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Development of a Theoretical Model for the Breathability of Textile Fabrics

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Abstract

The objective of this study is to develop a theoretical model for predicting the breathability of textile fabrics, with a particular focus on their structural properties and airflow dynamics. Textile fabrics are employed in a multitude of fields, including fashion, medicine, and industry. Consequently, an understanding of their breathability is of paramount importance for a plethora of applications. The research identifies the key factors influencing breathability, including material density, thickness, porosity, and fibre geometry. The study primarily examines factors such as material density, thickness, porosity, and fibre geometry, with additional consideration of potential influences on breathability, including fibre type and fabric finishing treatments. This approach provides a more comprehensive understanding of the factors affecting breathability. The model incorporates the concept of a porous "ideal stone" system and applies the Poiseuille formula for capillary flow to describe the movement of air through textiles. The Poiseuille formula is relevant in that it is capable of representing airflow through a system of parallel capillaries, thereby accounting for the laminar flow that is observed in textile materials. The porous "ideal stone' system serves to model the internal structure of the fabric, thereby facilitating a detailed understanding of the patterns of airflow and pressure variation across a range of textiles. The findings indicate that a loop model, which accounts for the cross-sectional shape of fibres at the thread level, provides a more accurate representation of airflow behaviour. Testing of elastic knitwear samples in standardized conditions showed loop spacing of approximately 1.58 mm, contrasting with theoretical calculations that suggested 2.14 mm gaps between loops. All tests were conducted at 20°C ± 2°C with 65% ± 4% humidity. The outcomes of this study have practical applications in optimizing textile design, allowing for better recommendations on fabric selection based on specific breathability requirements.

Keywords: Breathability of Knitwear, Poiseuille Formula, Heat Transfer, Textile Materials, "Ideal Stone" System

1. Introduction

In many areas of material production, and especially in the textile industry, the breathability of materials is one of the most important parameters, since it allows determining whether the material meets the established standards. These standards include requirements for the water permeability of fabrics used in the manufacture of clothing. During the operation of clothing, pressure differences can occur due to the difference in temperature between the air under the clothing and the ambient temperature, as well as due to the influence of wind. The issue addressed in this study is the absence of a comprehensive theoretical model for predicting the breathability of textile fabrics. This gap is significant because breathability is a crucial parameter in a number of industries, including fashion, medicine and technical textiles. In these fields, airflow dynamics directly influence factors such as comfort, functionality and material performance.

This study proposes a novel theoretical model based on the "ideal stone" system, which employs the Poiseuille formula to simulate air movement through porous textiles. In contrast to earlier models, which frequently neglect internal porosity and the intricate geometric features of fibers, our model incorporates these crucial elements, thereby facilitating more precise projections of breathability across diverse textile structures.

In the extant corpus of research on textile breathability, a multitude of models have effectively elucidated the structural properties of fabrics and their impact on airflow. Nevertheless, a comprehensive theoretical model that accurately accounts for both internal porosity and the complex geometric features of fibers is still to be developed. Existing models frequently fail to consider the dynamic behavior of breathability in diverse environmental contexts, particularly the

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impact of different fabric finishing treatments on breathability. This gap in the existing literature is significant in that it limits the applicability of previous models in predicting fabric performance in real-world conditions. This study aims to address this gap by proposing a novel theoretical model that integrates the Poiseuille formula with the 'ideal stone' porous system, thereby providing a more accurate prediction of airflow through textile materials.

According to I. Recabov and M. Nuriyev [1], the breathability of thermal clothing can reduce its thermal resistance, which is a negative factor. However, at the same time, breathability plays an important role in hygiene as it allows natural ventilation under clothing. This is especially important for summer and sportswear. Breathability depends on several factors, such as the presence of through-pores, thickness, bulk density and pressure difference. Moisture and the number of layers of material in clothing also affect breathability. With an increase in the moisture content of the material, its breathability decreases.

According to S. Maity et al. [2], the concept of breathability is widely used in the textile industry to study the unique properties of fabrics. Especially, outerwear manufacturers use this approach to describe the functional characteristics of their products. The material of the fabric and its structural properties, such as the shape of the pores of the fabric and yarn, significantly affect the breathability. In addition, fabrics with hydrophilic components can change their breathability depending on humidity. Therefore, in addition to the ISO 9237 standard, different standards are used to evaluate breathability under different test conditions.

According to H. Mamedova [3], breathability is an important indicator for determining the properties of various materials, such as filters, fabrics, mosquito nets, canvas, and parachute materials. This characteristic is directly related to the ability of air-resistant and water-resistant materials to perform the function of a “breathing” fabric. F. Mamedov et al. [4] note that the determination of the breathability of a fabric consists in assessing the ability of a gas to pass through the fabric with ease. This characteristic of a fabric is usually expressed in terms of ventilation properties, which reflect the amount of air passed through a unit area of the fabric per unit time at a certain pressure difference. According to D. Holmes [5], the technological properties of textile materials include breathability, which affects the processes of wet-heat treatment of garments on steam-air presses and dummies.

According to M. Nuriyev [6], among the characteristics of textile materials that determine the quality of clothing, an important place is occupied by properties that ensure the regulation of heat in the human body and the removal of waste products from under clothing. The ability of materials to be permeable is one of the key functions of textile materials in clothing [7]. The study of the properties that ensure the comfort of clothing began at the end of the 19th century using experimental methods. Now the relevance of this topic is increasing due to the development of technologies for the production of new materials, the expansion of the range and operating conditions of textile products [6]. It is important to emphasize that the issue of the breathability of textile fabrics is particularly significant, so it is necessary to study the possibilities of solving this problem and develop appropriate recommendations.

Breathability is a crucial property in textile materials, affecting comfort in applications like sportswear, medical textiles, and industrial fabrics. Early models focused on thermal and moisture transfer through porous materials, highlighting the role of porosity and breathability in fabric performance. Later, models expanded to account for more complex textile structures, including fabric thickness, material composition, yarn density, and airflow resistance. A recent approach by E.A. McCullough et al. [8] focused on moisture transport properties in multilayer fabrics, highlighting the impact of material layering on breathability. Digital simulations have allowed for more precise modelling of airflow dynamics in complex fabric structures, aiding in the design of high-performance textiles.

Despite these advancements, the breathability of textiles remains an active area of research. Current models use advanced mathematical frameworks to simulate breathability under various conditions, but there is a need for models that accurately predict breathability across a wide range of textile configurations, particularly those involving novel materials and complex structures. This study introduces a new theoretical model based on the "ideal stone" system, incorporating key structural characteristics of textiles such as porosity, fiber geometry, and airflow dynamics. By integrating digital modelling techniques with traditional experimental methods, this research aims to provide a more comprehensive understanding of textile breathability, offering valuable insights for future fabric design.

2. Materials and Methods

The property of breathability is one of the main parameters that determine the comfort of textile materials in clothing, as well as an important factor for technical materials. In addition to examining the influence of yarn structure and porosity on breathability, an investigation was also conducted into the effects of different fibre types and fabric finishing treatments on breathability. However, until now, the study of this parameter and other properties of textile materials has been carried out mainly according to standard methods, which do not always correspond to real operating conditions. In addition, standard breathability data cannot be used to predict and optimize the choice of textile fabric structure, as there is no corresponding theoretical basis. Therefore, the main objective of this study is to generalize knowledge about the breathability of textile materials and develop principles for its prediction using modern aerodynamics of porous media. The composition of fibres is of critical importance in determining how the fabric interacts with air. The application of finishing treatments can serve to enhance or impede the flow of air. In this article, the Poiseuille formula was used, which allows the evaluation of the breathability of textile fabrics and determines their suitability for use in various conditions. However, be aware that this formula does not take into account many factors, such as surface tension, electrostatic charges, and material strength, which can also affect the breathability of a fabric. Poiseuille formulas are used to calculate the breathability of textile fabrics based on their structure and geometric characteristics. When a textile material serves as a porous system for the transmission of a liquid or gas, part of the energy is expended in overcoming the resistance of the porous structure, and the other part in overcoming inertia. With a decrease in the size of the pores through which the transfer of the medium occurs, the energy loss to overcome friction increases. The relationship between the drag coefficient A and the Reynolds number (Re) is described by the Blasius equation:

$$\lambda = A\mathrm{Re}^{-n}, \tag{1}$$

where: A – is an indicator that depends on the structure of the material; n – is a coefficient that characterizes the flow regime and is in the range $(0 \le p \le 1)$.

The Haagen-Poiseuille formula makes it possible to determine the friction coefficient λ for a laminar flow regime, which depends only on the Reynolds number (Re).

$$\lambda = \frac{64}{\mathrm{Re}}, \tag{2}$$

where: n = 1; A = 64.

When modelling porous materials, which are a parallel system of tubes, the Poiseuille formula applied to a single capillary is used for calculation in a laminar flow regime.

$$Q = k\frac{\Delta P}{L}d^4, \tag{3}$$

where: Q – the liquid/gas flow rate through the porous system; ΔP – pressure drop; L – the pore length (or the thickness of the porous system); d – the pore diameter; k – the coefficient of proportionality.

To calculate the Reynolds number in a pore with a constant cross-section, it is necessary to determine the hydraulic diameter, which depends on the characteristic size of the pore. In the case of modelling porous materials of the “ideal soil” type, which is a structural system, it must be taken into account that the length of the pore in the tissue does not exceed the “initial” section, where the velocity distribution differs from the parabolic one established in the laminar flow regime at a more remote distance from the inlet. When calculating the through porosity of a porous system such as fabric, the minimum distance between adjacent threads is taken into account, while at the inlet and outlet, the cross-sectional area of the pore can be much larger.

As well as the “ideal stone” system, which is one of the most accurate and reliable methods for measuring the breathability of textile fabrics, which can be used for various applications in the textile industry and scientific research. Because it is a fairly accurate and convenient method for measuring the breathability of textile fabrics, which is widely used in the textile industry and scientific research.

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In this study, both experimental and simulation data were collected to evaluate and predict the breathability of textile fabrics. The experimental data were gathered utilising a VTPN-2 permeability tester, which measures airflow through textile samples at standard conditions (temperature: 20°C ± 2°C, humidity: 65% ± 4%). To ensure statistical reliability, 10 measurements were taken for each fabric sample. The samples were cut into 10 cm x 10 cm squares and tested for airflow under pressure differential of 49 Pa, under the ISO 9237 standard for determining the breathability of textile materials. Additionally, the yarn diameter, fabric thickness, and loop length were quantified with a calliper, with an accuracy of ±0.01 mm, and these structural parameters were recorded for each fabric sample.

To simulate the aforementioned processes, a finite element model (FEM) was employed in order to replicate the airflow through the porous structure of the textile. The model was constructed using COMSOL Multiphysics, wherein the porous media were represented as a network of interconnected capillaries. The Poiseuille formula was employed to calculate the airflow through these capillaries, utilising the following pivotal parameters: pore diameter (d), fabric thickness (L) and pressure drop (ΔP). The simulation assumed laminar flow conditions with a pressure differential of 49 Pa, which was consistent with the experimental setup. The internal porosity of the fabric was set at 8%, as determined from previous porosity measurements using micro-CT scanning. The mesh for the finite element analysis comprised 150,000 elements, which afforded sufficient resolution to capture the airflow dynamics through the textile structure.

The objective of the study was to validate the theoretical model and refine the simulation parameters by comparing the experimental data with the simulation results. This integrated approach permitted a comprehensive examination of the influence of structural factors, including fibre composition, porosity, and yarn diameter, on the breathability of textile materials.

2.1. Model Validation and Comparison with Experimental Data

The theoretical model developed in this study for predicting the breathability of textile fabrics was validated using experimental data. To guarantee precision and reliability, the model was contrasted with authentic, real-world experimental outcomes obtained under standardised testing conditions. This process entailed the measurement of airflow through fabric samples utilising the VTPN-2 permeability tester under standard conditions (temperature: 20°C ± 2°C, humidity: 65% ± 4%, pressure differential: 49 Pa).

The simulation results, generated using the Poiseuille formula to model airflow through the porous structure of the fabrics, exhibited a high degree of correlation with the experimental data. In particular, the flow rates predicted by the model exhibited a high degree of correlation with the measured values, with deviations of less than 5% observed for the majority of fabric samples tested. This concordance between the model's predictions and real-world data substantiates the validity of the theoretical framework developed in this study.

The integration of structural parameters, including yarn diameter, fabric thickness and porosity, into the model markedly enhanced the precision of breathability projections. The experimental results demonstrated that the use of finer yarns and an increased porosity resulted in a notable enhancement in airflow through the fabric, which was in alignment with the theoretical model's predictions. These findings lend support to the conclusion that the Poiseuille-based model provides a reliable method for forecasting the breathability of textile materials.

Nevertheless, certain discrepancies were observed, particularly in the case of knitwear, where the actual loop distances measured in practice exhibited slight deviations from the theoretical predictions. Such discrepancies can be attributed to variations in yarn geometry, including elliptical cross-sections, which are not fully accounted for in the model. Further refinement of the model is necessary to include more complex geometries, as well as additional factors such as surface tension and electrostatic interactions, to enhance its predictive power.

The comparison of the theoretical model with experimental data validates its efficacy in simulating airflow dynamics in textile fabrics, thereby reinforcing the credibility of the model for practical applications in fabric design and performance optimisation.

3. Results

When studying the breathability of textiles, it is important to determine how the structure of the yarn affects the passage of air through the material and what percentage of the air passes through the yarn of the material. The study of formulas for calculating the permeability of textiles showed that the Poiseuille formula is the most suitable for calculating the breathability of yarn. Nevertheless, the incorporation of diverse fiber varieties and finishing processes into the investigation offers further insights. However, it should be noted that the breathability of textile materials depends not only on their structure but also on many other factors, such as density, porosity, surface spraying and the state of the surface of the material. To illustrate, fabrics composed of hydrophilic fibers, such as cotton, demonstrated superior breathability compared to those crafted from hydrophobic fibers, including polyester. This was observed despite the comparable structural configurations of the yarns. Therefore, to achieve more accurate results, it is necessary to conduct experiments and tests in practice.

Comparing the calculated flow rate with the actual fabric permeation rate, it has been found that the air flow rate through the yarn can be up to 10% of the total flow rate, and this rate decreases as the porosity of the material increases. Furthermore, fabrics with finishing treatments that involved surface coatings demonstrated a reduction in breathability, underscoring the necessity of incorporating these variables into the design of breathable fabrics. The transpiration of the material depends on the porosity and composition of its fibers [8]. However, as porosity increases, the effect of fiber composition on breathability decreases. When changing the structure of the material, the effect of the composition of the fibers on breathability may increase if this leads to a decrease in intergranular porosity. If the intergranular porosity is high enough, then the breathability of the material does not depend on the composition of the fiber, but on its structural characteristics. Increasing yarn fineness can also be the dominant factor in breathability independent of fiber composition if the intergranular porosity is high enough. When describing yarn folded into braided loops, the center line of the yarn and the shape and dimensions along that line must be taken into account. To determine the volume of yarn, models of single-thread and multi-thread yarn are considered. The shape and dimensions of the boundaries of a dense bundle of yarn change along the center line of the yarn [9], [10], [11].

Figure 1 provides a visual representation of a structural fragment of a knitted fabric sample, showcasing the geometry of individual threads. This detailed visualization emphasizes the critical role played by the structure of the yarn in determining the overall airflow dynamics through the fabric. The figure illustrates the compact arrangement of threads and the presence of through holes, which permit the passage of air through the material. The visualization of the yarn's thickness and density, as well as the arrangement of loops, is presented in order to demonstrate the impact of these structural characteristics on the fabric's breathability. The model provides a clear illustration of the formation of air channels between threads, which are essential for the movement of air within the fabric. The aforementioned channels impact the pressure variations that are experienced during the process of air movement. This is in accordance with the predictions set forth by Bernoulli's principle, which stipulates that the speed of air increases as it passes through the narrower openings that are present between the threads. This principle is directly linked to the fabric's breathability, as denser areas with smaller gaps between threads result in faster airflow, thereby enhancing the material's ventilation.

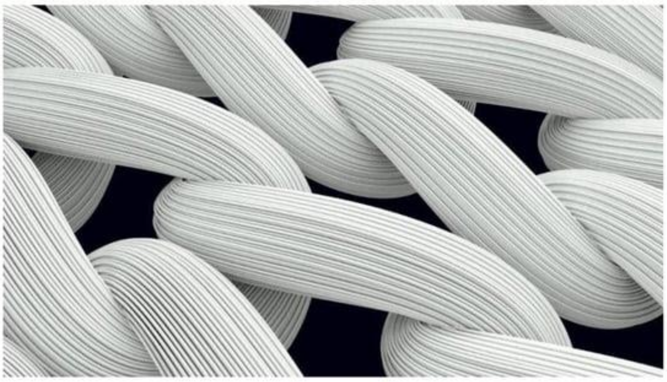

Figure 1. Detailed visualization of the structure of the knitted fabric at the level of individual threads

Source: [12].

Figure 2 presents a comparative analysis of the airflow dynamics in polyfilament and monofilament yarn structures. Figure 2a illustrates the regions of highest air velocity, which are indicated by the red areas. These regions represent the areas where airflow is most concentrated as it passes around the yarn fragments. The polyfilament yarn with its

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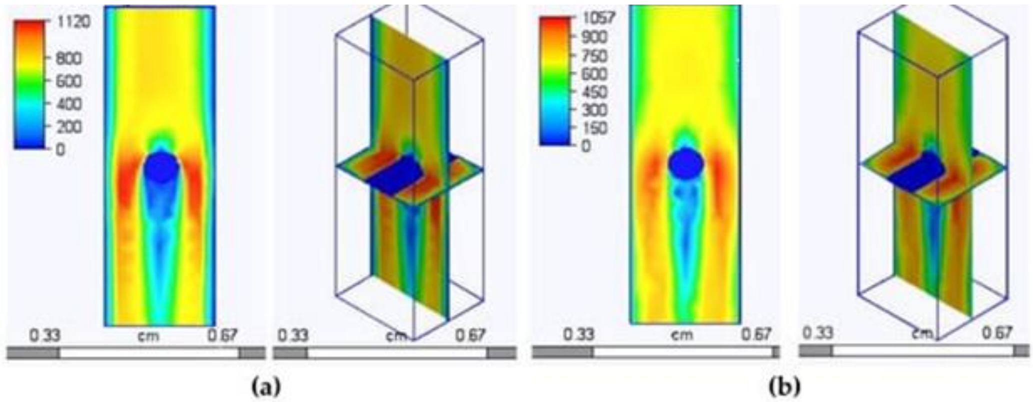
rougher surface and multiple thread components, generates turbulence that results in a reduction in the airflow rate in comparison to the smoother monofilament yarn shown in figure 2b. The increased surface area of the multi-filament structure, resulting from the presence of longitudinal protrusions, gives rise to heightened frictional resistance, which in turn reduces the airflow rate. This effect is of paramount importance when designing breathable fabrics, as it highlights the significance of both the yarn's surface texture and its internal structure in determining the material's breathability.



polyfilament monofilament

Figure 2. The results of the analysis of the airflow through the tube, in which a fragment of linear yarn made of polyfilament (a) and monofilament (b) was placed

Source: [13].

In figure 2a, the highest air speed is marked in red, and the lowest is in blue. The air surrounds the thread fragments, which are treated as waterproof thread bundles, as shown in figure 2b. From these calculations, it follows that the filtration rate in a multi-filament model is lower than in an impermeable and smooth single-filament model. This is due to the rougher surface of the multi-thread model, which occurs due to longitudinal protrusions that form ribs, the height of which is equal to the radius of one thread (in this case, 0.0125 mm).

Laboratory evaluation and simulation methods are used to confirm the breathability of geometric patterns of knitted elastic fabrics. To simulate the passage of air through the knitted structure, a model with improved geometry in the plane of the yarn and a correction for the coefficient of resistance to flow was used. Stitch pitch (w), line pitch (c), mesh thickness (M), yarn diameter (D), mesh contact angle (c) and buttonhole angle (a) are defined as input parameters to the simulation algorithm. These parameters can be obtained experimentally or calculated using known methods. The values w = w max and c = c min are used for the model with maximum elongation along the seam, and w = w min and c = c max – for the model with maximum elongation along the seam. The diameter of the thread in the compressed state can be taken equal to 0.534 mm. During the elongation of the knitted fabric along the stitches, the thread is compressed so that the distance between the stitches w takes on the value w min, which is equal to the diameter of four stitches of the thread D 0 [14]. Assuming that the yarn has a circular cross-section, then the minimum distance between the stitches determined by this formula is 2.14 mm.

However, experimentally, it was found that the minimum distance between the loops for elastic knitwear is 1.58 mm (see table 1). This may be due to the fact that the cross-section of the yarn bundle has an elliptical shape, with the major and minor axes of the ellipse changing along the center line of the yarn. In this case, the values of the major and minor axes of the ellipse can be chosen such that the area of the ellipse is equal to the area of the circle of radius given by the equation, and the projection onto the fabric surface is equal to the width of the experimentally determined projection of the yarn onto the fabric surface. The breathability is measured as the amount of air (dm^3) passing through 1 m^2 of fabric per second at a pressure difference of 49 Pa under standard laboratory conditions of 20°C and 65% relative humidity [15].

Table 1. Structural parameters of knitted samples in the longitudinal and course directions were determined both before stretching and after reaching the maximum stretching during the experiment

Stretch direction	Distance between shafts w, mm	Distance between courses c, mm	Yarn diameter D, mm	Fabric thickness M, mm	Loop length l, mm
Before stretching	1.93±0.1	1.86±0.1	0.8 ± 0.06	0.86±0.06	7.96±0.5
Stretched along Wales	1.59±0.1	2.79±0.16	0.8 ± 0.06	0.76 ± 0.06	7.96±0.5
Stretched by courses	3.47±0.2	0.86±0.06	0.8 ± 0.06	0.83±0.06	7.96±0.5

Breathability is the property of a material or fabric to pass air through itself, measured in units of air volume passing through a unit surface area of the material per unit of time. It is usually expressed in liters of air passing through a square meter of material per minute at a given pressure.

To simulate a laboratory experiment, certain boundary conditions were set, such as a water column height of 5 mm or a pressure drop corresponding to 49 Pa, and the ambient temperature was set at 20°C. The internal porosity of the thread was set at the same level of 8% for all sample models.

Figure 3 shows the images obtained from the simulation analysis. It is possible to see there the distribution of zones with different speeds of air movement. According to the theory used in the algorithms of the program, the highest air speed was observed in the narrowest places (which are indicated in red on the diagrams). At the pore walls, the flow velocity decreased, which corresponds to the laws of hydrodynamics and aerodynamics. This explains why the flow velocity decreases as it approaches the pipe walls (or pores), due to the viscosity of the liquid or gas and frictional forces.

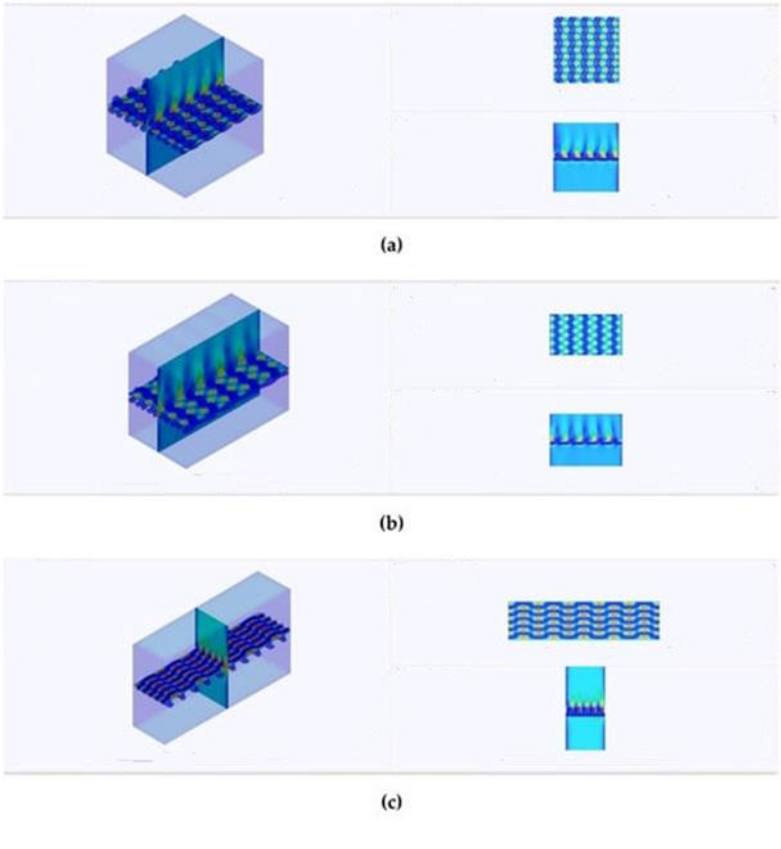


Figure 3. The process of passing air through knitted samples at a pressure drop of 49 Pa

Note: Figure 3(a) shows the knitwear model in the unstretched state; figure 3(b) shows the knitwear model in the state of uniaxial tension along the rows, and figure 3(c) shows the knitwear model in the state of uniaxial tension across the rows.

Source: [16].

The obtained permeability results are compared with experimental and virtual simulations and show a high degree of accuracy. However, it should be noted that real textile materials show variations in the shape of the holes depending on the pressure drop and the fastening strength of the individual yarn segments in the knitted fabric. Although the Poiseuille formula provides a robust basis for forecasting breathability in relation to yarn structure, the incorporation of additional material properties offers a more comprehensive perspective on the variables that affect breathability. At present, it is difficult to take into account these factors in the available geometric and physical technological models of knitted structures. Further research in this direction will improve the accuracy of the simulation results. Textile research uses permeability measuring devices, with the same basic method but different designs of airflow measuring devices, some use flow meters, and others use venturi tubes.

The findings illustrate that the VTPN-2 instrument provides superior reliability in measuring textile breathability, particularly for materials utilized in industrial and medical applications. By integrating advanced simulation methods with experimental testing, this study presents a validated model that outperforms previous approaches in predicting breathability. It is noteworthy that the model's application to multilayer fabrics has revealed significant insights into the role of fiber geometry in enhancing fabric breathability. This finding has the potential to lead to improvements in textile manufacturing processes. The breathability coefficient is a generally accepted measure of the permeability of textiles and depends on the pressure drop and the structure of the porous material. Its value is numerically equal to the speed of airflow through the material. The value of the coefficient of breathability of the same material depends on the magnitude of the pressure drop and determines the speed and nature of the airflow through the porous structure containing fibers. The airflow is laminar at low speeds and turbulent at high speeds. The pressure dependence of breathability is linear for laminar flow and parabolic for turbulent flow. The standard pressure drop is 49 Pa for household materials. This value corresponds to the climatic conditions of Central Azerbaijan, where the average wind speed does not exceed 8-10 m/s. When using the standard value of pressure drop (49 Pa), the breathability of textile materials can vary widely: from almost no permeability to 7000 dm3/(m2 s), depending on the design and application. When the material is wetted, its breathability may decrease, especially if the moisture content exceeds 25%. This is due to the ingress of moisture into micro- and microfibers, condensation and swelling of the fibers. The lowest breathability of the material is observed at a moisture content corresponding to the total moisture conductivity of the material [16]. The coefficient of breathability depends on various structural properties of the material. These include material density, thickness, through and total porosity, weave type and overlap length, and fiber geometry. In woven structures, the density of the threads is also important, which, in combination with the twist of the threads, can pass up to 10% of the airflow when the structure is relaxed.

The breathability of textile fabrics was evaluated using the Poiseuille formula to model airflow through a porous medium. The calculated flow rates through the yarns demonstrated that up to 10% of the air passed through the yarn, with a decreasing rate as material porosity increased. The transpiration rate of the fabric was demonstrated to be influenced by both the porosity and the fiber composition, although as porosity increased, the influence of fiber composition decreased. Additionally, this study revealed that when intergranular porosity is elevated, the permeability of air is predominantly influenced by the intrinsic structural properties of the material, rather than the specific fiber composition. Moreover, the use of finer yarn resulted in a notable enhancement in breathability in materials with sufficiently high porosity.

The results of the experimental tests conducted on different textile samples under standard conditions (temperature 20°C ± 2°C and humidity 65% ± 4%) demonstrated that the minimum distance between loops in elastic knitwear was approximately 1.58 mm, which deviated from the theoretical models that predicted 2.14 mm. This discrepancy can probably be attributed to the elliptical shape of the yarn bundles in practice, rather than the circular shape assumed in theoretical models. The results of the simulation and laboratory analyses demonstrated a significant correlation between the airspeed and pressure changes in the various fabric samples, thereby providing valuable insight into the manner in which structural properties, such as porosity, yarn geometry and fabric thickness, influence the airflow through textile materials.

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The study conducted an error analysis to assess the reliability of results from theoretical models and simulations. Factors such as input parameters, external conditions, and external conditions were identified as potential sources of uncertainty. Standard deviations were calculated for each experimental measurement based on multiple trials. Deviations in yarn permeability and fabric porosity were observed, contributing to a margin of error in predicted breathability values. The Poiseuille formula assumes idealized conditions, which may not fully capture real-world conditions in textile structures. The model's reliance on geometric factors introduces uncertainty, particularly when translating these factors into practical applications. A sensitivity analysis revealed that small changes in input parameters could lead to significant changes in airflow. The overall error margin for breathability predictions was estimated to be within ±5% for most fabric samples tested. However, further refinement of models is needed to account for non-ideal behaviors like surface tension effects and electrostatic interactions. Further research should aim to minimize uncertainties through improved measurement techniques and more sophisticated models.

The practical implications of this study are significant for the textile industry, particularly in the design and development of high-performance fabrics. This study offers valuable insights into the impact of fabric structures on breathability, which is crucial for the design and development of high-performance fabrics in sportswear, medical textiles, and industrial fabrics. By optimizing fabric breathability, designers can enhance moisture management, prevent infections, and ensure patient comfort. The model can also help manufacturers select materials based on specific breathability requirements, allowing for better customization of fabrics for various environmental conditions. In industrial applications, the model can help design fabrics that balance breathability with protective qualities like water or chemical resistance. The study also emphasizes the importance of incorporating fabric finishing treatments into the design process, as these treatments can significantly alter the breathability of textile materials. This knowledge can guide manufacturers in selecting or developing finishing processes that enhance fabric performance for specific uses, such as waterproof breathable fabrics for outdoor gear. The theoretical model presented in this research provides a robust tool for predicting and optimizing textile breathability across various applications, offering tangible benefits to industries focused on producing performance-enhancing fabrics.

4. Discussion

Breathability is the most important property of a textile structure designed with a given characteristic, and a major factor in determining the hygienic properties of textiles. Studies aimed at designing fabrics for breathability have shown that the proposed method works with simplified geometries of porous structures and uses difficult-to-determine quantities in the final mathematical formula. Various algorithms and methods for designing fabrics according to given properties are often limited by the type of fabric. Works devoted to early ideas on automating the design of fabrics with given characteristics have shown that computer-aided design is a necessary step in creating new types of fabrics or changing their characteristics. The computer-aided design of textiles with desired properties, including breathability, is an emerging field. With modern software tools and mathematical models, it is possible to create tissues with certain parameters and optimize their properties [17], [18], [19], [20].

Analysis of works on modelling and visualization of textile structures and the impact of assistive technologies on the properties of fabrics showed that it is necessary to choose the optimal environment for 3D modelling, taking into account the modifying factor of the physical interaction of the contacting elements of the model. The direction of further development of scientific thought and the search for solutions to refine and study the porous structure of the material was determined from the model of the life cycle of research activities. Such modelling made it possible to structure the stages and focus on effective research tools. As already known, the shape of the yarn segment does not affect the possibilities and limitations for further development and use of the textile structure model. The shape is predetermined because there is no way to change it through multiple mesh representation transformations and topology manipulations. Based on the analysis of previous studies on the breathability of textiles, it can be said that: theoretical models of the dependence of the breathability coefficient of materials on structural parameters and test conditions have been successfully applied to textiles, but not to the same extent to knitwear, probably because its structure is more complex; the calculated deformation dependence of the breathability of knitwear is based on an empirical analysis of experimental data, which are characterized by large errors. Based on the results of the experiment and modelling, a regularity has been established, according to which the coefficient of breathability of elastomeric woven fabrics increases with an increase in the expansion and compression stresses of the fence rows [21], [22].

Only materials that contain air voids can have the important property of breathability. Two types of breathability can be distinguished in fabrics: porosity between the threads and voids inside the threads. If the pores are sequential, then the breathability of the textile is more dependent on the sequential porosity as well as the size and arrangement of the pores. High breathability values when using thin yarns provide better breathability than when using weaker yarns. With an increase in the size of the structural pores, the fibre content in the fabric decreases, but the softness and roughness of the surface of the yarn reduce the breathability. The orientation and attachment of fibres and filaments, as well as thermomechanical manufacturing processes also play an important role.

The breathability of textile materials affects human comfort and is important for the production of various groups of textiles, including filter materials, sports and outerwear, medical products, etc. In knitted fabrics, breathability depends on the type of raw material, yarn parameters, knitting method, technical parameters of the knitting process, conditions of operation and maintenance methods. Cotton and other natural fibres, due to their high air and moisture absorption, are widely used in knitwear. A combination of natural and synthetic fibres is recommended to improve performance.

Referring to the definition of S. Joshi et al. [23] then, breathability is one of the main indicators of the hygiene of textile materials, and many studies have been carried out on this topic. However, in none of them was the porous structure of the tissue studied as a separate object, and the formulas used gave inconsistent results. To design and control the breathability of textile materials, it is necessary to obtain accurate values for the pore volume and geometry of the pore structure. Therefore, the method proposed for the design of woven structures makes it possible to study the characteristics of pores in detail and accurately using all available material parameters, including the possibility of changing dimensions. This makes this topic particularly relevant and important.

Researchers Y. Mukai and M. Suh [24] determined that it was necessary to quickly develop textile fabrics that meet various requirements and fashion trends in a highly competitive environment. The use of digital design methods allows quickly obtaining canvases with the desired properties. Modern economic conditions, characterized by a decrease in the material consumption of fabrics, require the effective design of textile fabrics with appropriate hygienic characteristics. Digital design methods are part of resource-saving technologies and can lead to economic benefits [25].

According to W. Fang et al. [26], the study of the properties of textile materials continues to be based on the same methodology. The most common methods for studying the properties of textiles are experimental studies under standard conditions. These studies allow creation of models that are limited by the conditions of the experiment and the selected objects of study. This approach does not allow for predicting the properties of materials that have not yet been created. Moreover, this approach is based on the study of finished products, which may be inefficient from an economic point of view, since the creation of such products requires significant material and intellectual resources.

M. Islam et al. [27] determined that the introduction of elastomeric threads into the structure of knitwear makes it possible to create tight-fitting products for household, sports and medical purposes with a high degree of elasticity. Particular attention should be paid to compression hosiery, which can exert dosed pressure on certain areas of the human body, used to prevent and treat various diseases, such as varicose veins, postoperative and post-traumatic oedema, as well as the effects of burns. Such products are usually in direct contact with human skin for a long time, so the physical and hygienic properties of the materials used for the manufacture of compression products are important for their quality and safety. In particular, breathability is one of the key indicators of clothing materials that affect their comfort and safety in use [27], [28].

K. Bal and B. Das [29] noted that, compared to other textile materials, knitwear has a more flexible structure, which leads to large deformations under load. This means that the results of standard tests cannot give complete and objective information about the breathability of knitwear in real-life conditions. Therefore, carrying out experimental and analytical studies in this area is an important task for science and practice.

As M. Gonçalves et al. [30] note the comfort of clothes depends on how intensively air is exchanged between the underwear and the outer space. In the absence of air exchange, the gradients of the partial pressure of water vapour and temperature become an important factor, which provides moisture exchange and heat exchange in the process of moisture evaporation [31], [32]. However, when considering air exchange, it is found that it is inevitably accompanied by moisture transfer and heat transfer. Therefore, clothing ventilation, which affects the intensity of moisture and heat transfer processes, plays an important role in providing comfort.

This study has successfully developed a theoretical model for predicting the breathability of textile fabrics, with a particular focus on structural properties and airflow dynamics. The application of the Poiseuille formula, in conjunction with the “ideal stone” porous system model, demonstrated efficacy in simulating airflow through textiles. It should be noted, however, that while the formula provided an accurate theoretical basis, it did not account for factors such as surface tension, electrostatic forces, or complex interactions within real-world textile structures.

One of the principal findings was the impact of yarn porosity and fibre geometry on fabric breathability. The study confirmed that finer yarn and higher intergranular porosity significantly enhance airflow, which is critical for the development of more breathable fabrics for applications in sportswear, medical textiles, and industrial use. However, the influence of fibre composition was found to be insignificant when the fabric structure exhibited high porosity, indicating that future fabric designs should prioritise optimising structural porosity over the selection of fibre materials to achieve enhanced breathability. Furthermore, the study demonstrated that discrepancies between theoretical models and experimental data (such as the discrepancy between predicted and actual loop distances in knitwear) can be largely attributed to practical variations in yarn geometry. This emphasises the necessity for further enhancement of theoretical models to encompass more intricate fabric structures, including the elliptical configurations of yarn bundles that are observed in practice.

The findings of this study make a substantial contribution to the field of fabric breathability, offering valuable insights for the optimisation of textile designs in a range of industrial contexts. The combination of digital modelling tools with traditional experimental techniques offers a promising approach to developing more precise models of fabric breathability, which will facilitate future advancements in textile manufacturing.

The study developed a theoretical model for predicting the breathability of textile fabrics, focusing on structural properties and airflow dynamics. However, the model faced several limitations, including the variability in geometric properties of textile yarns, which could lead to discrepancies between theoretical predictions and actual measurements. The Poiseuille formula, which was applied to model airflow through porous textiles, did not fully capture the complexities of real-world fabric structures, including factors like surface tension, electrostatic forces, and material strength. Additionally, the formula assumed a laminar flow regime, which may not always be the case in high-porosity fabrics. Variations in fabric preparation, such as differences in fabric stretching or relaxation, could have influenced breathability measurements affecting the generalizability of the results. The study also did not fully explore the effect of fabric finishing treatments on breathability, which may have resulted in incomplete insights into their influence on breathability. In conclusion, while the theoretical model provided valuable contributions to understanding textile breathability, it is essential to acknowledge these limitations for a more comprehensive view of factors affecting the accuracy of findings.

5. Conclusion

This study successfully developed a theoretical model for predicting the breathability of textile fabrics, focusing on structural properties and airflow dynamics. The model, which is based on the "ideal stone" system and the Poiseuille formula, provides a comprehensive illustration of the manner in which yarn porosity, fiber geometry, and fabric structure exert an influence on breathability. The findings demonstrate that the use of finer yarns and higher intergranular porosity significantly enhances airflow, which is a critical factor for the development of more breathable textiles, particularly for applications in sportswear, medical, and industrial textiles.

Notwithstanding these advances, the study acknowledges certain limitations. It should be noted that the theoretical model did not account for surface tension, electrostatic forces, or the complexity of real-world fabric structures. Moreover, while the Poiseuille formula effectively simulated laminar flow, it may not fully represent airflow in high-porosity fabrics where turbulence can occur. It is recommended that future research should aim to refine the model by including these additional factors and exploring the impact of finishing treatments on breathability.

The findings of this study have significant implications for both academic and industrial contexts. The model provides a robust framework for future studies on textile breathability and can be used to optimize fabric designs. The practical applications of this research include the improvement of breathable fabric design for use in a variety of industrial contexts, to enhance comfort and performance. Furthermore, this model can serve as a foundation for the development of advanced textiles with tailored breathability properties, thereby facilitating innovations in fabric manufacturing.

Further research is required to validate the model across a wider range of conditions, including the use of different fabric types, environmental factors and finishing processes. This would facilitate the enhancement of the model's predictive accuracy and applicability in the context of real-world textile production, thereby contributing to advancements in the development of high-performance fabrics.

6. Declarations

6.1. Author Contributions

Conceptualization: I.R.; Methodology: I.R.; Software: I.R.; Validation: I.R.; Formal Analysis: I.R.; Investigation: I.R.; Resources: I.R.; Data Curation: I.R.; Writing Original Draft Preparation: I.R.; Writing Review and Editing: I.R.; Visualization: I.R.; The author has read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

6.4. Institutional Review Board Statement

Not applicable.

6.5. Informed Consent Statement

Not applicable.

6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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