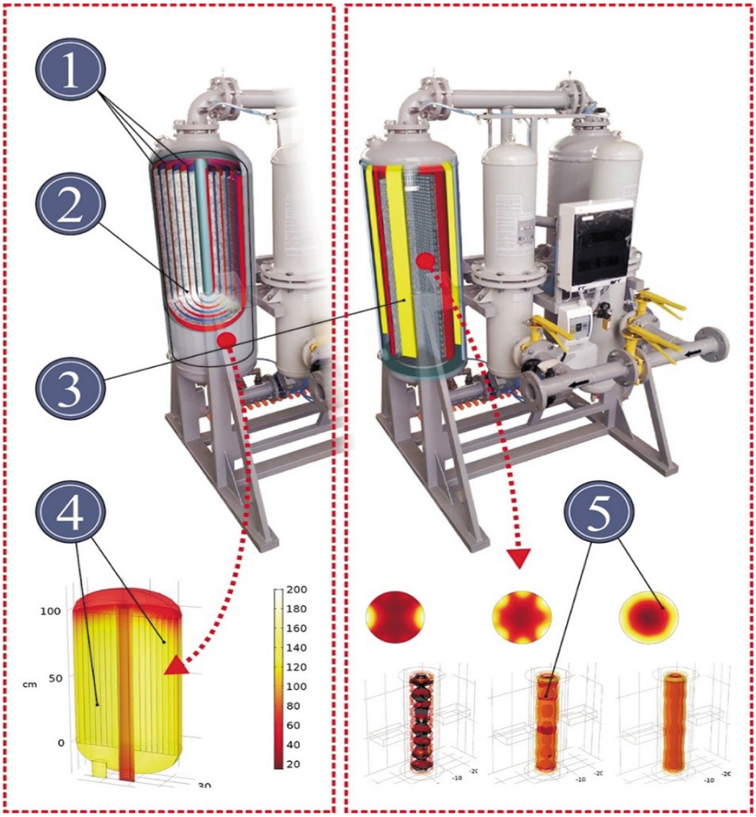

Fig. 1. Design of adsorption columns with pole plates and waveguide system and energy distribution in the adsorbent volume.

An increase in the number and power of magnetrons leads to the appearance of local overheating zones on the outer layers of the adsorbent volume without increasing the total intensity of regeneration. Dehumidifiers with a productivity of 5 m^3/min and more have an ad-sorption tower diameter of more than 250 mm and cannot use microwave radiation effectively enough due to the limited penetration depth. Meanwhile, high-capacity dehumidifiers are widely used in production. Also, in the chemical and gas industry, adsorption plants are used in which the diameter of the adsorption columns is several meters. In this case, exposure to radiation from the outside does not affect even if the energy is uniformly distributed over the outer surface of the adsorbent volume.

To solve this problem, it is proposed to use concentric pole plates, which are located in the volume of the adsorbent (Fig. 1, pos.1).

Pole plates are made in some form:

1) several nested cylinders (Fig. 2, pos. 1), the axes of which coincide with the axis of the column;
2) two nested spirals (Fig. 2, pos. 2);
3) a set of parallel planes (Fig. 2, pos. 3) inscribed in the cylindrical volume of the adsorption column.

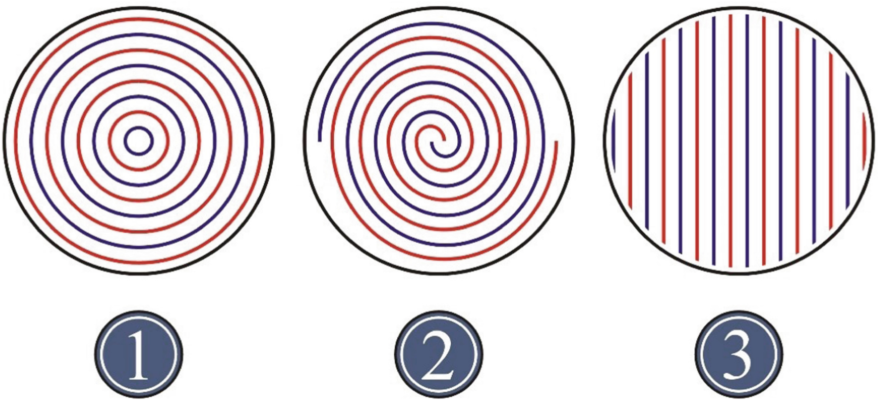

Fig. 2. Variants of the pole plates placement in the adsorption column cavity (column horizontal section, top view).

The presented study is devoted to the study of the effect of microwave energy on the adsorbent in a dryer with columns having cylindrical pole plates.

3 Materials and Methods

The research is carried out using several mathematical multiphysics computer models of adsorption column. The models are constructed to study the movement of the purge airflow through the adsorbent, the intensity of the high-frequency effect on the adsorbent, and to evaluate the uniformity of temperature distribution in its volume. Simulation is performed using the Komsol Multiphysicstm software environment.

The calculation is carried out using the mathematical model of a desiccant adsorption tower with a capacity of 50 m^3/min. The adsorption tower model is a hollow cylindrical body. The cylinder is closed from two ends with elliptical bottoms. The body material is steel. Concentric pole plates are located inside the column body. An adsorbent is placed in the spaces between the pole plates (Fig. 1, pos. 2,4). Thus, the adsorbent volume is divided by plates into separate concentric cylindrical volumes.

The purge air blowing is carried out in the vertical direction, with the blowing air moving through the adsorbent bed endlong the pole plates.

The purge air moves from the top-down direction, (Fig. 4) along the axis of the adsorption column.

Adsorbents have a different porosity at a scale of a separate granule. This defines the adsorption capacity and affects the intensity of the regeneration process.

The gas-dynamic process, considered at a scale of the adsorption column, will be determined by the size and shape of the adsorbent granules. This defines the bulk density of the adsorbent volume. The adsorbents, used in dryers, have the same characteristics: adsorbent granules have a spherical shape and a diameter of 3 to 7 mm. The normal range of porosities in granular systems is 5% to 35%. A hexagonal or cubic close pattern is assumed with the calculated packing density is 0.7045, gives a porosity void fraction of 0.2955, provided that all the balls are the same size. The difference in grain size will create a lower porosity. But adsorbent retaining grids of modern dryers can remove small granules and products of their shredding. Due to this the spread in the diameters of the granules is small. This makes it possible to use in the model the value of porosity of the adsorbent volume to be 20%. Granules will not give closed pores, so the effective porosity is considered equal to 100%. The physical properties of silica gel are shown in the table (Table 1). The properties of silica gel [44] are corrected taking into account the moisture content and the bulk density of wet silica gel.

Table 1. Silica gel physical properties.

Parameter	Dimension	Value
Density	kg/m^3	2900
Bulk density	kg/m^3	780
Heat capacity	j/(kg*K)	730
Relative permeability	1	16
Relative permittivity	1	4,1
Electric conduction	S/m	0
Heat conduction	W/m	0,2

Linear dimensions of the model (Fig. 3) are given in the table (Table 2). The model uses steel material for the column and walls.

Since the flow rate of the purge air in the column throughout the entire path does not exceed 1.2 m/s, the flow is calculated as laminar flow using equation [45, 46].

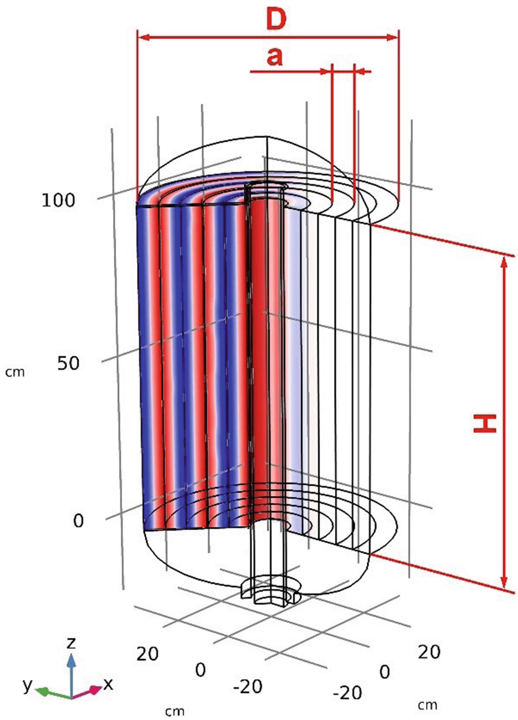

Fig. 3. Linear dimensions of the adsorbent volume and the distance between the pole plates.

Table 2. Linear dimensions of the adsorption column.

Index	Size	Dimension, mm
H	Column height	1000
D	Column diameter	760
a	Distance between the pole plates	32/40/64

The impact on the adsorbent of high-frequency energy is carried out by applying an alternating voltage to the pole plates. The process is modeled as inductive heating. An alternating voltage across the pole plates is generated using a sinusoidal function with a given angular frequency. The voltage is determined by the amplitude of the function.

The stationary problem of the air medium's motion was calculated by the equation:

$$\rho(u \cdot \nabla)u = \nabla\left[-pl + \mu\left(\nabla u + (\nabla u)^T\right) - \frac{2}{3}\mu(\nabla \cdot u)l\right] + F \quad (1)$$

$$\nabla \cdot (\rho u) = 0 \quad (2)$$

where: u - is the velocity, p - is the pressure, and μ - is the dynamic viscosity.

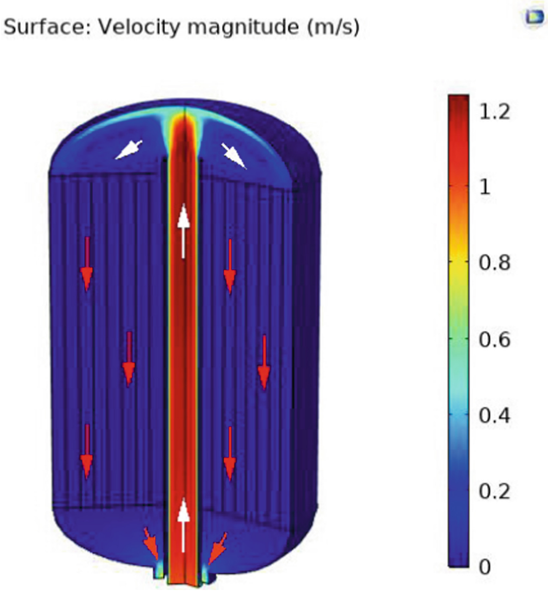

Fig. 4. The movement of the purge air in the adsorbtion column cavity and also through the adsorbent layer.

The movement of air in the volume of the adsorbent was modeled as a motion in a porous medium and was calculated by the equation:

$$\frac{1}{\epsilon_p}\rho(\mathrm{u}\cdot\nabla)\mathrm{u}\frac{1}{\epsilon_p} = \nabla\left[-p\mathrm{l} + \mu\frac{1}{\epsilon_p}\left(\nabla\mathrm{u} + (\nabla\mathrm{u})^{\mathrm{T}}\right) - \frac{2}{3}\mu\frac{1}{\epsilon_p}(\nabla\cdot\mathrm{u})\mathrm{l}\right] - \left(\mu k^{-1} + \beta_F|\mathrm{u}|\frac{\theta_m}{\epsilon_p^2}\right)\mathrm{u} + F \quad (3)$$

$$\nabla\cdot(\rho u) = Q_m \quad (4)$$

where: θ_m - the value of porosity of the material.

The dynamic heat transfer problem was calculated by the equation:

$$\rho C_p \mathrm{u}\cdot\nabla\mathrm{T} + \nabla\cdot q = Q + Q_{vd} \quad (5)$$

$$q = -k_{eff}\nabla\mathrm{T} \quad (6)$$

where: Cp - heat capacity value, T - temperature, Q - quantity of heat.

Heat transfer in a porous medium was calculated as:

$$k_{eff} = \theta_p k_p + \left(1 - \theta_p\right)k + k_{disp} \quad (7)$$

where: θ_ρ - is the volume fraction of the material, k_ρ - is the thermal conductivity.

The influence of purge air flow on thermal processes in the column is calculated as dynamic heat transfer model through the following equations:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p v_{trans} \cdot \nabla T + \nabla \cdot q = Q + Q_{ted} \tag{8}$$

where ρ is the density, C_p – heat capacity, q – heat flux, T – temperature, Q_e – heat sources and sinks.

The initial temperature of the adsorbent is the same at all points in the volume of the adsorbent and is 20 °C. The purge air also has an initial temperature of 20 °C. The same temperature is conventionally considered the adsorption temperature.

The electric field generated in adsorbent volume is calculated with equations:

$$\nabla \times (\mu_\gamma^{-1} \nabla \times E) - k_0^2 \left(\varepsilon_\gamma - \frac{j\sigma}{\omega \varepsilon_0} \right) E = 0 \tag{9}$$

$$\nabla \cdot J = Q_{\mathrm{j,v}} \tag{10}$$

$$J = \sigma E + j\omega D + J_e \tag{11}$$

$$\omega = 2\pi f \tag{12}$$

where μ_γ is the complex relative permeability; E – complex amplitude representing an oscillating electric field; ε_γ – complex relative permittivity; ω – circular (angular) frequency, k_0 – phase constant of free space, σ – electrical conductivity, j – is an imaginary unit, J – externally generated current density, D – electric displacement, $Q_{\mathrm{j,v}}$ – charge, f – frequency (Fig. 5).

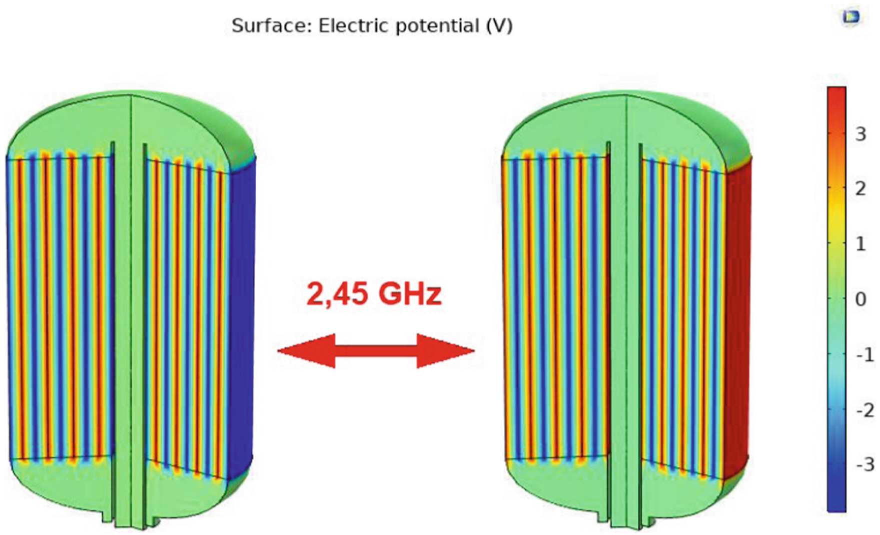

Fig. 5. Variable electrical potential in the space between the pole plates.

The heating of the adsorbent due to the effect of alternating voltage is calculated as:

$$\rho C_p u \cdot \nabla T = \nabla \cdot (k \nabla T) + Q_e \tag{13}$$

$$Q_e = J \cdot E \tag{14}$$

The force, which is effects on the water molecule is calculated as:

$$\overline{F} = \overline{\rho} \cdot \overline{E} \tag{15}$$

$$F = \Sigma_i \frac{\partial \overline{E}}{\partial x_i} \rho_i \tag{16}$$

$$E = \frac{U}{d} \tag{17}$$

$$E = -\nabla V \tag{18}$$

where $\overline{F}$ is the electric displacement, $\overline{\rho}$ – dipole moment, U – potential difference, d – distance between the pole plates, V – electric potential.

The calculations were carried out in the time interval from 0 to 180 min, with step 5 min.

4 Results and Discussion

The calculation of the computer model shows that the high-frequency action can be used to increase the temperature in the adsorbent volume for regeneration (Fig. 6).

Neglecting the change in the absorption coefficient of water as the frequency changes and also taking into account that the dipole moment of water (1.84 Debye) is a constant value, we can influence the efficiency of exposure to microwave energy by changing the frequency of exposure (9), the voltage between the pole plates and the distance between them (17).

The calculation of the comparative model shows the positive effect of increasing the frequency on the dynamics of the growth of the average temperature of the adsorbent volume (Fig. 7).

It should be noted that obtaining a high polarization frequency is a technically difficult task and requires specialized equipment. This is because most general-purpose semiconducting elements operate effectively in the frequency range up to 20 MHz. In this case, the problem of high voltages commutation is solved relatively easier and cheaper.

The performed calculation shows a positive effect of an increase in the voltage which is supplied to the pole plates on the dynamics of an increase in the average temperature of the adsorbent volume (Fig. 8).

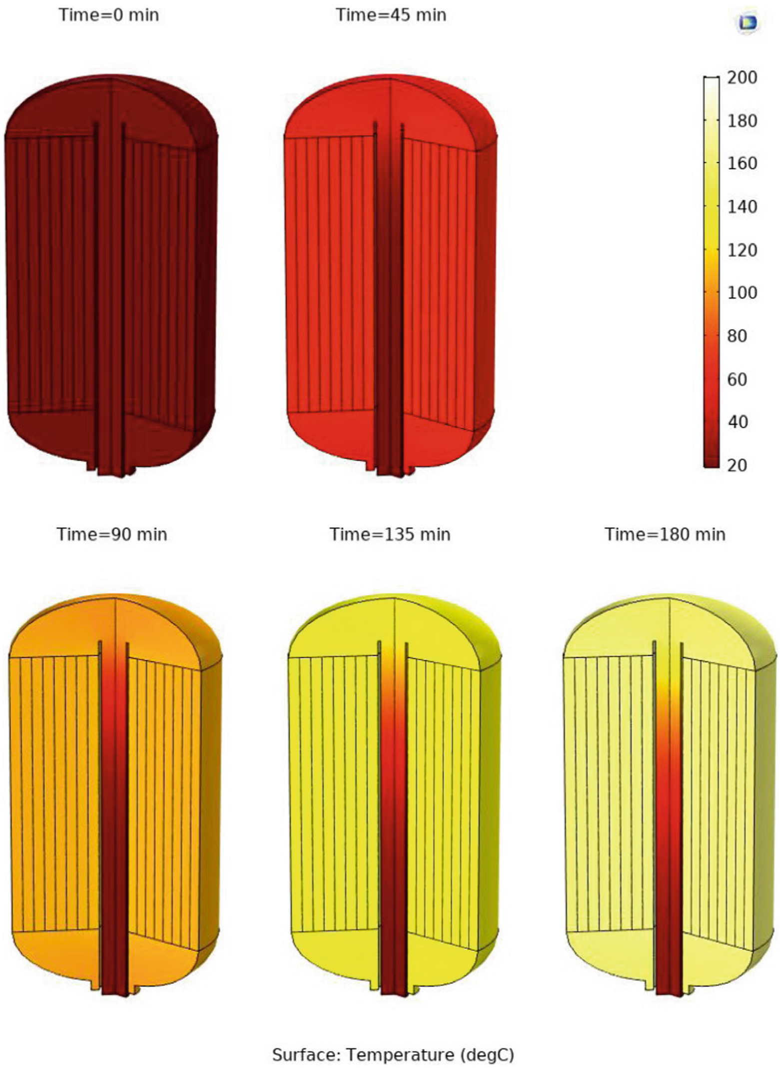

Fig. 6. Dynamics of temperature rise in the volume of the adsorption column under the influence of microwave energy.

The disadvantage of this method is the danger of high voltage electric shock. Therefore, increasing the voltage on the pole plates to the level of hazardous ones (over 60 V) will require complicating the design of the adsorption column. This is due to the need to ensure the safety of the operating personnel and will entail an increase in the cost of the dryer design (Fig. 9).

Also, the dynamics of the growth of the average temperature of the volume of the adsorbent (Fig. 8) are positively affected by a decrease in the distance a between the pole plates (Fig. 3).

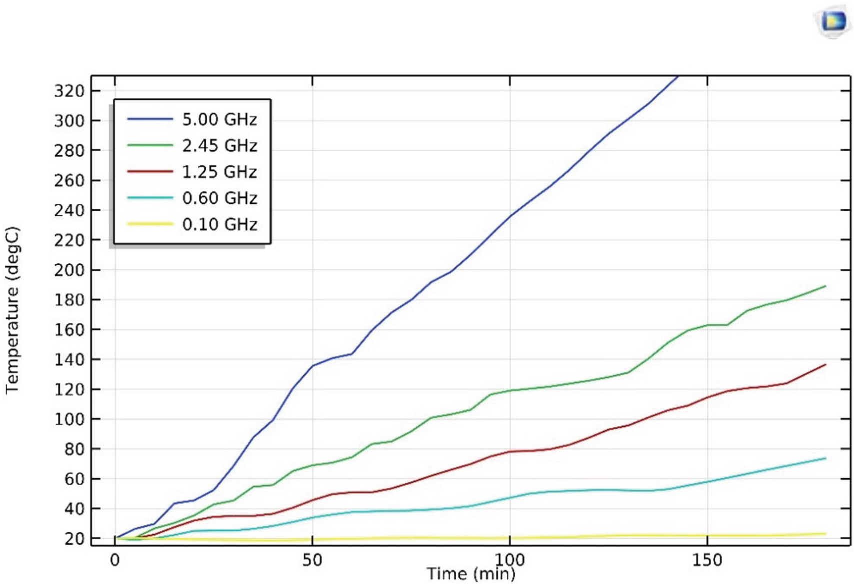

Fig. 7. A figure Dynamics of growth of the average temperature in the volume of the adsorbent depending on the frequency. Voltage (peak) = 4 V, distance between pole plates = 4 mm.

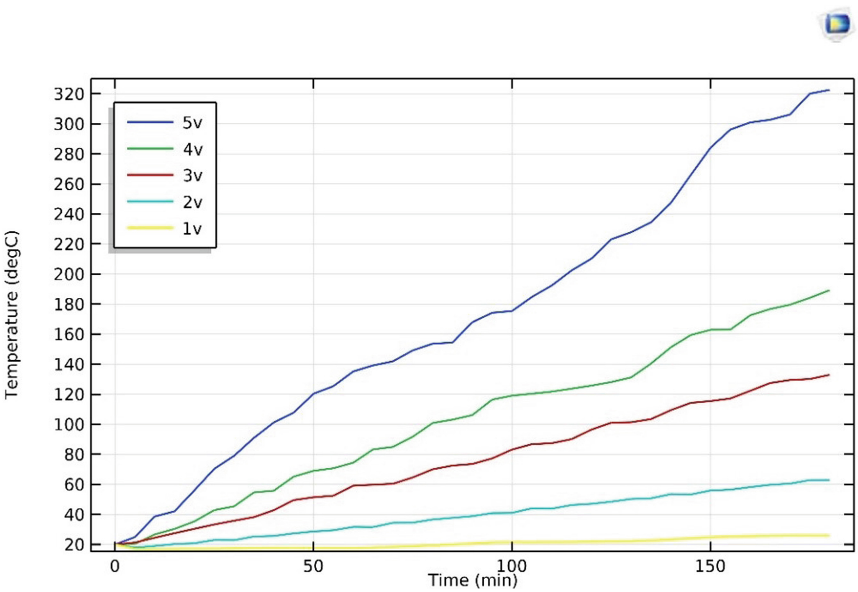

Fig. 8. The dynamics of the growth of the average temperature in the volume of the adsorbent depending on the (peak) voltage on the pole plates. Frequency = 2.45 GHz, distance between pole plates = 4 mm.

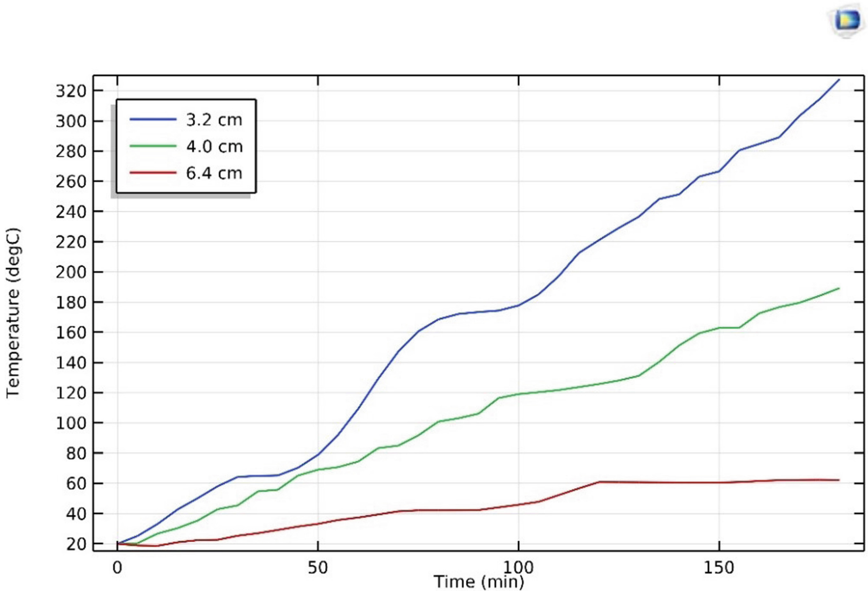

Fig. 9. Dynamics of the average temperature growth in the adsorbent volume depending on the distance between the pole plates. Frequency = 2.45 GHz, Voltage = 4 V.

It should be noted that the specified distance cannot be reduced to a size less than 10 mm, which corresponds to the minimum diameter of the adsorbent granule used in dryers. Also, reducing the distance between the pole plates will require an increase in their quantity. This, in turn, will complicate the design of the equipment and entail an increase in its cost.

5 Conclusions

The presented work shows the possibility of using the energy of microwave radiation during the regeneration of adsorbents applied in compressed air dryers with high productivity, more than 50 m^3/min. It is shown that the impact on the adsorbent using pole plates makes it possible to uniformly distribute energy in a large volume of the adsorbent.

The influence on the intensity of exposure to microwave energy of such factors as frequency and voltage on the pole plates, as well as the distance between them is considered.

The economic effect of the use of microwave energy in the process of regeneration of nanoporous structures is achieved due to the intensification of drying in comparison with blowing with preheated air. Research shows the applicability of the described technology in high throughput adsorption dryers. This opens up opportunities for increasing the efficiency of this type of industrial equipment.