Research of the process of creating a vacuum on air-permeable surfaces

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Abstract. A research of the process of vacuuming on air-permeable surfaces is carried out. A mathematical model is presented for calculating the parameters of the gas filtration process through porous surfaces during their vacuumation. This model allows you to calculate the parameters of vacuum systems for gripping devices necessary for reliable capture of breathable materials.

1. Introduction
Vacuuming on air-permeable surfaces is directly related to the filtration of gas through these surfaces. Filtration theory is considered in the section of hydrodynamics devoted to the study of the movement of liquids and gases through porous media [1, 2]. These studies have been conducted for more than 100 years, since filtration phenomena occur both in everyday life and in industry. However, this topic has not been fully studied and requires solving a number of tasks. The study of gas filtration is related to solving problems such as accidents in gas fields, processing inhomogeneous surfaces, as well as the use of vacuum grippers in industry and robotics. Therefore, it is necessary to develop mathematical models for describing and calculating the process of gas movement through air-permeable surfaces at pressure drops.

2. Mathematical model
"Porous medium" refers to a solid material with a complex branched system of connected voids. These voids allow gases and liquids to be distributed unevenly. As a result of the inhomogeneous pressure distribution in porous media, the process of non-stationary filtration occurs [2, 3]. Since the pore structure has a complex system with channels of different sizes and their random distribution over the volume, to study filtration processes, a porous material is considered as a continuous medium with averaged porosity characteristics. The porosity of a medium is defined as the pore volume per unit volume of a solid:

\[ a = \frac{V_p}{V} \]

where \( V_p \) is the pore volume and \( V \) is the total volume of the medium.

To build a mathematical model, we take an air-permeable material as a stationary homogeneous porous medium, and then from the filtration laws, the movement of gases in a porous medium [4] can be described by the following equations:

Continuity equation:
\[ \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \]

The equation of motion of gas:
\[ \rho \left( \frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla) \vec{v} \right) = -\nabla p + \vec{F} + \rho g \]

The equation of energy of a solid medium:
\[ (1 - a) \rho_s c_s \frac{\partial T_s}{\partial t} = \alpha(T - T_s) + (1 - a) \lambda \nabla^2 T_s \]

The energy equation of gas:
\[ \rho c_v \left( \frac{\partial T}{\partial t} + (\vec{v} \cdot \nabla) T \right) = \frac{p}{\rho} \left( \frac{\partial \rho}{\partial t} + (\vec{v} \cdot \nabla) \rho \right) + \vec{F} \cdot \vec{v} + \lambda_g \nabla^2 T - \alpha(T - T_s)/a \]

The equation of state:
\[ p = \rho RT \]

where \( p \) – the gas pressure, \( \vec{v} \) – the gas velocity, \( \rho \) – the gas density, \( \rho_s \) – the density of the solid medium, \( \vec{g} \) – acceleration of free fall, \( \vec{F} \) – the strength of interfacial friction, \( c_v \) – the heat capacity of the gas, \( c_s \) – the heat capacity of the solid medium, \( T, T_s \) – temperatures of gas and solid media, \( \lambda_g, \lambda \) – thermal conductivities of gas and solid media, \( \alpha \) – constant of intensity of interphase heat exchange, \( R \) – the gas constant, and \( \nabla = \partial/\partial x_i \) – the gradient operator for the spatial coordinates.

These equations are derived from filtration laws using a number of simplifications that do not affect the result of modeling:
1. The absence of phase transitions.
2. The interfacial friction force \([5, 6]\) is determined by the gas velocity \( V \) “relative to the porous medium, the size or porosity \( a \), the permeability coefficient of the porous medium \( k [m^2] \), and the dynamic viscosity of the gas mixture \( \mu \):
\[ \vec{F} = a \frac{\mu}{k} \vec{v} \]
3. In the solid phase, the work of internal forces, due to the assumption of immobility of the solid medium, is zero.
4. The thermal conductivity and temperature of a gas and a porous solid medium are constant.

To calculate the gas energy, we take into account the heat capacity of the gas at constant pressure \( c_p \), then:
\[ \frac{p}{\rho} \frac{\partial \rho}{\partial t} = \frac{\partial p}{\partial t} - R \frac{\partial T}{\partial t} \]

where \( R = c_p - c_s \). Hence, the gas energy is calculated from:
\[ \rho c_p \left( \frac{\partial T}{\partial t} + (\vec{v} \cdot \nabla) T \right) = \left( \frac{\partial p}{\partial t} + (\vec{v} \cdot \nabla) p \right) + a \frac{\mu}{k} \vec{v}^2 + \lambda_g \nabla^2 T - \alpha(T - T_s)/a \]

The ability of a porous medium to pass a liquid is characterized by permeability. Its definition is closely related to the basic law of fluid motion in a porous medium, called Darcy’s law. Under certain conditions, this law is valid for both liquids and gases with a steady viscous flow through porous surfaces. Darcy’s law is also called the linear filtration law, which means that the average flow rate of a gas or liquid through a channel is proportional to the pressure difference at the inlet and outlet at
Reynolds numbers $Re << 1$ [4]. Then the stationary gas filtration process can be described by a system of equations:

$$\vec{\nabla} \cdot (\rho \vec{u}) = 0$$

$$\vec{\nabla} p = \rho \vec{g} - a \frac{\mu}{k} \vec{v}$$

$$p = \rho RT$$

3. Results and discussion

A number of devices have been developed and investigated [7 - 10] for automatically opening, holding and closing flexible containers using vacuum grippers (figure 1). In the presented devices, the product is captured due to the difference between atmospheric pressure and vacuum pressure, which is formed between the internal capture cavity and the product plane using a vacuum pump or based on the ejector principle. A vacuum is most often called a region of space filled with gas at a pressure below atmospheric pressure [11].

![Figure 1](image1.png)

(a) flexible container is captured by all sections, (b) flexible container is captured by the central sections, 1 - control cabinet, 2 – pneumatic cylinder, 3 - vacuum gripping device, 4 - flexible container.

Vacuum gripping devices can be suckers or gripping devices with vacuum chambers (figure 2). One of the ways to manufacture such devices can be additive technologies [8]. They allow you to make gripping devices with vacuum chambers made in the form of truncated cones, oriented with their large base to the working surface. The chambers can be positioned in a staggered manner or in a honeycomb to make full use of the area of capture. A large number of vacuum suckers are used to increase the reliability of retention in the event of failure of some of them due to insufficient contact with the gripping surface.
For mathematical modeling of the filtration process by the area of the vacuum suction Cup, let's assume that the process of vacuuming on an air-permeable surface is time-established and has a constant speed, pressure, and other parameters of the filtration process. We project the vacuuming process, where \( P_0 \) - the vacuum pressure, \( P_a \) - the atmospheric pressure, \( u \) - the gas filtration rate per unit of the porous medium, and \( H \) - the height of the porous surface (figure 3).

Then the mathematical description of the vacuum is reduced to:

\[
\begin{align*}
    u &= av \\
    \frac{d(\rho u)}{dx} &= 0 \\
    \frac{dp}{dx} &= -g \rho - u \frac{\mu}{k(x)} \\
    p &= \rho RT
\end{align*}
\]
\[ q = u \rho = \text{const} \]

where \( q \) - the gas flow rate – the volume flowing through the cross – section of the flow per unit time.

Pressure at the boundaries of the porous layer:

\[
q = \frac{p_0^2 - p_a^2 \exp \left( \frac{2g}{RT} \right) \int_0^H \exp \left( \frac{2g}{RT} \xi \right) \frac{d\xi}{k(\xi)}}{2\mu qRT} \]

\[
\rho = \frac{p}{RT} \quad u = \frac{q}{\rho} \]

When a vacuum is formed inside the suction Cup, atmospheric pressure exerts an effect on the surface of the suction Cup pressing it against the plane of the object. The pressure force acts evenly on the suction Cup and on the surface on which it is located on the reverse side, and is proportional to the vacuum level inside the suction Cup. Having vacuum chambers with an area of \( S \) and creating rarefied air in their cavities, it is possible to determine the clamping force by the formula [12]:

\[ F = S(P_a - p_0) \]

However, this formula is only feasible for sealed connections of the vacuum to the surface, that is, in the absence of air suction along the boundary of the vacuum chamber. If this phenomenon is taken into account, it is necessary to Refine and Supplement the mathematical model, which is the goal of further research.

4. Conclusions
Modeling of gas filtration under vacuum on a breathable surface, namely the gas flow in micro channels of woven material of the container, allow to calculate the flow and speed of gas flowing through the breathable surface, the maximum achievable force of the vacuum pressure of the vacuum chamber at known parameters of the vacuum system, as well as to identify the characteristic flow regimes in micro channels.

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