Assessment of energy efficiency and environmental impacts of cotton processing pneumatic systems for sustainable manufacturing

Khasanboy Yuldashev[1*], *Elyorbek* Shamsiddinov[2], *Vitaliy* Kalashnikov[2], *Dilshodbek* Ergashev[2], and *Khusanboy* Khaydarov[2]

[1]Department of Textile Industry Technology, Namangan State Technical University, 160103, Namangan, Uzbekistan
[2]Department of Mechanical Engineering Technology, Andijan State Technical Institute, 170119, Andijan, Uzbekistan

Abstract. This research examines the environmental and operational impacts of cotton handling processes on pneumatic conveying systems, particularly in the context of transporting raw cotton to gins, which are recognized as a fundamental component of the cotton textile industry. The study examines the impact of pipe diameter on air velocity, energy consumption, and system efficiency. Theoretical analysis shows that increasing pipe cross-sectional area results in increased air and energy consumption, while diameter optimization can significantly reduce energy consumption. Despite using a larger-than-necessary pipe diameter (d = 0.4 m) to prevent clogging and ensure stable air mixture formation, the results indicate that improved uniform cotton feeding can allow the use of narrower pipes without compromising flow performance. This contributes to increased energy efficiency, reduced operating costs, and a reduced environmental impact—key factors in developing more sustainable and environmentally responsible cotton handling systems in the textile industry.

1 Introduction

Cotton fiber is used to make textile products worldwide. The "International Consultative Committee on Cotton" (ICAC) reports that around 24.0 million tons of cotton fibers have been produced globally in recent years. There are roughly 18.0 million tons of inventories and about 25.0 million tons of consumption. Future demand and consumption of cotton fiber are predicted to rise as a result of the population's rapid growth. Because of this, manufacturers of fiber put a lot of effort into modernizing their goods, increasing the competitiveness of cotton fiber on the international market, and creating new technologies that result in products that are modern, reliable, and of high quality. The country development of the textile industry, 2022 - 2026 increases the volume of production and export of textile

* Corresponding author: yoldashev93992020@mail.ru

industry products in 2026 to establish a full processing of yarn in the country itself... tasks are defined" is part of the new Uzbekistan's development strategy for 2022 –2026.

This initiative aims to increase the production of textile and light industrial products by creating cotton-textile clusters in our nation. It is crucial to build a resource-efficient pneumatic transport pipeline construction method to boost the efficiency of the cotton transportation process and guarantee the completion of these jobs.

Cotton conveying systems are made up of different kinds of machinery aimed at transporting cotton in large quantities throughout various phases of the processing chain. As cotton is a bulky and fibrous substance that poses challenges for manual handling, these conveying systems facilitate the process, minimizing the chances of contamination and physical harm to the fibers.

2 Materials and methods

Additionally, these systems reduce labor costs and improve efficiency, ensuring that cotton moves quickly through the entire production process. A key aspect of cotton industry equipment is its ability to process raw materials at high speeds—from 12 to 30 m/s—which makes some interactions inevitable [1].

It is recommended to determine optimal speeds for these processes while preserving the natural properties of the seeds and fibers. Cotton is known to be significantly damaged at higher speeds, so the speed in pneumatic conveying systems and cleaning equipment is typically limited to 25 m/s.

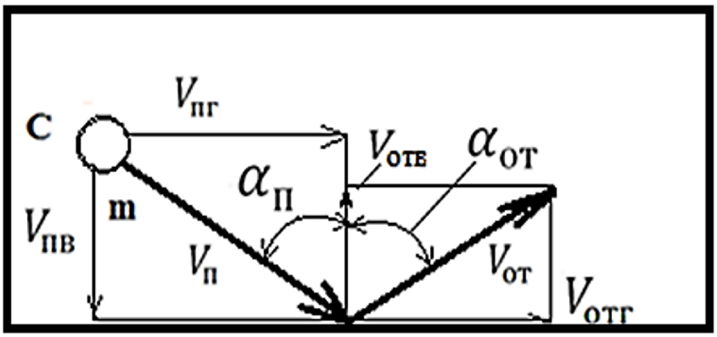

Fig. 1. Cotton's shocking impact on the pipe's inner wall.

Figure 1 shows how a mass of cotton moves through a pneumatic transport system and hits the inside of a pipe. As the cotton tufts or fibers travel with the airflow, their speed and direction change based on their mass, shape, and resistance to air. When a cotton particle nears the pipe wall, its movement can be split into vertical ($V_{ов}$) and horizontal ($V_{ог}$) parts, depending on its approach angle ($\alpha_о$) and speed ($V_о$). Some kinetic energy is lost when the cotton hits the pipe due to deformation and friction, while the rest helps it bounce back. The rebound speed ($V_{от}$) also has two parts: tangential ($V_{отγ}$) and normal ($V_{отв}$), and it moves away from the wall at a new angle ($\alpha_{от}$).

The traditional theory of shock does not study the shock itself; rather, it examines the state of the material item both before and after the shock. It can be acquired using the following equation:

$$m(V_1 - V_2) = \int Fdt = Ft^*_{уд} \tag{1}$$

where V_1 is the speed up to the impact,

V_2 - speed after impact,

F - impact force,

$t*$ - stroke time, 0.000001 ÷ 0.00001 s.

The impact force must be very high at such small values $t*$, but until our work, this magnitude had not been accurately measured [3]. The experimental value obtained with tube sensors and high-frequency equipment $t*$ was 0.0025–0.003 s; its large value exceeds the above indicator and varies in the range of 20–130 cN. This matches the account books as stated in (1).

From (2.21) $V_2 = kV_1$ from originating.

$$mV_1(1-k) = Ft_z \quad =>$$

$$F_3 = \frac{mV_1(1-k)}{t_3} \tag{2}$$

The coefficient of recovery in this case is k.

The mass comes out to be 0.75÷3 grams when the coefficient of recovery is calculated in the 0÷1 range at a step of 0.1. It is evident that at a cotton ball impact time of 0.0025÷0.003, the impact force shifts $t*$ to 4200÷10500.

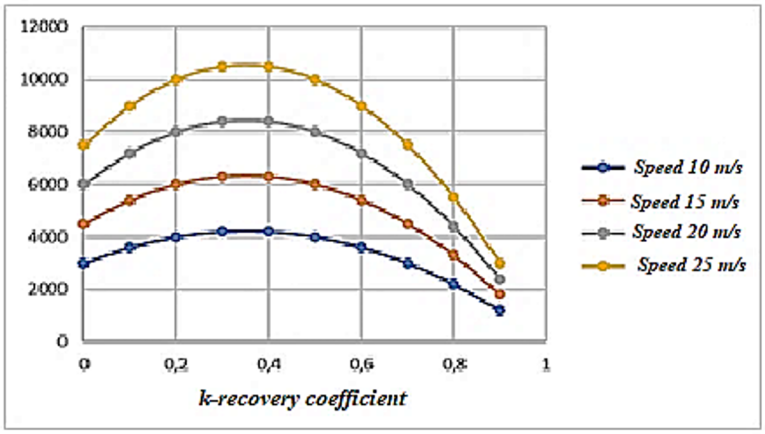

Fig. 2. Variation in shock force according to speed and recovery coefficient.

Figure 2 shows that the impact force is greatest at these recovery coefficient values and will equal the value when the speed is 25 m/s. The impact force is lowest at these values of the recovery coefficient and is 10 m/s [2].

Figure 3 shows the impact force's range of influence at four distinct speeds based on the weight of the cotton piece moving in the pneumatic transport, as indicated by the recovery coefficient values above. This indicates that a piece of cotton weighs between 1.75 and 1.5 kg when the impact force is between 4200 and 10500.

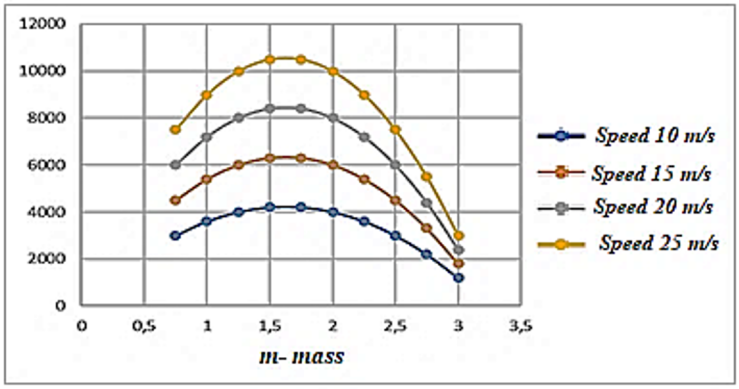

Fig. 3. Impact force variation concerning cotton ball weight and speed.

A good chance to analyze is the approach velocity V_1 and return in the direction normal to the surface V_2, as demonstrated by the effective use of classical shock theory. It is possible to accurately determine the recovery factor ratio k with $V_2 = kV_1$ accuracy $k < 1$. Because of its simplicity, this model is also frequently used to describe shocks. According to tests, cotton ginning businesses in the Republic move raw materials for cotton multiple times using pneumatic transportation [3]. The quantity of cotton transported via pneumatic transport might reach 4-6 times, depending on how close the workshops and cotton warehouses are to one another.

Pneumatic devices, depending on the near-far distance of transportation, centrifugal fans with a power of 30, 55, or 75 kW/h and air consumption of 3.5, 5.5, or 6.4 m 3 /s are used by the VS-8M, VS-10M, and VS-12M types. Steel pipes with an internal diameter of 0.4 m and a thickness of 2-3 mm make up material conductors, often known as pipes. The requirements of transportation via the pipeline at various stages and pneumatic systems of raw cotton materials have been the topic of numerous researches. We apply engineering computations to examine this paper based on the concepts and suggestion from our earlier research.

One of the most important characteristics of pneumatic equipment is its ability to handle materials. It is described as follows:

$$P = \frac{M}{t} \tag{3}$$

Where t is the transportation time and M is the weight of the cotton. Calculate the mass of the cotton along the entire length of the pipe using this integral:

$$M = \pi R^{\alpha} \int_0^L (1 - m) y dx \tag{4}$$

The flow equation m should be used to ascertain the medium's porosity v_0, which is the raw cotton material. The following equivalence is true in the stationary transfer mode if the pipe's rate and the raw material's beginning feed rate are known at any cross-section v:

$$1 - m = (1 - m_0)\, v_0 \gamma_0 / \gamma \;\; v \tag{5}$$

This section examines the porosity and density of the cotton raw material at the pipe inlet, as well as the velocity and density at any particular segment of the pipe, applying the additional equations mentioned earlier. Based on these equations, the volume taken up by the raw material can be determined, assuming that the density and flow velocity of the substance within the pipe remain unchanged. $m_0 \gamma_0$ the porosity and density of the cotton raw material, at the pipe inlet are determined, as are the velocity and density of the raw material at a selected section of the pipe, which are calculated using the additional equations described earlier. If

density and velocity of raw material remain constant along the entire length of pipe, then the equations $v = v_0, \gamma = \gamma_0\ m = m_0$, and $M = \pi R^2(1 - m_0)L\gamma_0$ are applicable, and the volume occupied by the raw material can be expressed as follows:

$$V = M/\gamma_0 = \pi R^2(1 - m_0)L \tag{6}$$

Since $V/V_k = (1 - m_0)$ 100 is the pipe volume, $V_k = \pi R^2 L$ is equal to the fraction (in percent) of the volume of the raw material along the pipe. If at the transmission limit $m_0 =$ 0.7 (70%) $v_0 = v_0$ (the speed of the raw material is equal to the speed of its transmission and does not change), the raw material 30% occupies part of the volume of the pipe. If the speed of the raw material $v = nv_0$increases to $\gamma = \gamma_0$ ($n \geq 1$)) and taken as $V/V_k = (1 - m_0)/n$ we obtain the equation. In particular, $m_0 = 0.7, n = 1.5$ at 20%.

The functioning of the separator, the final component of the pneumatic device, determines the conveying process's throughput (this indicator is also called throughput). The exisitng separator equipment has the following productivity: SS-15A type separator is 15 t/h, and SX type separator is 22 t/h.

The drying machine (type 2 SB-10, SBO)has a throughput of 10 t/h, the cotton spearator (battery) has a thoughput of about 10 t/h, and the small trash cleaning machines UXK and 1XK have productivity of 5-7 t/h. When the less productive muchines are completely loaded, surplus cootn builds up in front of htem due to the porcess machine's varying throughput.

This is therefore unfeasible since it couses wirk areas to become overcrowded and poses a fire risk. As a result, estimates are based on P = 10 - 12 t/h, which is the maximum throughput of the majority of machinery and eauipment.

P= (10÷12) t/s = 2.78÷3.33 kg/s is the productivity number converted to kg/s. If the ratio of transport distance to the speed is used to determine transport time:

$$\mathrm{M} = \frac{\Pi \cdot t}{V_{\mathrm{M}}} \tag{7}$$

The weight of cotton matches the length of the M-tube. This *l* formula holds under these circumstances: $\lambda > 0;\ v_m > 0$.

In our previous research, we measured the cotton and air velocities at the pipe inlet. The velocity at the pipe inlet is equal to the speed of infeed conveyor. The conveyor speed used is 3 m/s. The air pressure causes the cotton's velocity to 4.5 m/s, after an interval of 1m. Considering the mean velocity, v_m = 3.75 m/s. In this case, the output is P = 2.78 kg/s, when l = 1 m.

$$\begin{aligned} &M = \frac{2.78 \cdot 1}{3.75} = 0.74\ kg; \\ &P = 3.33 \text{ kg/s},\ l = 1 \text{ m} \\ &M = \frac{3{,}33 \cdot 1}{3.75} = 0.89\ kg. \end{aligned} \tag{8}$$

Based on the data obtained, the transportation of cotton through pneumatic systems yields a weight of only 0.74 to 0.9 kg for each meter of pipe [4]. Our earlier studies indicated that the density of cotton emerging from the gin is roughly γ= 35 kg/m³, and if the mass of the cotton is M = 0.74 to 0.9 kg, the volume of this material can be calculated as follows:

$$\mathrm{V} = \mathrm{M} / \gamma = (0.74 - 0.9)/35 = 0.021\text{-}0.026\ \mathrm{m}^3.$$

The pipe has a volume of $V = 1 \cdot p \cdot r^2 = 1 \cdot 3.14 \cdot 0.2^2 = 0.1256\ \mathrm{m}^3$ and is 1 meter in length. We calculate their percentage ratio:

$$\Delta V\,\% = (17.6 - 20.7)\% \tag{9}$$

s

3 Results and discussion

As the cotton moves through the pipe, its speed rises while the airspeed falls. A Cotton's density is halved (γ 36/2 = 18 kg/m³), and its porosity doubles (from 0.4 to 0.8) over a distance of 50 meters. As air velocity decreases to 15 m/s, the cotton velocity reaches approximately 9–10 m/s (with an average velocity of approximately v_m = 6.5 m/s). If we perform calculations using the following parameters:

$$M = \frac{(2.78 \div 3.33) \cdot 50}{6.5} = 21.38 \div 25.62\ kg \quad (10)$$

The space taken up by cotton is $V = M / \gamma = (21.38 \div 25.62)/18 = 1.19 \div 1.42$ m ^{3}. The 50-meter pipe's volume will be $V_k = 50 \cdot 0.1256 = 6.28$ m ^{3}. If we calculate their proportion:

$$\Delta \text{ V\% is equal to 19.0–22.6\%.} \quad (11)$$

Assessing the obtained results, if we assume that cotton moves uniformly during pneumatic transport, then when distributed along the entire length, it occupies only 18-323% of the pipeline's volume. A large section of the pipeline is left empty during pneumatic conveying cotton transfer, according to calculations [5]. This section has a large carrying capacity and is air-filled. Our assessment of the inefficient utilization of pneumatic transport power appears to be more plausible when we consider that air and material velocities are significantly lower than the values determined in the calculations.

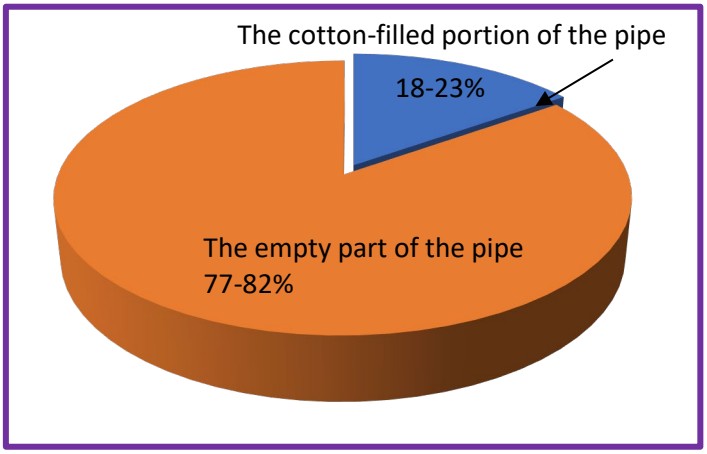

Fig. 4. Transportation of raw materials through cotton pipes with internal volumes determined by the occupied share.

Figure 4 illustrates the internal distribution of raw cotton in a pneumatic conveying pipeline. The diagram shows that cotton fibers occupy approximately 18–23% of the total cross-sectional area of the pipeline, while the remaining 77–82% of the space remains unfilled, providing air passage and facilitating material transport. This ratio highlights the relatively low bulk density of cotton in pneumatic conveying systems, where airflow plays a decisive role in maintaining movement and preventing blockages. The empty portion of the pipeline serves as the main channel for airflow, ensuring efficient transport, minimizing blockages, and reducing mechanical stress on the system walls. Quantifying the occupied and unoccupied volume of the pipeline provides important information about the pneumatic conveying capacity, pressure drop, and overall system efficiency. As airflow accelerates in the pipeline, the cross-sectional area decreases, leading to a significant increase in electrical power consumption. Conversely, a decrease in airflow leads to a decrease in power. Thus,

pneumatic conveying is carried out with a pipeline diameter of d = 0.4 m, a relatively large diameter that indicates the need to adjust the starting point of uneven cotton flow. The presence of larger aggregates in the flow can lead to blockages, requiring preventive measures. To ensure smooth movement in the pipeline system and prevent blockages, it is crucial to use an air mixture unit at the inlet. This ensures the smooth transport of cotton particles and specialty materials through smaller-diameter pipes.

The permissible air velocity is 20 to 25 m/s when using a 400 mm diameter pipe, where the flow rate (Q) is equal to FV and varies from 2.51 to 3.14 m³/s. When using a 280 mm diameter pipe, the air flow rate (Q), calculated as FV, ranges from 1.28 to 1.6 m³/s. For a 315 mm diameter pipe, the air flow rate (Q) ranges from 0.61 to 0.74 m³/s. In the case of a 355 mm diameter pipe, the flow rate drops to 0.04–0.67 m³/s. Research conducted by H. T. Akhmedkhodjaev and S. Kadirkhodjaev (2005) focused on air velocity during cotton transport, particularly at the bottom of the pipe where contact occurs, which negatively impacts cotton quality. Their findings showed that in a 400 mm diameter pipe, cotton remains suspended at air velocities of 28 m/s and above. In our theoretical analysis, we observed that air velocity near the pipe wall is higher in smaller diameter pipes than in larger ones. Based on these data, we hypothesize that in small diameter pipes, it is possible to maintain suspended cotton movement at air velocities of 22–25 m/s. Thus, high air velocities are not necessary for smaller diameter pipes, as adequate movement of suspended cotton can be achieved at lower velocities, reducing excess energy consumption. Furthermore, pneumatic conveying systems expand operational capabilities by allowing the use of a lower-power fan instead of a high-power fan, resulting in energy savings.

When using a VTS-10M fan (55 kW) instead of a VTS-12M (75 kW), energy consumption is 20 kWh; on the other hand, replacing a VTS-10M with a VTS-8M (30 kW) results in energy consumption of 25 kWh. These figures increase significantly—by a factor of 4-6—given the frequent use of pneumatic conveying systems. This contradicts the scenario where recommended standards are applied uniformly to all pneumatic conveying systems within a facility. The potential exists.

Cotton conveying systems play a vital role in the modern cotton industry. These systems optimize cotton handling, increase productivity, reduce labor costs, and ensure consistent end product quality. As technology advances, cotton processing plants will increasingly utilize advances in automation, energy efficiency, and data integration, making cotton handling systems even more critical to the industry's development. With the growing need for faster and more sustainable cotton processing, investments in sophisticated handling systems have become essential for companies seeking to remain competitive in the global market.

4 Conclusion

Using smaller diameter air ducts in pneumatic conveying and air cleaning systems offers a number of significant technical and economic advantages that significantly improve system performance. One of the key benefits is the reduction in the volume of contaminated air that must be processed. Because a smaller diameter air duct transports less air per unit of time, the overall load on the filtration and air cleaning systems is reduced. This significantly reduces energy consumption, operating costs, and maintenance requirements associated with air cleaning. This efficiency is particularly important in the textile and fabric industries, where airborne contaminants such as loose fibers, dust, and microparticles pose a threat to both the environment and the longevity of equipment. A smaller diameter air duct also helps reduce the release of fibers into the environment. Controlled airflow and lower turbulence mean fewer loose fibers are released from the system into the production area. This not only improves workplace hygiene but also minimizes the risk of fiber accumulation on sensitive

equipment components, thereby extending equipment life and reducing the frequency of unscheduled maintenance.

From a design perspective, smaller diameter ducts require less metal and fewer structural materials, which directly reduces initial manufacturing and installation costs. The resulting lighter pneumatic infrastructure also offers increased mechanical stability and may require fewer supporting structures. This contributes to improved dynamic performance, simplified installation procedures, and long-term system upgrades. Furthermore, reduced airflow volume reduces the time required to clean and recycle contaminated air, resulting in faster work cycles and reduced downtime. Taken together, these advantages demonstrate that the implementation of smaller diameter ducts offers both economic and functional benefits. This reduces exhaust air treatment costs, reduces fiber emissions, minimizes material consumption, and improves the performance of pneumatic conveying equipment. Thus, implementing smaller diameter ducts is a highly effective strategy for improving efficiency, environmental control, and overall system performance in industrial pneumatic conveying systems, smaller air pipe can reduce expenses associated with cleaning contaminated air, reduce the release of free fibers into the air, lower the metal requirements for pneumatic transport equipment, and further improve the overall performance of pneumatic transport equipment. In addition, it will also reduce the amount of time it takes to clean contaminated air. It should be underlined at this point that using small air pipes lowers the cost of cleaning contaminated and used air, the amount of metal used by pneumatic transport equipment, the release of free fibers into the air, and the potential for further enhancing its operational characteristics.

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