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Method for determining optimal parameters of vortex devices for drying compressed air to reduce operating costs of production processes

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Abstract. For most technological processes, low humidity air is used, obtained in various ways. The possibility of using the vortex effect for drying compressed air used in industrial plants and providing savings in operating costs is shown. A mathematical model of the process for reducing moisture content is developed. A method for calculating the optimal geometric dimensions of the drying device is established. The main goal is to develop an effective device for air drying and calculate its optimal parameters. The developed method of calculation allows one to determine the optimal geometric dimensions of the vortex device for drying compressed air, which is more cost-effective, based on the minimum moisture content under the condition of low hydraulic losses.

1. Introduction

In the modern economy, one of the most important efficiency factors is energy and resource saving, on which the effectiveness of production processes depends. In reducing operating costs on the basis of energy and resource saving, the possibility of using the vortex effect for drying compressed air is considered.

In many production machines compressed air of high, intermediate and low pressure is used as a working medium. The air received such widespread use due to its undeniable advantages: accessibility, ease of use and storage, environmental and fire and explosion safety, sufficient environmental stability (temperature). However, it has a number of significant disadvantages. First of all, it is the presence of moisture (liquid and vapor), which makes it difficult to transport and use air for technical purposes, reduces the reliability of the pneumatic elements. Since water is a good solvent, the solution of impurities (oil, corrosive gases and gas mixtures) in the water causes a corrosive environment in the closed cavities. This results in rapid mechanism wear, failure of the automation and control units, lubrication deterioration of the wearing surfaces of the pneumatic drive elements. In addition, at low temperatures the condensate can freeze and cause failures, equipment downtime, emergencies [1]-[2]. Another disadvantage of compressed air is the presence of dust and other solid contaminants in it, which can cause abrasive wear of parts and elastic seals and, then, an increase in leaks. Thus, drying and cleaning of compressed air reduces the operating costs of production processes.

To avoid negative influence of moisture on various technological processes, it is necessary to exclude the possibility of forming liquid and solid water phases. At present for drying compressed air the following methods are used [3]:

- mechanical;

- adsorptive;
- physical.

Each of the methods is with disadvantages, but has tangible advantages over others. For example, the adsorptive method is very effective, because it is based on the property of silica gel filter to absorb water and water vapor. However, the use of filters causes a large loss of total pressure, resulting in an increase in energy consumption. Also a significant disadvantage of this method is the high cost of filters and the need for their timely replacement. The mechanical method is simple, environment friendly, productive and low-cost, but falls short of adsorption in efficiency. It is in increasing the efficiency of the mechanical method that some authors [4] see the direction of further development of methods for drying compressed air.

2. Problem statement

In this regard, the main goal is to develop an effective device for air drying and calculate its optimal parameters.

The use of vortex chambers for drying air and gases [5]-[6], based on the mechanical method, has become widespread in practice. However, the use of swirling flow does not require additional costs and time for maintenance, element replacement and has no moving parts. It is also characterized by small pressure losses.

It is proposed to use a vortex chamber (Figure 1) with tangential inlet nozzle 1 of rectangular cross section with h height and b width. The length and diameter of the cylindrical chamber part are Lch and Dch, respectively. The following initial data are taken for calculation: the volume flow rate of gas Q, its temperature Tinl and pressure rinl, geometrical specifications of the chamber (length Lch and diameter Dch) and the pressure pa of the medium in which the leak occurs.

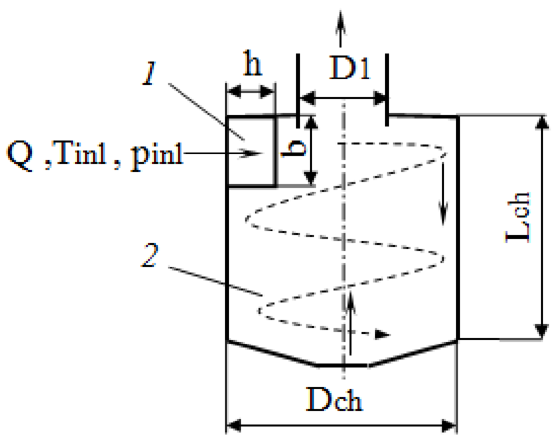

Figure 1. Scheme of the vortex chamber.

3. Theory

In leaking two-phase mixture flowing from the chamber tangential nozzle, a vortex flow, consisting of a liquid film condensing on the chamber wall and the gas core, is formed. Part of the liquid can flow down the end wall of the chamber into its axial area. The formation and retention of this film is due to the strong field of centrifugal forces. Under its acting the condensate injected into the chamber is transferred to its periphery and deposited on the wall. In this case, in the axial flow moisture content will be significantly reduced.

Since the maximum values of the tangential component of the flow rate are achieved in the chamber nozzle section, the peripheral liquid film is formed mainly in the sections of the chamber close to the nozzle ones. In the end chamber sections in the direction of liquid motion, the destruction of the film, the breakdown of drops and their transfer to the axial area are possible. In the vortex chamber, two flows with opposite axial motion, exchanging energy and mass, are formed. In doing so, the axial layers are cooled, and the peripheral ones are heated. The presence of such a radial temperature gradient causes condensation of the liquid phase in the axial flow. The heat released in this case increases the temperature of the axial flow. In addition, part of the fine liquid does not have time to leave the axial flow and leaves the separation chamber through the diaphragm along with the axial flow. The remaining drops fall into the peripheral flow, where they partially or completely evaporate. This causes a decrease in the temperature of the peripheral flow.

Simultaneous processes of condensation and evaporation reduce the radial temperature gradient in the separation chamber. The process of phase separation is carried out mainly by separating the liquid phase on the wall of the chamber. The influence of each process on the total effect of phase separation depends on the parameters of the gas-liquid mixture, as well as the basic geometric dimensions and ratios of the vortex device.

Thus, the presence of a radial temperature gradient in the separation chamber (the Ranque effect), evaporation and condensation processes, disruption and destruction of the liquid film away from the nozzle section, the flow of liquid down the end wall into the axial area will reduce the effect of dehumidification.

Since the efficiency of liquid phase separation in the vortex chamber depends on the ratio of the tangential $V\varphi$ and axial Vr components of the flow rate, the drying effect will be a function of the relative axial flow rate μ. At small values of μ, when the centrifugal forces are large and the axial Vz component of the rate is small, the major part of liquid will concentrate on the walls of the chamber and be carried away with the peripheral flow. With the growth μ (axial flow rate) the liquid entrainment with axial flow is likely to increase.

For calculating one adopted axisymmetric model of the viscous compressible fluid flow in the vortex chamber (Figure 2) for tangential and radial rate components depending only on the radius, i.e. $V\varphi = V\varphi(r)$ and $Vr = Vr(r)$, the axial component (linear in z) and the axial pressure gradient independent of the radius. In the vortex chamber the pressure change at altitude can be neglected, so $p = p(r)$. For simplification we consider the isothermal case, i.e. with a constant value of viscosity ν.

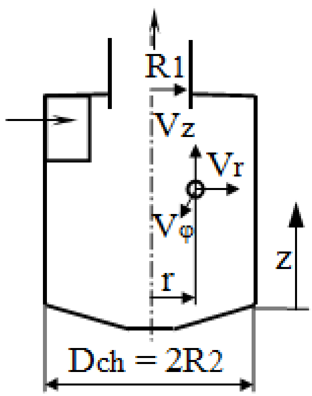

Figure 2. Computational model for vortex chamber.

The problem is solved outside the boundary layer of the end walls for the formed flow, independent of the input structure and having initial values of the rate components at $r = R2$; $V\varphi = V\varphi 2$; $Vr = Vr2$; $Vz = Vz2$.

In this formulation, the continuity and Navier-Stokes equations should be supplemented with the missing boundary conditions:

- there is no axial movement of the liquid on the bottom end cover, i.e. at z = 0 Vz = 0;
- liquid leaves the chamber through a central hole of radius R1 in the upper end cover, i.e. at z = Lch R1≤r≤R2 and Vz = 0;
- the symmetry condition of the problem implies the axis at r = 0 Vr = Vφ = 0.

4. Experimental results

On the basis of this mathematical model the method for calculating optimum geometrical parameters of the drying device was created. The solution of the equations system is cumbersome [7], so the method for calculating the compressed flow is based on the combination of theoretical and experimental results. On the basis of the constructed mathematical model methods for calculating gas-dynamic parameters and optimal sizes of the vortex device were developed, the computer calculating program was developed.

Based on the calculation results, in the case of moist air intake to the vortex chamber (moisture content d = ρc/ρв where ρc is the density of dry gas, ρв is the density of water vapor), with parameters Q = 10 m3/min, Tinl = 293 K, pinl = 0.6 MPa, dinl = 0.64, the following optimum dimensions of the chamber were obtained, with the air moisture content at outlet d1 = 0.004:

Lch = 0.943 m, Dch = 0.093 m, h = 0.037 m, b = 0.018 m.

The initial option variation in the field of optimal value (the other parameters are unchanged) has led to the dependence of moisture content on the outlet of the device d1 and the pressure losses Δp on the following options: pressure at the inlet to the vortex device chamber (Figure 3), the air flow at the inlet of the device (Figure 4), chamber diameter (Figure 5) and the length of the chamber (Figure 6).

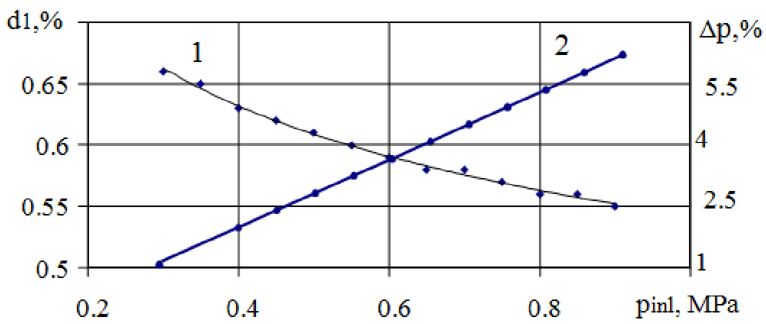

Figure 3. Dependence of the air moisture content d1 (graph 1) and pressure losses Δp (graph 2) on the inlet pressure pinl.

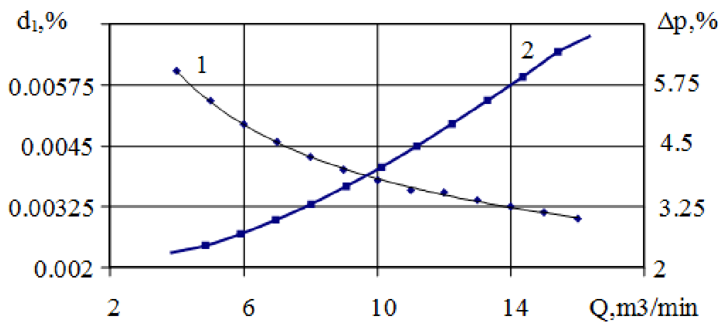

Figure 4. Dependence of the air moisture content d1 (graph 1) and pressure losses Δp (graph 2) on the inlet flow Q.

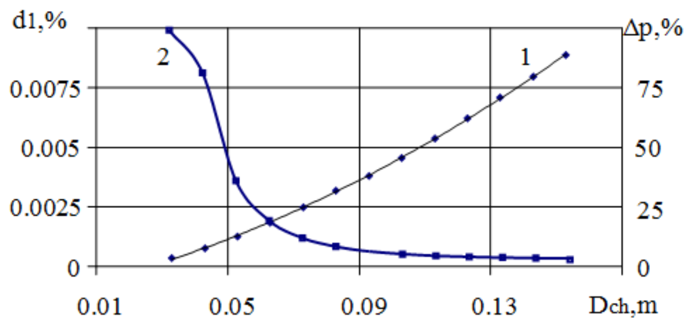

Figure 5. Dependence of the air moisture content d1 (graph 1) and pressure losses Δp (graph 2) on the chamber diameter Dch.

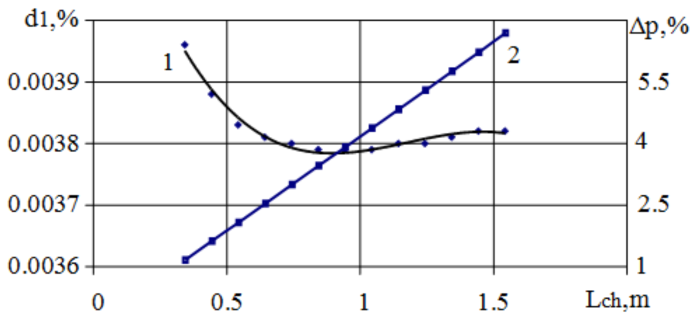

Figure 6. Dependence of the air moisture content d1 (graph 1) and pressure losses Δp (graph 2) of the chamber length Lch.

5. Discussion of experimental results

As shown in Figures 3-6, moisture content reduces with increasing flow rate and inlet pressure, as well as decreasing chamber diameter. This is due to the intensification of swirling processes, an increase in the tangential component of the flow rate. However, the pressure loss increases. In decreasing the length of the chamber from the optimal value, the moisture content increases sharply, since moisture does not have time to condense on the walls. In increasing the length of the chamber from the optimum value, the process of destruction of the liquid film and the breakdown of droplets in the axial region begins, resulting in an increase in moisture content.

6. Conclusion

Thus, the developed method of calculation allows one to determine the optimal geometric dimensions of the vortex device for drying compressed air, which is more cost-effective, based on the minimum moisture content under the condition of low hydraulic losses ($\Delta p \leq 10\%$).

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