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Development of a new-generation vacuum pump for degassing units

Abstract. The paper investigates the process of manufacturing tubular fiber-reinforced polymer products in a rotor-type installation using a controlled vortex air flow. The physical features of the motion of discrete fiber elements in a confined working space are analyzed, and the conditions of their deposition on the inner surface of the forming element are determined. The design features of the installation are described, ensuring the formation and stabilization of the vortex flow, as well as the implementation of compaction and impregnation processes. A mathematical description of the process is proposed based on classical mechanics equations adapted to the operating conditions of the installation. The obtained relationships establish a connection between the rotor speed, geometric parameters of the working space, and the conditions of layer formation. The results can be used to justify operating parameters and optimize the manufacturing process of fiber-reinforced polymer products.

Keywords: fiber-reinforced polymer products, vortex flow, rotor installation, forming, fiber deposition, polymer matrix, mathematical modeling

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Introduction.

The increasing requirements for the performance characteristics of modern materials determine the active development of technologies for manufacturing composite products, particularly tubular structures reinforced with fibers. Such products are characterized by high strength, corrosion resistance, and durability, which explains their wide application in various industries.

At the same time, traditional methods of manufacturing composite materials, including filament winding, pressing, and centrifugal forming, have several disadvantages related to technological complexity, limited control over material structure, and

high energy consumption. In this regard, the development of new forming methods that ensure better control over the distribution and orientation of reinforcing elements is highly relevant.

One of the promising approaches is the use of vortex air flows, which enable transportation, orientation, and deposition of discrete fiber elements within a confined space, leading to the formation of a uniform material structure.

Review of the research sources and publications

The issues of manufacturing polymer composite materials are widely covered in scientific studies devoted to forming and processing technologies of

reinforced structures. Works [1–6] present general principles of composite material formation and their structural characteristics. Studies [7–10] focus on the analysis of fiber placement methods and the formation of reinforcing frameworks.

A separate group of studies is devoted to the motion of particles in air flows and their deposition on surfaces [11–15]. These works demonstrate that flow characteristics significantly influence particle trajectories and layer formation.

However, existing approaches do not provide a comprehensive consideration of the influence of equipment design parameters and operating conditions on the process of forming tubular products. This necessitates the development of a method that integrates physical process description with installation parameters.

Definition of unsolved aspects of the problem

The aim of this study is to investigate the process of forming tubular fiber-reinforced polymer products in a rotor-type installation by establishing the relationship between physical process parameters and the structural characteristics of the equipment using a mathematical description.

Problem statement

The purpose of this work is to determine the main regularities of the process of forming fiber-reinforced polymer products based on the analysis of structural and operational parameters of the developed device using mathematical modeling of airflow motion and discrete fiber elements, which allows establishing the relationship between process parameters and quality characteristics of the formed layer.

Basic material and results

The process of forming a tubular fiber-reinforced polymer product occurs in a confined working space

where a controlled vortex air flow is created (Fig. 1). Discrete fiber elements are introduced into this space and, under the influence of airflow, acquire complex spatial motion.

Under the action of aerodynamic forces, fibers are entrained by the flow and move along trajectories with both axial and tangential components. During movement, they gradually shift toward the peripheral zone of the working space, where a perforated cylindrical mold is located.

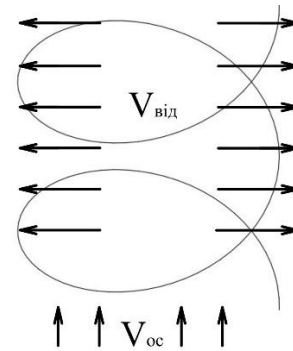


Figure 1 – Scheme of vortex flow motion in the working space

Upon reaching the inner surface of the mold, fiber elements are deposited and form a primary layer. After that, the layer is compacted with compressed air and impregnated with a liquid polymer. Repeated cycles allow forming a multilayer structure of specified thickness.

The novelty of the study lies in the first adaptation and application of a mathematical description of vortex airflow motion and discrete fiber elements to the process of forming tubular fiber-reinforced polymer products implemented in a device protected by a Ukrainian patent [19].

The equipment (Fig. 2) includes a frame (1), drive (2), bowl (3), and polymer supply tank (4).

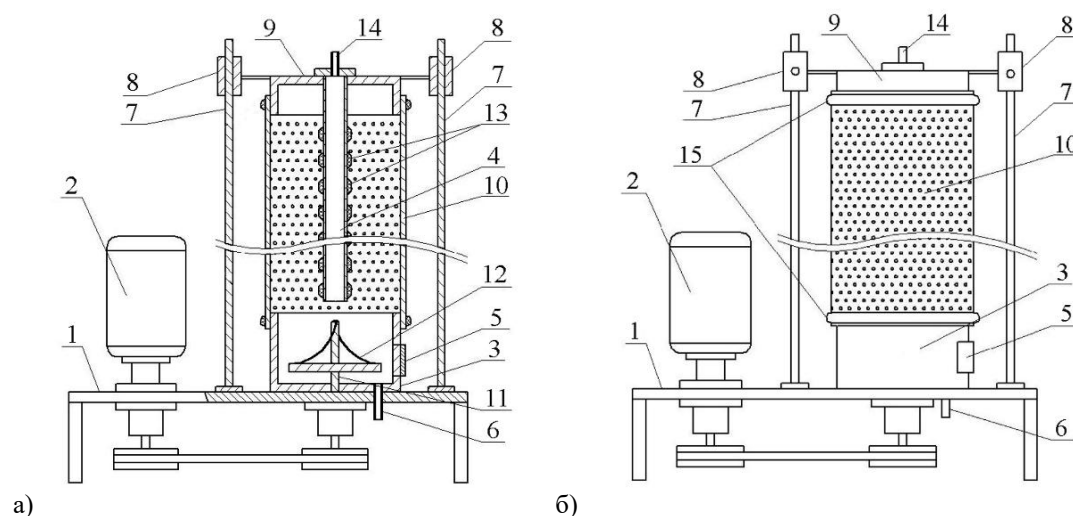


Figure 2 – Equipment scheme: a) section view; b) general view
 1 – frame; 2 – drive; 3 – bowl; 4 – polymer tank; 5 – loading opening; 6 – compressed air pipe; 7 – guides; 8 – brackets; 9 – cover; 10 – perforated cylinder; 11 – shaft; 12 – rotor; 13 – nozzles; 14 – check valve; 15 – clamping rings.

The rotor generates a vortex airflow inside the working space.

The equipment consists of a frame (1) on which a mechanical rotation drive (2), a bowl (3), and a container (4) for polymer supply are mounted. The bowl (3) is cylindrical in shape and is equipped with an opening with a shutter (5) for loading fiber elements, as well as a nozzle (6) for supplying compressed air. Guide rails (7) are also mounted on the frame (1), between which a cover (9) is fixed by means of brackets (8), with the possibility of its movement along the guides (7). The cover (9) has the same diameter as the bowl (3). A perforated PVC cylinder (10) is installed between the cover (9) and the bowl (3) for product formation. The perforations of the cylinder (10) are intended to relieve excess pressure on the inner surface of the cylinder wall and promote uniform distribution of fiber elements over its inner surface. Clamping rings (15) (Fig. 2b) are most commonly used to form the working space and ensure reliable connection of the bowl (3), the cover (9), and the perforated cylinder (10).

In the lower part of the perforated cylinder (10), there is a shaft (11) with a rotor equipped with blades (12) mounted on it, designed to generate a complex vortex air motion within the working space. In the upper part of the perforated cylinder (10), the container (4) for polymer supply is installed, which is equipped with nozzles (13) and a check valve (14). The container (4) serves as a means of introducing liquid polymer into the working space and contributes to the formation of circular motion of the fiber–air mixture.

In the lower part of the working space, a rotor with blades is installed, driven by a mechanical drive. The rotation of the rotor ensures the formation of a vortex air flow with a complex structure.

In the upper part of the device, a polymer supply system equipped with nozzles is installed, ensuring uniform spraying of the liquid phase. Additionally, a nozzle for supplying compressed air is provided, which is used to compact the formed layer.

The perforated cylinder performs a dual function: shaping and relieving excess pressure, which contributes to stabilization of the forming process.

To determine the parameters of the air flow in the working space of the device, the classical hydrodynamics framework is used, in particular the Navier–Stokes equations [9,10, 16], which describe the motion of a viscous fluid or gas. In general form, they can be represented as:

$$\rho \left(\frac{d\vec{v}}{dt} + (\vec{v} \cdot \nabla) \vec{v} \right) = -\nabla p + \mu \nabla^2 \vec{v} \quad (1)$$

where:

- ρ - air density (kg/m³);
- \vec{v} - velocity vector (m/s);
- $\frac{d\vec{v}}{dt}$ - local acceleration;
- $(\vec{v} \cdot \nabla) \vec{v}$ - convective acceleration;
- p - pressure (Pa);
- μ - dynamic viscosity (Pa·s).
- $\nabla^2 \vec{v}$ - velocity diffusion operator.

In the case under consideration, the air motion can be assumed quasi-steady; therefore, the term $\frac{d\vec{v}}{dt}$ may be neglected. Due to the rotation of the rotor, a vortex flow is formed within the working space, which is characterized by the presence of a tangential velocity component.

The tangential velocity of the air flow is determined by the following relation:

$$v_{\theta} = \omega r \quad (2)$$

where:

- v_{θ} - tangential velocity, m/s;
- ω - angular velocity (rad/s);
- r - radial coordinate (distance from the axis of rotation), m.

From the given relationship, it can be seen that the air velocity increases with increasing radius, which causes the movement of fiber elements toward the walls of the forming cylinder.

To describe the motion of an individual fiber element, Newton's second law is applied [11-15], according to which the equation of motion takes the following form:

$$m \frac{d\vec{u}}{dt} = \vec{F}_c + \vec{F}_d + \vec{F}_g \quad (3)$$

where:

- m - mass of the fiber element, kg;
- \vec{u} - velocity of the fiber element, m/s;
- \vec{F}_c - centrifugal force;
- \vec{F}_d - aerodynamic drag force;
- \vec{F}_g - gravitational force.

The centrifugal force acting on a fiber element in a vortex flow is determined by the following expression:

$$F_c = m\omega^2 r \quad (4)$$

where:

- ω - angular velocity of rotation, s⁻¹;
- r - distance from the axis of rotation, m.

This force is the determining factor in the movement of fibers toward the peripheral zone.

The aerodynamic drag force, which opposes the motion of a particle relative to the air flow, can be determined by the following formula:

$$F_d = \frac{C_d \rho A}{2} (v - u)^2 \quad (5)$$

where:

- C_d - drag coefficient;
- ρ - air density, kg/m³;
- A - characteristic cross-sectional area of the fiber, m²;
- v - air flow velocity, m/s;
- u - velocity of the fiber element, m/s.

The condition for effective deposition of fiber elements on the inner surface of the perforated cylinder is determined by the relationship between the centrifugal force and the drag force. Deposition occurs

when the centrifugal force exceeds the aerodynamic drag force:

$$m\omega^2 r > \frac{c_d \rho A}{2} v^2 \quad (6)$$

This relationship makes it possible to determine the minimum angular velocity of the rotor required to ensure stable layer formation.

To generalize the conditions of motion and deposition of fiber elements, it is reasonable to consider the ratio of the centrifugal force to the aerodynamic drag force, represented by a dimensionless deposition criterion of fiber elements:

$$K_f = \frac{F_c}{F_d} \quad (7)$$

Substituting the corresponding expressions, we obtain:

$$K_f = \frac{m_f \omega^2 R}{\frac{1}{2} c_d \rho (\omega R)^2 A} \quad (8)$$

After simplification, we obtain:

$$K_f = \frac{2m_f}{c_d \rho A R} \quad (9)$$

The proposed expression is of fundamental importance, as it shows that the criterion K_f does not depend on the angular velocity of the rotor. The angular velocity affects the intensity of the process but does not change the fundamental possibility of fiber deposition.

After the deposition of fiber elements on the surface of the mold, a fibrous layer is formed, which is characterized by a certain surface density. It is defined as:

$$\sigma = \frac{m_f}{S} \quad (10)$$

where:

- σ - surface density of the layer, kg/m²;
- m_f - mass of deposited fiber elements, kg;
- S - area of the inner surface of the cylinder, m².

The next stage of the process is layer compaction under the action of compressed air. The change in surface density due to compaction can be described by the following relationship:

$$\sigma = \sigma_0(1 + kP) \quad (11)$$

where:

- σ_0 - initial surface density of the layer, kg/m²;
- k - empirical compaction coefficient;
- P - compressed air pressure, Pa.

At the final stage, the formed layer is impregnated with a liquid polymer. The process of polymer penetration into the porous structure of the layer is described by Darcy's law [16, 17]:

$$Q = \frac{k_p A \Delta P}{\eta L} \quad (12)$$

where:

- Q - volumetric flow rate of the polymer, m³/s;
- k_p - permeability coefficient of the layer, m²;
- A - impregnation area, m²;
- η - pressure difference, Pa;
- ΔP - pressure difference, Pa;

L - layer thickness, m.

Based on the proposed mathematical model of the process of forming tubular fiber-reinforced polymer products, analytical calculations were carried out to determine the influence of design and technological parameters of the installation on the behavior of fiber element deposition and the formation of the material layer.

According to the calculation results, graphical dependencies were obtained (Figs. 3, 4), which make it possible to clearly evaluate the influence of process parameters and confirm the adequacy of the proposed approach.

The analysis of the presented graphical dependence shows that with an increase in the cylinder radius, the value of the K_f criterion decreases monotonically. This behavior is explained by the reduction of the relative influence of inertial forces on the fiber elements as the geometric dimensions of the working zone increase. This allows us to conclude that it is necessary to reasonably select the dimensions of the perforated cylinder (item 10 in Fig. 2) at the design stage of the installation.

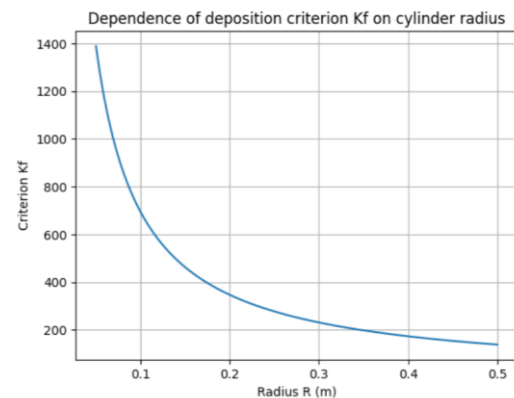


Figure 3 – Dependence of the deposition criterion K_f on the radius of the perforated cylinder

In addition, based on the material balance equation of the layer formation process, a relationship was obtained between the thickness of the formed layer and the mass of the supplied fiber elements.

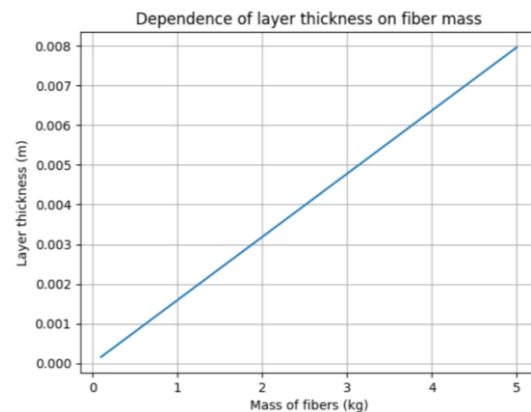


Figure 4 – Dependence of the formed layer thickness on the mass of the supplied fiber elements

The graphical dependence is linear, indicating that the layer formation process can be controlled by dosing the fiber material, and also allows predicting the geometric characteristics of the finished product at the stage of technological process design.

The graphical dependence is linear, indicating that the layer formation process can be controlled by dosing the fiber material, and also allows predicting the geometric characteristics of the finished product at the stage of technological process design.

Conclusions

The paper proposes a substantiated approach to studying the process of forming tubular fiber-

reinforced polymer products using a mathematical model based on classical equations adapted to vortex flow conditions.

Unlike previous studies [1–15], this work integrates these models considering aerodynamic fiber deposition in a single technological process implemented in a patented device [19].

The approach allows establishing relationships between structural and operational parameters and product characteristics, enabling transition from laboratory to industrial scale without full-scale experiments.

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Дослідження процесу формування трубчастих фіброполімерних виробів у роторній установці з вихровим повітряним потоком

Анотація. У статті розглянуто процес формування трубчастих фіброполімерних виробів у роторній установці з використанням керованого вихрового повітряного потоку. Досліджено фізичні особливості переміщення дискретних фібрових елементів у замкненому робочому просторі та встановлено умови їх осадження на внутрішню поверхню формуючого елемента. Розкрито конструктивні особливості установки, що забезпечує створення та стабілізацію вихрового потоку, а також реалізацію послідовних технологічних операцій ущільнення та просочування сформованого шару. Запропоновано математичний опис процесу, який базується на використанні стандартних рівнянь механіки з урахуванням конструктивних параметрів установки та режимів її роботи. Отримані залежності дозволяють встановити взаємозв'язок між частотою обертання ротора, геометрією робочого простору та умовами формування шару матеріалу. Результати дослідження можуть бути використані для обґрунтування параметрів роботи обладнання та оптимізації процесу виготовлення фіброполімерних виробів

Ключові слова: фіброполімерні вироби, вихровий потік, роторна установка, формування, осадження волокон, полімерна матриця, математичне моделювання.

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