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NUMERICAL CALCULATION OF AIR PERMEABILITY OF WARP-KNITTED JACQUARD SPACER SHOE-UPPER MATERIALS BASED ON CFD

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Abstract:

In order to realize the rapid design of warp-knitted jacquard spacer shoe-upper materials and to explore the influence of different fabric surface organization structures on their air permeability, it is proposed to numerically simulate the air permeability performance of jacquard shoe-upper materials using ANSYS fluid analysis. First, four kinds of shoe material specimens with different upper and lower layer mesh alignment relationships are designed and tested, then the corresponding geometric structure models of the fabric are established based on the samples and appropriately processed, and finally the air permeability of the shoe material is numerically simulated and calculated based on computational fluid dynamics. The results show that, under the same conditions, the air permeability of double-sided mesh structure is significantly better than that of single-sided mesh structure, and its air permeability can be optimized by adjusting the relationship between the upper and lower layers of the fabric mesh; the airflow mainly passes through the fabric pores and gaps between the yarns, and the closer the fabric structure is, the more the air flow is hindered, and the worse the air permeability is. The simulation results of the established numerical model are consistent with the measured results, and the error is less than 10%, so it can be used to simulate and predict the air permeability of the warp-knitted jacquard spacer footwear materials, and provide theoretical support for the design and performance research of footwear materials.

Keywords:

Warp-knitted jacquard, spacer shoe-upper materials, air permeability, numerical calculation, CFD

1. Introduction

The warp-knitted jacquard spacer shoe material is a three-layer three-dimensional structure mesh fabric composed of the upper and lower surface layers and intermediate spacer layer [1], because of its unique jacquard technology, lightweight, light and airy, high production efficiency, and the ability to knit and shape in one time, it has become the main material for the production of a variety of high-end leisure sports brands. With the increase in sales of sports shoes brought about by the sports and fitness craze, consumers have increasingly high requirements for the air permeability and comfort of jacquard shoe-upper materials.

In the research on the air permeability of warp-knitted jacquard spacer shoe-upper materials, some scholars have improved the wearing properties of shoe-upper materials by studying the spacer structure of fabrics and the influencing factors of air permeability. However, in actual production, test weaving and performance testing are required before the development of shoe-upper materials, since it is difficult to obtain the fabrics, the jacquard warp knitting machine is precise and complex, and the processes of yarn changing and threading are tedious. The traditional test methods not only consume a large amount of raw materials, manpower, and resources, but also fail to analyze the flow characteristics of the gas inside the fabrics and the influence of the fabric structure on the air permeability effect. It is difficult to carry out the experimental explorations under various different conditions, which reduces the efficiency of shoe material development and performance research. Therefore, the use of finite element simulation technology to study and innovate the air permeability of fabrics has become an inevitable trend, and there is also an urgent demand for it in the market. At present, research on the simulation of air permeability performance of warp-knitted fabrics both domestically and internationally mainly includes the following research. Dai et al. [2] used ANSYS CFX to study the air permeability of fabrics and change the rule of the movement of the airflow inside the fabric. Zahra et al. [3] studied through experiments and numerical simulations the air permeability of different warp-knitted fabrics. Wu et al. [4] studied the air permeability of different warp-knitted fabrics based on the image processing technology and Solidworks fluid analysis, where Solidworks fluid analysis was used to study the effect of different structural parameters on the air permeability of warp-knitted spacer fabrics. Liu [5] studied the relationship between the structure, compression performance, and air permeability effect of large mesh warp-knitted fabrics by a combination of numerical simulation and experiments. In summary, current research on simulation of the calculation of fabrics air permeability is mainly aimed at ordinary warp-knitted fabrics or warp-knitted spacer fabrics, while the research on the air permeability of warp-knitted jacquard spacer upper fabrics through simulation has rarely been reported.

Therefore, based on computational fluid dynamics (CFD), this article first designed four kinds of samples with different surface texture parameters, test their air permeability and obtain the test data, then constructed a three-dimensional geometrical structure model conforming to the real state of the fabric by using Solidworks software, and then simulated the dynamic air permeability process of the fabric using ANSYS software. Finally, through comparative analysis the effectiveness of numerical simulation for fabric air permeability behavior is proved. The purpose of this article is to explore a new method for theoretical prediction of air permeability of warp-knitted jacquard spacer shoe-upper materials, with a view to guide the optimization of air permeability in the design stage of products for shoe-upper materials.

2. Experimental

2.1. Raw materials and instruments

2.1.1. Raw materials

Raw materials used included 75D glossy polyester FDY, 40D monofilament, 150D polyester DTY, and 150D semi-glossy polyester (all provided by Fujian Bailong Precision Machinery Co., Ltd).

2.1.2. Instruments

Instruments used were RDPJ6/2 double needle bed Raschel jacquard warp knitting machine (Japan Karl Mayer Co., Ltd), YG461-III automatic air permeability meter (Ningbo Textile Instrument Factory), and Nikon E100 electron microscope (Beijing Ruike Zhongyi Technology Co., Ltd).

2.2. Experimental methods

2.2.1. Design of samples

First, based on the principle of jacquard technique, two types of samples were designed: single-sided mesh structure (S1) and double-sided through-hole structure (S4). Based on sample S4, the mesh position on one of the surface layers was rearranged in both horizontal and vertical directions, resulting in two new samples: horizontal through holes (S3) and vertical through holes (S4), enhancing the diversity and three-dimensional sense of the mesh structure.

2.2.2. Preparation of samples

To ensure that the shoe material has basic mechanical properties, polyester with high strength and good abrasion resistance is chosen as the raw material of the upper and lower surface layers to meet the design requirements. Polyester monofilament with excellent elasticity and a certain degree of bending strength is chosen as the raw material of the upper and lower surface layers to meet the design requirements. Polyester monofilament with excellent elasticity and a certain degree of bending strength is chosen as the raw material of spacer filament to play a cushioning and compression-resistant role. The bottom comb is made of 150D semi-gloss polyester, the spacer yarn is made of 40D polyester monofilament, the jacquard comb is made of 150D polyester DTY, the jacquard comb pectus is configured in the back needle bed, and the basic cushion yarn organization is 1-1-1-0/1-1-1-1-2//. The ground weave on both layers of the fabric is a chain stitch. The mesh upper fabric is woven by jacquard warp knitting machine. The sample is then washed at high temperature, pre-shaped, dyed, and other finishing processes to meet the standard. The sample is shown in Figure 1, and the basic weaving process parameters of the sample fabric are shown in Table 1.

2.2.3. Air permeability test

Referring to GB/T 5453-1997 "Determination of air permeability of textiles," YG461-III fully automatic air permeability meter is used to measure the volume of air that flows through the fabric per unit area per unit time, which is the air permeability of the

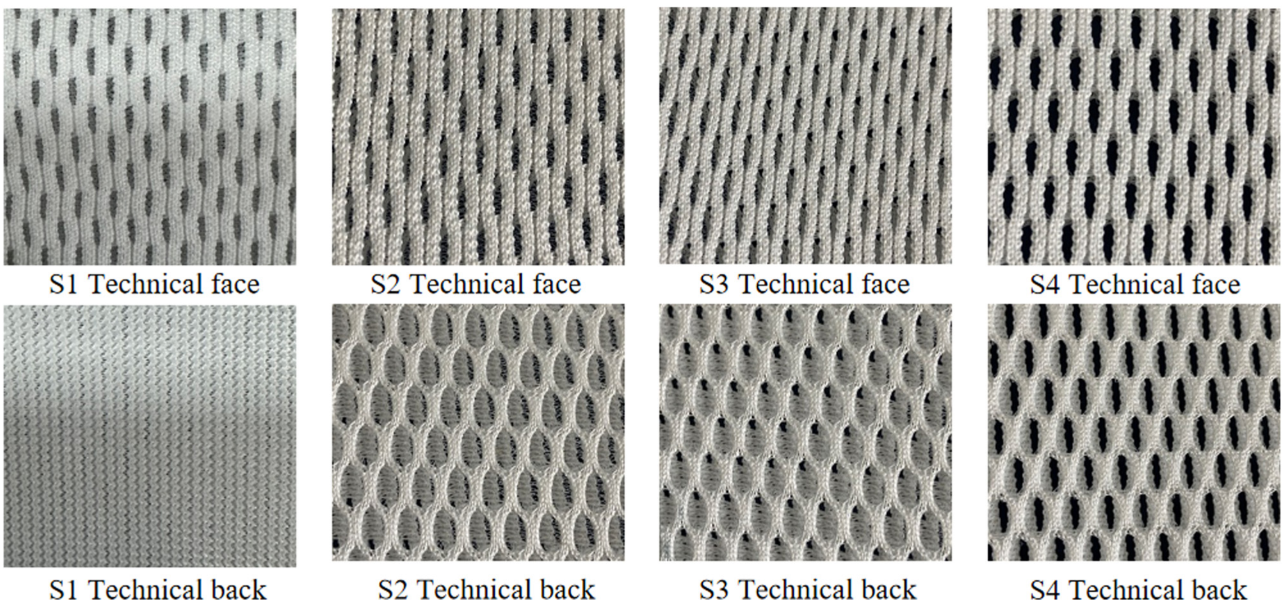

Figure 1. Actual sample pictures.

Table 1. Basic weaving process parameters for fabrics

Comb number	Chain notation	Raw material specifications	Threading method	Beam warping	Warp run-in (mm rack^{-1})
GB1	(1-0-1-1/1-2-1-1) × 4/(3-4-1-1/3-2-1-1) × 4//	75D glossy polyester FDY	One in one out	357 × 6	1,580
GB2	(3-4-1-1/3-2-1-1) × 4/(1-0-1-1/1-2-1-1) × 4//	75D glossy polyester FDY	One in on out	357 × 6	1,580
GB3	1-0-1-0/0-1-0-1//	40D monofilament	Fully threaded	476 × 6	6,800
JB4	1-1-1-0/1-1-1-2//	150D polyester DTY	Fully threaded	238 × 6	2,180
JB5	1-1-1-0/1-1-1-2//	150D polyester DTY	Fully threaded	238 × 6	2,180
GB6	1-1-0-1/1-1-1-0//	150D semi-glossy polyester	Fully threaded	476 × 6	1,540

Figure 2. Air permeability test picture of sample fabric.

fabric [6]. Before the test, the sample to be tested needs to be pre-moisturized, and the sample should be placed in a standard atmospheric pressure environment with a temperature of 20 ± 4°C and a relative humidity of 65 ± 4% to achieve equilibrium. Then, the testing area on the instrument should be set to 20 cm^2. Since the shoe-upper material is a wearing fabric, the pressure difference between the two sides of the sample should be set to 100 Pa, and a suitable nozzle caliber should be selected, so that the same sample is tested ten times, and the measured value should be calculated as the arithmetic mean value of the fabric. The air permeability is used to characterize the air permeability performance of the fabric. The air permeability test chart of the sample fabric is shown in Figure 2.

2.2.4. Tests results

Through the experimental tests, the results of air permeability tests of the four samples were obtained as shown in Table 2.

3. Numerical simulation calculation part

3.1. Fabric geometry modeling

Three-dimensional geometric models of fabrics were constructed using Solidworks software, which has the ability to accurately

Table 2. Testing results of air permeability

Sample number	Nozzle diameter (mm)	Air permeability data (mm s^{-1})
		Average (ten samples)
S1	8	1,253
S2	12	2,275
S3	12	2,400
S4	12	2,773

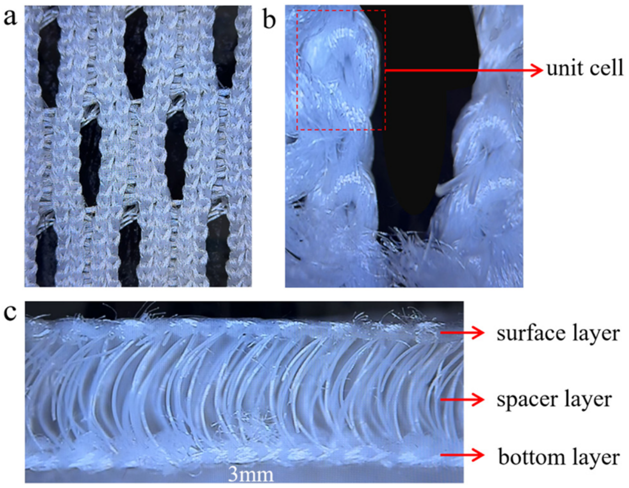

Figure 3. S4 through-hole structure: (a) top view, (b) unit view, and (c) side view.

simulate solid features and to import the created models into external analysis software for more in-depth analysis and optimization [7]. In order to ensure the stability of the model and improve the accuracy of the simulation, as well as to reduce the running load of the computer, the following basic assumptions need to be made in the modeling: (1) Assume that all the structural properties of the fabrics and yarns are desirable, while assuming that the yarns are rigid rods with uniform elasticity. (2) Consider the fabrics with a complex spatial structure as a homogeneous and porous material, and at the same time consider the spacer layer and the upper and lower surfaces of the fabrics as a whole. (3) Through the analysis of the sample fabric, it is found that the surface layer of the fabric is knitted by multiple comb pairs, and this complex structure makes it difficult to clarify its influence on the fabric properties and increases the difficulty of modeling. Therefore, only the representative tissues of the fabric surface layer were modeled and characterized to simplify the model and facilitate the subsequent analysis and calculation.

The physical samples were placed under a microscope, and the real morphology of the fabric in different viewing angles as shown in Figure 3 and the real cross-sectional morphology of the unit coil as shown in Figure 4(a) were observed. The geometrical structure parameters were obtained through measurements and input into Solidworks to generate coil space curves, and then the scanning features in the software were used to assign cross-sectional diameters to the curves, thus obtaining the coil unit model as shown in Figure 4(b). Then the array tool was used to perform comprehensive modeling and modeling reproduction of each sample fabric. Finally, the spacer filaments were reorganized to form a whole by connecting them to the upper and lower layers. Four simplified models of fabrics with different mesh alignment relationships between the upper and lower surface layers were obtained as shown in Figure 5.

3.2. Model pre-processing and grid partitioning

ANSYS is a widely used and powerful engineering simulation software that can solve problems such as structural analysis and fluid dynamics [8]. After the fabric geometric models are constructed, these models need to be placed in a rectangular cavity and processed using Boolean operations, in order to partition the solid and solid domains in the cavity, and thus establish a fluid virtual boundary domain. Specifically, the yarns within the fabric need to be deleted to obtain the flow region of the gas, which is the fluid domain. The fluid domain is the foundation of fluid dynamics analysis, which helps to understand the flow of gases within the fabric [9].

For fluid analysis, finite element analysis is mainly used, where iterative calculations are performed at the nodes of the mesh, so that the fluid mainly passes through the part with the mesh. The delineation of the mesh is the basis of the simulation calculation, and its quality directly affects the speed and convergence of the iterative calculation [10]. To ensure the quality of the mesh, this article uses ANSYS Mesh software to mesh the model. The fluid domain of sample S1 is shown in Figure 6, and the results of meshing are shown in Figure 7.

3.3. Model boundary condition setting

In order to ensure the accuracy and reliability of the simulation, it is necessary to reproduce the experimental environment and conditions when setting the fluid parameters for the simulation calculations, which means that the simulation conditions should be consistent with the actual experimental conditions. Specifically, when defining the conditions of the unit area, it is necessary to set the inlet boundary, outlet boundary, and wall boundary of the model, and more importantly, it is important to ensure that the

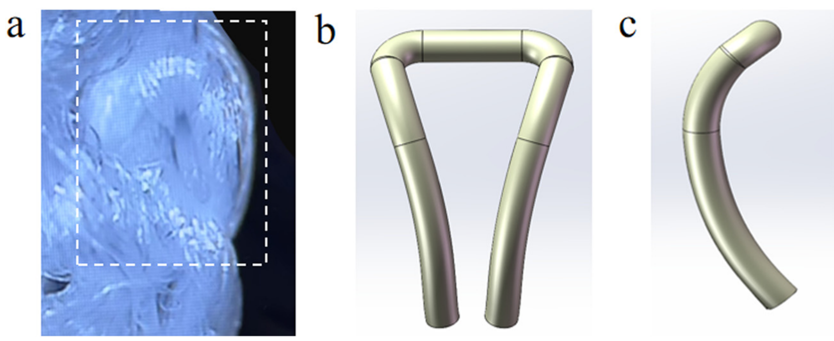

Figure 4. (a) Actual pictures of unit coil, (b) front view, and (c) side view.

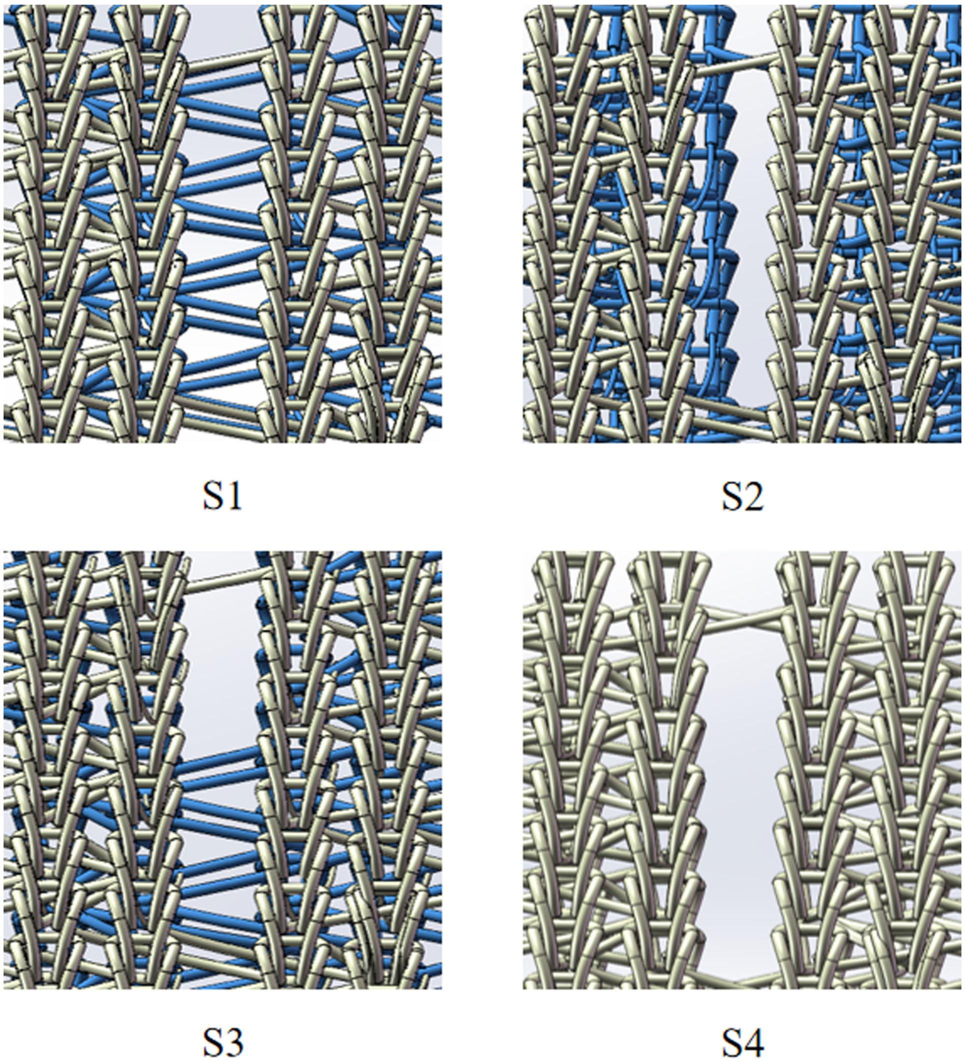

Figure 5. Fabric geometric structure model.

pressure difference between the inlet and outlet boundary of the model is kept constant, which is 100 Pa. The inlet boundary type: inlet, attribute value: 0 Pa; the outlet boundary type: outlet, attribute value: −100 Pa; the wall boundary type: wall, attribute value: 0 Pa; the wall boundary type: −100 Pa; the inlet boundary type: −100 Pa; attribute value: 0 Pa; wall, attribute value: 0 Pa. Figure 8 illustrates the boundary conditions and parameters of the sample model.

4. Simulation calculation results and discussion

4.1. Characteristics of gas flow within the fabric

Figure 9 shows the trajectory diagram of the velocity change and flow path distribution of the gas flow within the fabric, which is modeled by a yarn body and a three-dimensional shaped

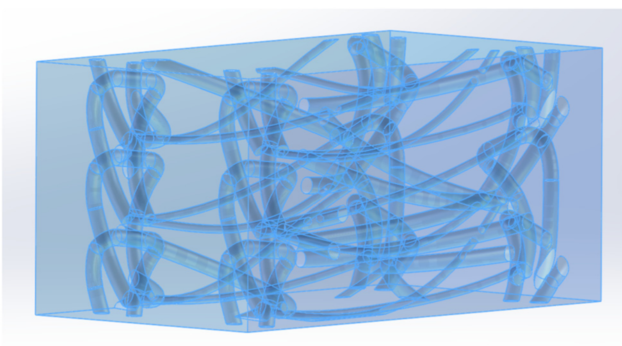

Figure 6. Fluid domain.

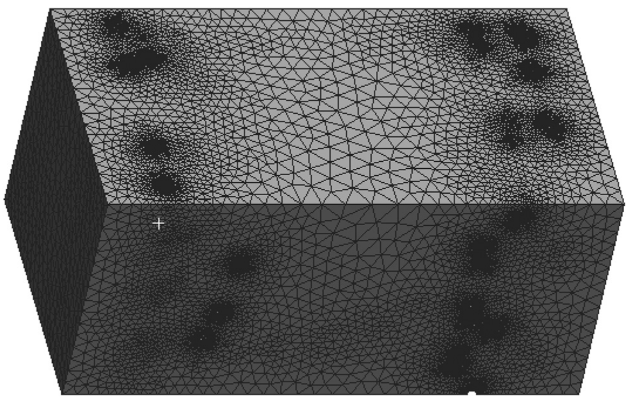

Figure 7. Grid division situation.

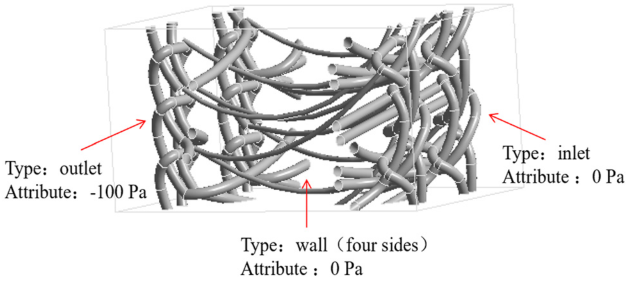

Figure 8. Boundary conditions and parameter settings.

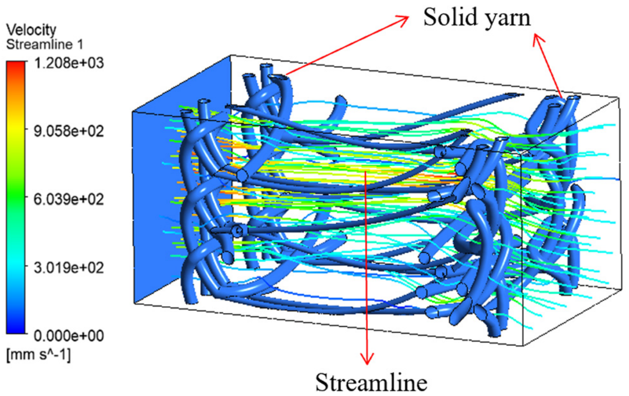

Figure 9. Path of airflow through the fabric.

fluid domain. In this case, the yarns are presented in solid form, while the flow paths of the gas flow are depicted by streamlines. The presence of the yarns results in pores and gaps between the yarns restricting the free flow of the gas so that the gas stream is subjected to significant resistance when passing through these regions, which in turn affects the flow path and velocity of the gas.

In the fluid domain, the gas flow will preferentially choose the location where it is easy to pass through [11], so the gas flow mainly flows along the gaps between the yarns, and after passing through the yarn gaps, the gas flow will be hindered when passing through the fabric, which slows down its flow speed. After passing through the yarns, a large number of gas molecules will gather toward the pores of the fabric, and due to the increase of the exit pores of the fabric, the airflow mostly gathers toward the mesh, and the flow velocity increases. The velocity distribution of the fluid is shown as a continuous curve, the fluid flows along a regular path within the fabric, the fluid is layered in an orderly manner, and the flow rate changes from slow to fast, and the flow process is relatively stable. In addition, the viscosity between the gas molecules makes the flow field show an orderly flow pattern, and the fluid exhibits the characteristic of layered flow along the direction parallel to the pipe wall in the fluid domain pipe.

4.2. Fabric simulation calculation results

After completing the mesh delineation and model boundary condition setting, its data need to be imported into ANSYS Fluent fluid analysis software in order to create a fluid simulation project. First of all, the simulated fluid is set as air, the flow type is set as spacer flow, and then the inlet is selected as the initialization condition, and the number of iteration steps is set to start the steady-state calculation. Through iterative calculations, a discrete quantitative description of the turbulence field inside the sample model can be obtained, so as to predict the motion law of the air permeability process inside the model, and the simulation calculations are completed and then imported into CFD-Post to output the required data, so as to more intuitively understand the hydrodynamic behavior inside the model.

Figures 10 and 11 show the airflow velocity clouds of the model simulation results, where Figure 10(a)–(d) shows the cross-sectional velocity clouds of models S1, S2, S3, and S4, respectively, along the direction parallel to the direction of air flow, with all the fluids flowing from right to left. From the cloud plots, it can be seen that the yarn model exerts a significant obstruction effect on the air flow, resulting in a reduction of the flow velocity. The inlet and outlet boundary conditions under different models have obvious effects on both the distribution and flow velocity of the airflow, and are directly related to the air permeability of the fabric.

Model S1 is a single-sided mesh structure with a dense organization at its inlet boundary. At the initial stage, the airflow is uniformly distributed in the dense surface layer. When the airflow contacts the bottom layer of the mesh through the intermediate spacer layer, the gas mostly gathers toward the mesh due to the larger pores of the bottom layer, so the air permeability rate of S1 has a certain advantage. Model S2 is a transverse semi-through-hole structure, i.e., the corresponding mesh pores of the upper and lower surface layers of the fabric differ from each other by one longitudinal row of coils, and its entrance boundary is the mesh organization. In the initial stage, the gas flow will gather toward the mesh at the entrance, resulting in the gas flow rate at the mesh being much larger than that at the surrounding non-mesh. When the gas passes through the spacer layer, the flow field is in the state of accelerated flow, and the gas will diffuse toward the bottom layer of the mesh, which in turn leads to a larger diameter of the exit flow field and an increase in the permeability rate. Model S3 is a longitudinal half-through-hole structure, i.e., the mesh corresponding to the upper and lower surface layers of the fabric differs by four coils across the row, and its entrance boundary is the mesh organization. The gas first accumulates toward the mesh at the entrance, then passes through the intermediate spacer layer and accelerates out of the bottom layer of the mesh. In addition, Figure 11 illustrates the velocity cloud along the direction perpendicular to the gas flow direction, i.e., the model exit velocity, from which it can be concluded that the exit permeability rate of model S3 is significantly higher than that of model S2; the gas flow rate between the pores in the coils is significantly lower than that at the longitudinal rows of intervals, which is due to the fact that the pores in the coils are smaller and the gas flow is restricted by the smaller space, which results in a lower flow rate, while the pores at the longitudinal rows of intervals of the fabric are larger, and the gas flow is also relatively free and hence the flow

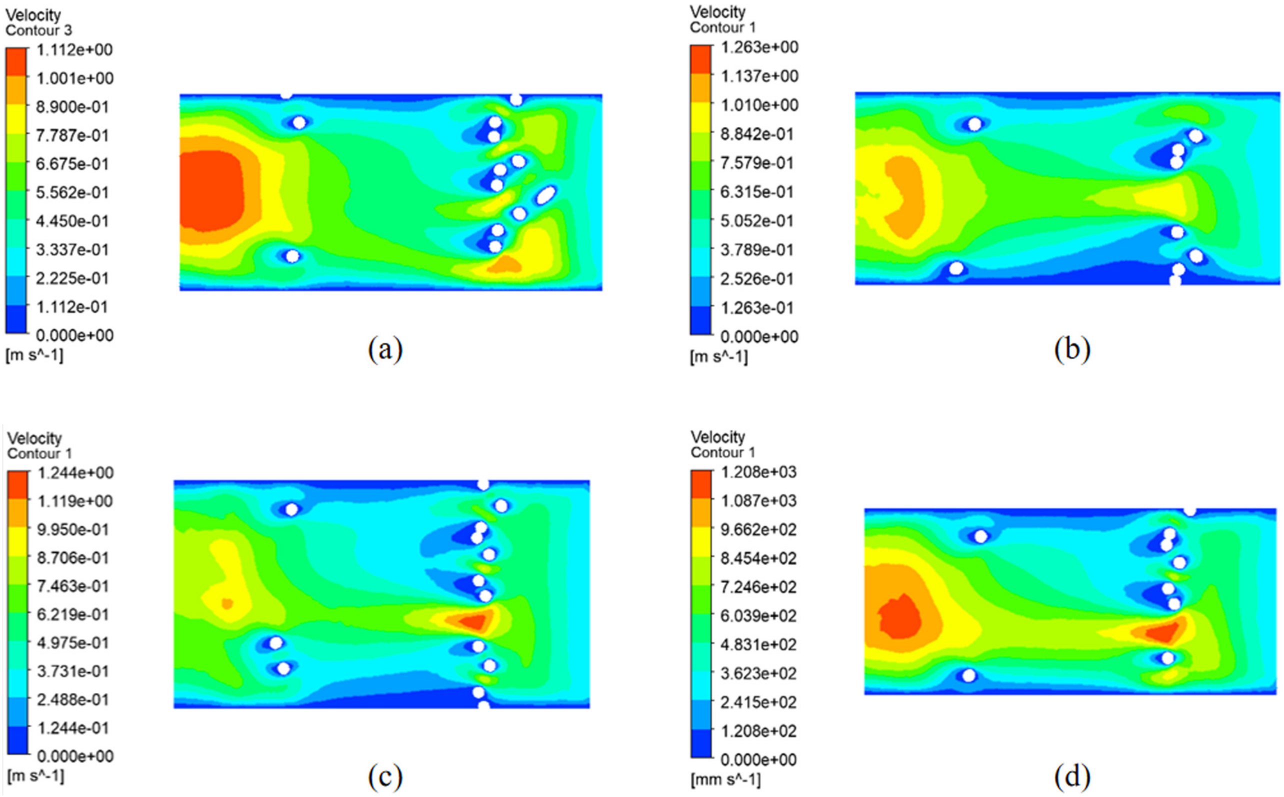

Figure 10. Cross section velocity cloud map. (a) S1, (b) S2, (c) S3, (d) S4.

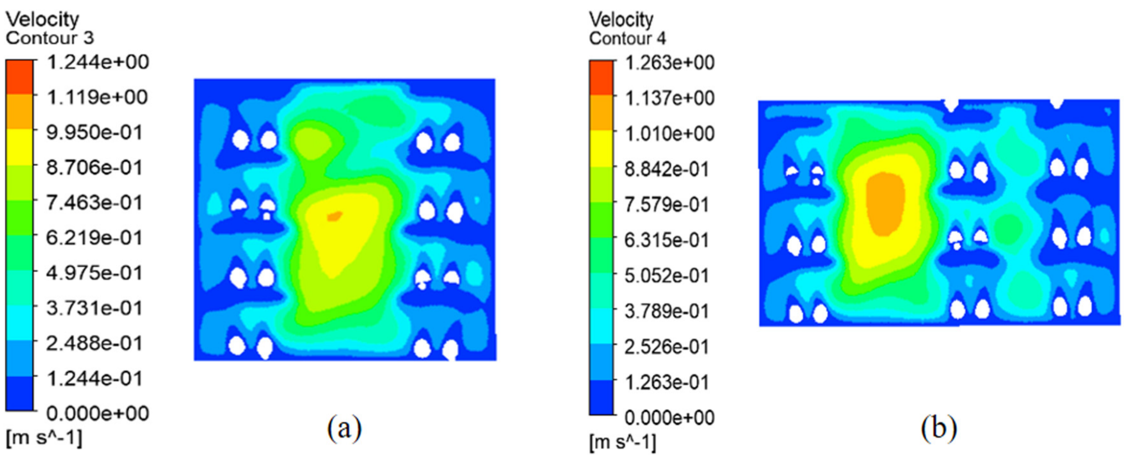

Figure 11. Outlet velocity cloud map. (a) S2, (b) S3.

rate is higher. Model S4 is a double-sided perforated structure with mesh organization at the inlet and outlet boundaries. When the gas flows in from the surface layer of the mesh, due to the large pores in the surface layer of the model, the gas will quickly pass through the intermediate spacing layer and then flow out from the bottom layer of the other mesh, and the whole flow field is in an accelerated outflow state, and the overall gas flow rate of the model increases, which leads to a large rate of outlet permeability. In summary, according to the model simulation results, the air permeability performance is ranked as follows: S4 > S3 > S2 > S1.

5. Data comparison and error analysis

Figure 12 shows the comparison between the test and simulation results for each sample. Through the comparison, it can be seen that the results of fabric air permeability obtained by simulation and test are consistent, both of which are S4 > S3 > S2 > S1. Despite the fact that the results of the two are similar in terms of data, there is a certain difference in the values, which is manifested in the fact that the simulated air permeability results are higher than the experimentally determined values. The reasons for the error mainly are (1) due to the subjective

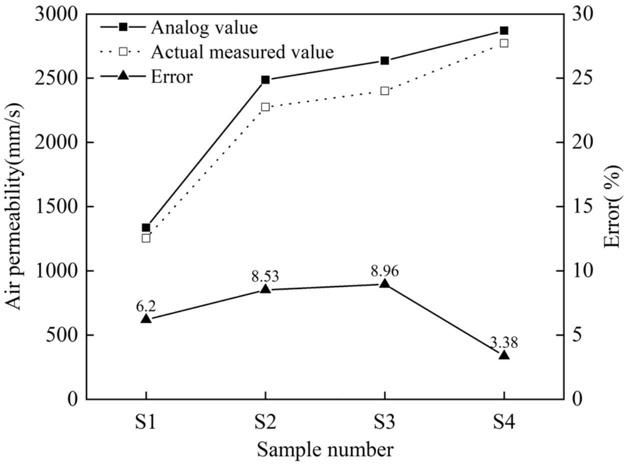

Figure 12. Comparison of measured and simulated air permeability.

judgment of the experimental parameters, the problem of the mesh quality and the actual irregularity of the actual yarn material, it will make the fabric model deviate from the actual samples to a certain extent. (2) In the simulation calculation, the yarn entity is simplified as an ideal rigid material, and the hair plume on the surface of the yarn as well as the friction force of the yarn and fibers on the air are ignored, which results in the impediment of the airflow through the yarn surface This results in minimizing the obstruction of airflow through the yarn surface, which increases the simulation results of air permeability. (3) When setting the boundary conditions, the simulated environment differs from the actual environment. A static constant pressure difference is used in the simulation, while the pressure difference between the two sides of the fabric is in a dynamic process during the actual test, which may lead to deviations in the air permeability values.

However, although a simplified fabric model is adopted in this article, this simplification does not affect the realism of the model, and also significantly reduces the difficulty of modeling, and can accurately reproduce the real organizational structure of the fabric, making the simulation results closer to the actual situation. Therefore, the simplified model not only improves the modeling efficiency, but also ensures the reliability of the modeling. In addition, by comparing the simulated and measured data, it can be concluded that the maximum deviation between the two is less than 10%, which is in the acceptable range, which indicates that the results of predicting the air permeability performance of footwear materials by numerical simulation methods are reliable. At the same time, the simulation of airflow inside the fabric by using finite element is of great significance to understand the pressure and airflow velocity inside the fabric and the change of the force of yarn, which is of some guidance to the fabric design.

6. Conclusion

The article focuses on the design of four unique mesh structures and constructs a three-dimensional geometric structure model of the corresponding fabric using Solidworks software. Based on CFD methods, the air permeability behavior of the structural model was simulated using ANSYS Fluent software, aiming to explore the differences in air permeability performance of warp knitted jacquard shoe materials with different surface structures. Finally, after comparing and analyzing the numerical simulation results with the actual measurement results, the following conclusions were drawn.

Under the same conditions, the permeability of the four samples is double-sided through-hole > longitudinal half-through-hole > transverse half-through-hole > single-sided mesh. The double-sided perforated shoe material has the best air permeability, and the air permeability of the jacquard spacer shoe material can be optimized by adjusting the alignment relationship between the upper and lower layer mesh holes of the fabric.

For two types of shoe fabrics with the same reverse structure, we found that adjusting the mesh structure on the front of the process also has a significant impact on the air permeability of the shoe material. Under the same conditions, when the surface mesh of the fabric undergoes longitudinal transformation, it is more conducive to the air flow inside the shoe material. In addition, it was found that the tightness of the fabric structure is negatively correlated with its air permeability, the tighter the structure, the greater the obstruction to air flow, and the poorer the air permeability.

Comparing the simulation results with the experimental results, it was found that the two were highly consistent, with a simulation error of less than 10%. This result fully demonstrates that the established numerical model can accurately simulate the air permeability behavior of warp knitted jacquard interval shoe upper fabric and truly reflect the actual characteristics inside the fabric, providing strong support for subsequent related research.

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Data availability statement: The data is available from the corresponding author upon request.

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