Magnetic-centrifugal drying of compressed air of pneumatic systems of machine-building enterprises

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Abstract. The article analyzes such basic methods of drying compressed air of pneumatic systems of machine-building enterprises as condensation, sorption, diffusion and force action and determines the advantages and disadvantages of each of these methods. It is noted that the method of force action on water particles due to the use of the centrifugal force allows you to remove only droplet moisture, and vaporous moisture remains in the compressed air. With further cooling of the compressed air, condensate reappears in it. Other methods are more efficient, but require consumables or complex devices for drying compressed air, which ultimately leads to an increase in the cost of such devices and an increase in operating costs. Based on the conducted analysis and on the fundamentals of theoretical mechanics, magnetic field theory and molecular physics, a method of magnetic-centrifugal drying of compressed air has been developed. The essence of the method is to use the Lorentz force, which acts on a water particle (a molecule, a dimer, a trimer, etc.) and coincides in the direction with the centrifugal force. When using the safe supply voltage of a 24 V solenoid that creates a magnetic field in which an electrically charged water particle moves, it is possible to increase the radial force (compared to the centrifugal force) acting on this particle by about 70 times. The authors also consider the methods of ionization of water particles that allow knocking out electrons from their outer shells. Experimental studies conducted on a mock-up sample showed a fairly high efficiency of this method, since it was possible to achieve the 3rd class of purity according to ISO 8573-1: 2001.

1. Introduction
When operating pneumatic systems in a cold season, there is a problem of condensate freezing in devices and pipelines located outside the premises, and the failure of the pneumatic system. In addition, condensate can get into the pneumatic actuators of machines and devices, lead to corrosion and, accordingly, to increased wear of moving elements. When wet atmospheric air is compressed, its volume decreases, but the amount of water vapor does not change. As a result, the amount of vapor per unit volume of compressed air increases almost in proportion to the degree of air compression, and often the compressed air becomes supersaturated and condensate is formed. In addition, in compressed air, the saturation state occurs at a higher temperature, which also increases the amount of condensate.

It is obvious that to exclude these phenomena, it is necessary to remove not only the condensate from the compressed air, but also part of the water vapor.

2. Materials and methods

Computational and theoretical studies were carried out using the Mathcad software package. The experimental studies used the HIH-4602-C humidity sensors, the National Instruments NI 6009 data acquisition board, and a computer. In the Labview 2011 program, which is supplied with the board, a scheme was implemented that allows you to connect the HIH-4602-C sensors and process the incoming information from these sensors.

The accuracy of the sensor readings was evaluated by comparison with the readings of a hygrometer and a digital thermometer, which were verified at the Mogilev Analytical Control Center, and the difference in the readings did not exceed 1%. The relative humidity and temperature of the compressed and the atmospheric air were measured.

3. Results

Works [3, 4, 5, 9, 14, 18] deal with four main methods of air drying: condensation, sorption, diffusion and force action. All these methods have their advantages and disadvantages. Let's consider them in more detail. During *condensation*, water is transferred from the vaporous to the liquid state, and then this liquid is collected and then removed. Condensation is carried out by changing air parameters such as pressure or temperature. When the pressure increases by compressing the air, the volume decreases, but the mass of water vapor in the air does not change. As a result, the amount of water vapor in a unit volume of compressed air increases, the air becomes supersaturated and condensate is released. The condensate is then removed and the air expands to atmospheric pressure. This method does not require additional devices – dehumidifiers, which is an undoubted advantage. The disadvantages include the need to install a high-pressure fan, which will lead to increased energy consumption. Also, the cost of such a fan will be higher compared to a conventional fan.

The dew point temperature is known to depend not only on the pressure, but also on the temperature: the lower the air temperature, the less water vapor in the state of saturation can be contained in this air. This property of moist air is the basis for the method of drying air by *condensation through cooling*. The air is cooled below the dew point temperature, and the condensate released during this process is removed with the help of a removal system. This method provides a fairly high degree of drying, but it also has the disadvantage of requiring an additional air cooler. In terms of energy consumption, this method is comparable to recompressing. This method of air drying is used in pneumatic systems of industrial enterprises, as well as to remove water vapor from natural gas [4, 14, 18].

In pneumatic drives of mobile machines, air drying by *sorption* (Latin *sorbeo* – absorb) is widely used, i.e. the absorption of moisture from the air by certain substances (sorbents). There are three types of sorption: adsorption, absorption, and chemisorption. Drying by *adsorption* (Lat. *ad* – on, at; *sorbeo* – absorb) is based on the property of adhesion, i.e. the adhesion of water molecules to the surface molecules of the adsorbent due to the forces of intermolecular interaction. To increase the interaction surface, the adsorbent is made porous. In this case, water particles are retained on the surface of the adsorbent, and chemical reactions do not occur. Silica gels, alumogels, zeolites, and activated carbon are used as adsorbents.

Absorption (Latin *absorptio, absorbere* – to absorb) is based on the absorption of vapors by a liquid absorber called an absorbent. This method is used for drying natural gas, but it is not used in pneumatic systems [5]. *Chemisorption* (chemical sorption) is based on the absorption of water vapor by a liquid or a solid body to form chemical compounds. In pneumatic systems, this method is not used either.

The essence of *membrane diffusion* is based on different sizes of the molecules that make up air. So, the effective size of water, oxygen and nitrogen molecules is 0.3 nm; 0.36 nm and 0.38 nm, respectively. Therefore, water molecules penetrate through the fiber membranes, but nitrogen and oxygen molecules do not. The membrane dehumidifier consists of many thin, hollow fibers, which are made of a strong polymer. The inner surface of the fibers is coated with another polymer that can only pass water molecules. Oxygen and nitrogen molecules move inside the membrane fibers, and water molecules pass through the fiber walls to the outer surface. A small portion of dry air without water molecules is taken away and blown outside the membrane fibers, captures water and is released into the atmosphere. Condensate is not formed with this technology, so there is no problem of its removal. Such dehumidifiers with a fairly simple design provide a high degree of air drying. But for its effective and long-term operation, it is necessary to pre-clean the air from solid particles and oil. Otherwise, the hollow fibers quickly become clogged and oiled, the efficiency of the membrane dehumidifier decreases, and the aerodynamic resistance increases.

Drying due to the *force action* on water particles is widely used in pneumatic systems of mobile and stationary machines. In this case, centrifugal forces of inertia or electrostatic forces are used. In centrifugal dehumidifiers, the air flow is given a circular motion, water particles are thrown against the housing walls due to the centrifugal forces and flow down into the moisture collector. Such dehumidifiers remove moisture only in the form of drops, and the vaporous moisture remains in the air. If a particle is given an electric charge and placed in an electrostatic field, it will be affected by the Coulomb force. This physical phenomenon is used to purify air. The intensity of the electrostatic field in this case should be significant: several tens of kV/m. At the same time, the requirements for the electrical safety of such a device significantly increase, which leads to its complication. The use of the centrifugal forces of inertia in ventilation systems for removing moisture drops is widely represented. Practically the method based on the use of the Coulomb force is not used in ventilation systems due to the complexity and high cost of such a device.

The simplest and the most reliable are dehumidifiers, which implement the method of drying by the forceful action on water particles due to the centrifugal forces of inertia. Centrifugal dehumidifiers in which the air flow is given a circular motion are often used in pneumatic systems. These dehumidifiers are simple in design, they effectively remove moisture in the form of drops, although the removal of vaporous moisture practically does not occur. When the flow of the compressed air moves along a curved trajectory, a centrifugal force F_c, N, acts on the water particle (Fig. 1) [17]:

$$F_c = \frac{mV_0^2}{r} \tag{1}$$

where m is the mass of the water particle, kg; V_0 is the portable (circumferential) velocity of the particle, m/s; r is the radius of the curved trajectory, m.

Dependence (1) shows that it is possible to increase the efficiency of the centrifugal dehumidifier by increasing the $F_ц$, since in this case the smaller particles will settle on the housing walls. An increase in $F_ц$, can be achieved by increasing V_0 or decreasing r. However, a significant increase in V_0 leads to an increase in aerodynamic energy losses due to the internal friction, and these losses depend on V_0^2. With a decrease in r, the channels of the dehumidifier are reduced, which leads to an increase in aerodynamic losses. Experimental studies conducted by the authors have shown that it is possible to increase the $F_ц$ in the centrifugal dehumidifiers used in pneumatic systems by changing V_0 and r by only 12-14 % [9].

It is possible to significantly increase the force acting on a water particle in the radial direction from the center to the periphery by using a magnetic field that acts on electrically charged particles moving in it. If particle 2 with the electric charge q moves along trajectory 1 in a magnetic field with the portable velocity V_0, then it is affected by the Lorentz force F_l (Figure 1). This force is determined using the well-known dependence [1, 2, 12, 19]:

$$\vec{F_l} = q[\vec{V}_0, \vec{B}] \tag{2}$$

where B is the magnetic field induction, Tl.

The modulus of the Lorentz force F_l, N is defined as follows:

$$F_l = qV_0 B \sin\alpha \tag{3}$$

where α is the angle between the vectors V_0 and B, deg.

To realize this phenomenon, it is necessary to give a water particle an electric charge and direct the flow of the compressed air in the magnetic field along a curved trajectory so that the forces of $F_ц$ and $F_л$ coincide in the direction. At the same time, the total radial force acting on the water particle can be significantly increased. In this case, it is necessary to remember that the Lorentz force changes the direction of the particle velocity without changing its absolute value [1]. It is also necessary to take into account that the gravity of G acts on the water particle.

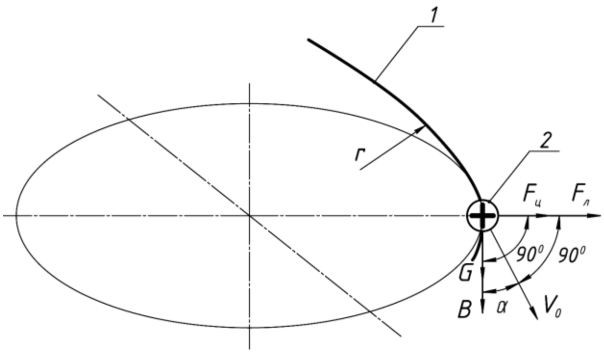


Figure 1. Forces acting on electrically charged particle 2 when it moves in a magnetic field along trajectory 1

This phenomenon is the basis for the development of a method for removing water particles from compressed air by using a magnetic field. In a centrifugal dehumidifier, a charged water particle moves along a spiral trajectory, so to achieve the highest value of F_l ($F_{l.мах}$ is reached at α = 90°), it is necessary for the vector B to be deflected from the axis of the device by an angle not exceeding the angle of elevation of the spiral line corresponding to the trajectory of the water particle with the compressed air flow in the dehumidifier. Obviously, in this case, the force vectors F_l and F_c will have a slightly different direction, i.e., the angle between these vectors will be equal to the angle of elevation of the spiral line. It is quite difficult to ensure that the directions of the F_l and F_c vectors coincide, so to form a magnetic field in the dehumidifier, you can use a solenoid in which the vector B is parallel to the axis of the dehumidifier (Figure 2).

The magnetic induction inside such a solenoid is determined by the well-known expression [1, 2, 19]:

$$B = \mu\mu_0 \frac{Iw}{\sqrt{l_s + D_{ave}^2}} \tag{4}$$

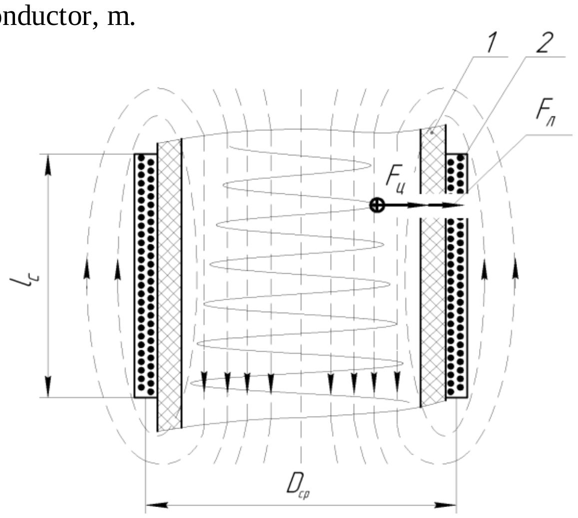
where I is the current flowing through the solenoid winding, A; μ_0 is the magnetic constant, $\mu_0 = 4\pi \cdot 10^{-7}$ N/ A^2 [11]; μ is the magnetic permeability of the medium; for air and paramagnetic materials, take $\mu \approx 1$ [12]; w is the number of turns of the solenoid, pcs.; D_{ave} and l_s are the average diameter of the solenoid winding and the length of the solenoid, respectively, m.

The effective operation of the dehumidifier is possible with a constant direction and the modulus B in time, which is achieved when the constant current I flows through the solenoid winding: $I = U/R$ (U is the voltage applied to the solenoid winding, V; R is the active resistance of the solenoid winding, ohms).

The resistance R is equal to:

$$R = \rho_c \frac{l}{S_c} \quad (5)$$

where ρ_c is the resistivity of the conductor, Ohms ·m; S_c is the cross-sectional area of the conductor, m^2; l is the length of the conductor, m.



1 – housing; 2 – solenoid

Figure 2. The layout of the solenoid for creating a magnetic field in the dehumidifier

Then the current will be determined as follows:

$$I = \frac{US_c}{\rho_c l} \quad (6)$$

Taking into account (6), dependence (4) will have the form:

$$B = \mu\mu_0 \frac{US_c w}{\rho_c l \sqrt{l_s^2 + D_{ave}^2}} \quad (7)$$

Taking into account the fact that $w = \dfrac{l}{\pi D_{ave}}$, we get:

$$B = \mu\mu_0 \frac{US_c}{\pi D_{ave} \rho_c \sqrt{l_s^2 + D_{ave}^2}} \quad (8)$$

The values of D_{ave} and l_s are always limited by the dimensions of the dehumidifier design. Therefore, the maximum value of B can be obtained by increasing U and S_c, since the values of μ and ρ for certain materials of the winding and housing of the dehumidifier are constant values.

Substituting the value of B from dependence (8) in (3), we obtain an equation for calculating the F_l acting on a charged particle of water moving along a curved trajectory in the magnetic field of the solenoid:

$$F_l = qV_0 \sin\alpha \, \mu\mu_0 \frac{US_c}{\pi D_{ave} \rho_c \sqrt{l_s^2 + D_{ave}^2}} \quad (9)$$

The implementation of this method is possible with the implementation of ionization of water molecules. The ionization energy of water molecules E is known and is equal to: E = 12,58 – 12,621 eV ≈ $2 \cdot 10^{-18}$ J [13, 14, 15].

When using electromagnetic radiation as an ionizer, the wavelength λ is determined by the dependence:

$$\lambda = \frac{hc}{E} \tag{10}$$

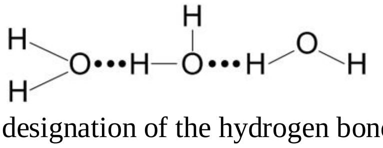
where h is Planck's constant, $h = 6.626 \cdot 10^{-34}$ J·s [10]; c is the speed of light in a vacuum, $c = 3 \cdot 108$ m/s [10].

Substitute the values of h, c and E in (10) and determine $\lambda = 9.94 \cdot 10^{-8}$ m, which corresponds to the wavelength of ultraviolet radiation [13]. Therefore, various ultraviolet emitters can be used to ionize water molecules.

Air is known to compose mainly of nitrogen molecules N_2 and oxygen O_2. The ionization energy of O_2 is approximately 12.1 eV, and N_2 is 15.6 eV [11, 13], i.e., the ionization energy of the molecules N_2 and O_2 is close to the ionization energy of water molecules. Therefore, to irradiate the compressed air flow, it is necessary to choose sources of ultraviolet radiation with a wavelength corresponding to $\lambda \approx 10 \cdot 10^{-8}$ m. In this case, the ionization of the molecules N_2 and O_2 can be avoided.

It should be noted that the masses of the H_2O, O_2, and N_2 molecules are different and amount to $2.993 \cdot 10^{-26}$; $5.315 \cdot 10^{-26}$ and $4{,}651 \cdot 10^{-26}$ kg, respectively [11, 13]. Therefore, when these molecules move along a spiral trajectory in the dehumidifier, the greatest $F_ц$ will affect the O_2 molecule. At the same time, the H_2O molecule is a dipole, which is due to the structure of its electron shells, that contain five pairs of electrons. The first pair is located near the nucleus of the oxygen atom, the second and third pairs form covalent O–H bonds, the remaining fourth and fifth pairs belong to unshared pairs [7]. Due to the presence of a dipole moment in H_2O molecules, the interaction between them is quite strong and is called a hydrogen bond. Therefore, in humid air, dimers, trimers, and polymers of water are most often formed, i.e. $(H_2O)_2$, $(H_2O)_3$ и $(H_2O)_n$ [7] (Figure 3). In the future, we will call these formations the term "water particles". In this case, the $F_ц$ will be proportional to the number of molecules in the water particle and greater than the $F_ц$ acting on the O_2 and N_2. molecules. Therefore, when the compressed air moves in a spiral line, the water particles are the most distant from the center of the dehumidifier. This means that the UV irradiator must be installed at the point farthest from the axis of the dehumidifier. As experimental studies have shown, it is necessary to irradiate the compressed air flow after it passes 1.8...2 turns of the spiral groove after entering the dehumidifier. At the same time, after about two turns, the highest concentration of water particles will be in the area of the irradiator, which will increase the efficiency of ionization.

In the magnetic field of the solenoid, the positive ions and electrons will move in opposite directions to each other.



– designation of the hydrogen bond

Figure 3. Diagram of a water particle (trimmer)

Under the action of F_c and F_l, water particles with a positive charge will fall on the inner wall of the housing, which will be covered with a thin layer of condensate before irradiation. Due to the hydrogen bonds, these water particles will bind to the water molecules of the condensate layer on the inner wall of the housing.

Oxygen is known to have the greatest electron affinity (1.47 eV). For nitrogen, this value is negative and is equal to -0.21 eV [7, 10]. This means that the electrons moving towards the dehumidifier axis will mainly capture the electrically neutral O_2 molecules. This phenomenon was applied by Chizhevsky A.L. in the development of air ionizers, named after the author "Chizhevsky's chandeliers" [16]. The number of O_2 molecules in the moist air stream significantly exceeds the number of water particles, so the problem of removing free electrons does not arise.

Let us analyze the effectiveness of this method. We will consider a water dimer with a single knocked-out electron. In this case, the mass of the dimer is m = 5.986 · 10^{-26} kg [1, 13], and the positive charge is q = 1.6 · 10^{-19} CL [16]. Based on the actual design of a small pneumatic system (for example, a machine tool) with the compressor ЭК 4В-М, we assume the movement radius of the dimer r = 63 mm. To ensure the safety of work, we supply the solenoid with the voltage of U = 24 V. With this voltage and the use of copper wire for winding with S_s = 3.92 · 10^{-6} m^2 and with l l_c = 130 mm, B = 0.018 Tl can be achieved. The compressed air supply is Q_c = 5 · 10^{-3} m/s, the cross-section area of the spiral channel of the dehumidifier is S_c = 0.113 · 10^{-3} m^2, and the angle of elevation of the spiral line is γ = 6º. The cross-sectional area of the spiral channel is assumed from the condition of equality of the cross-sectional area of the pipeline connected to the dehumidifier. The angle γ = 6 ° corresponds on average to the known centrifugal dehumidifiers of pneumatic drives of stationary machines. For such parameters, using equations (1) and (9), we obtain the ratio F_l / F_c = 70.02. This means that the Lorentz force acting on the ionized water particle under consideration is about 70 times greater than the centrifugal force acting on the same particle.

Experimental studies conducted on a mock-up sample showed that the magnetic-centrifugal method of drying the compressed air of pneumatic systems, based on the effect of a magnetic field on electrically charged water particles in the compressed air flow in a centrifugal dehumidifier, makes it possible to provide for a high degree of drying of the compressed air of the pneumatic system to the 3rd class of purity according to ISO 8573-1:2001. At the same time, energy costs are significantly reduced, there are no consumables (adsorbents), and the stability of high values of the degree of drying is ensured throughout the entire operation of the dehumidifier.

4. Conclusion

The use of the magnetic-centrifugal method makes it possible to significantly increase the degree of drying of compressed air, since the total force acting on the water particle is almost two orders of magnitude greater than the centrifugal force. As a result of bench experimental studies of the pneumatic system with the EK 4V-M compressor and a magnetic-centrifugal dehumidifier, it was found that the compressed air at the outlet of the dehumidifier corresponds approximately to the 3rd class of purity according to ISO 8573-1: 2001. When using only a centrifugal dehumidifier, the compressed air at its outlet is in a state of saturation and with further cooling, condensate is formed in it. This condensate entering the elements of the pneumatic drive leads to their corrosion and rapid wear, and in conditions of negative temperatures, the condensate freezes and there is a failure of the pneumatic drive.

This work was carried out at the expense of the budget funds of the Russian Federation and the Republic of Belarus as part of the financing of the teacher's working day.

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