(REFEREED RESEARCH)

PREDICTION OF AIR PERMEABILITY OF KNITTED FABRICS BY MEANS OF COMPUTATIONAL FLUID DYNAMICS

HESAPLAMALI AKIŞKANLAR DİNAMİĞİ YARDIMIYLA ÖRME KUMAŞLARIN HAVA GEÇİRGENLİĞİNİN TAHMİN EDİLMESİ

Serin MEZARCIÖZ[1], Serkan MEZARCIÖZ[2], R.Tuğrul OĞULATA[1]

[1]Çukurova University, Department of Textile Engineering, Adana, Turkey
[2]Çukurova University, Department of Mechanical Engineering, Adana, Turkey

Received: 26.12.2013 Accepted: 30.06.2014

ABSTRACT

The aim of current study is to develop a novel approach for simulation of the single jersey fabrics' air permeability based on the present abilities of Computational Fluid Dynamics (CFD) systems. 3D simulation of the through-thickness permeability of knitted fabrics was performed by using FLUENT® software package. The numerical results were verified on the basis of experimental data. At the end of study, it is found that experimental results are highly compatible with the numerical CFD results.

Key Words: Air permeability, Knitted fabric, Pore, CFD, Fluent.

ÖZET

Bu çalışmanın amacı, Hesaplamali Akışkanlar Dinamiği (HAD) sistemlerinin bugünkü yeteneklerine gore, suprem kumaş hava geçirgenliği simülasyonu için yeni bir yaklaşım geliştirmektir. Örme kumaşların kalınlık boyunca geçirgenliğinin 3 boyutlu simülasyonu FLUENT® yazılım paketi kullanılarak gerçekleştirilmiş, nümerik sonuçlar deneysel veriler temelinde doğrulanmıştır. Çalışma sonunda, deneysel sonuçların nümerik HAD sonuçları ile büyük ölçüde uyumlu olduğu bulunmuştur.

Anahtar Kelimeler: Hava geçirgenliği, Örme kumaş, Gözenek, CFD, Fluent.

Corresponding Author: Serin Mezarcıöz, smavruz@cu.edu.tr, Tel: +90 535 746 95 24,

1. INTRODUCTION

Knitted fabrics are the preferred structures in athletic wear in which demand for comfort is a key requirement. Comfort is the perceived psychological feeling of a wearer under current conditions of the physical activities and the environment. Knitted fabrics are known for their excellent comfort properties. They possess high extensibility under low load allowing comfortable fit on any part it is pulled onto (1).

Knitting structures are important because they offer several advantages. Physically, they present properties of comfort such as high elasticity, conformity with the shape of the body, softer and better touches feeling of freshness, and others (2).

Precise assessment of air permeability during the design stage of textiles is of great importance, as it can reduce the cost in development of new structures (3).

There are lots of studies computing air permeability of knitted fabrics by means of image analysis and theoretical methods. Ogulata and Mavruz established a theoretical model for the porosity and predicted air permeability of plain knitted fabrics. For this purpose, a theoretical model of porous systems based on Darcy's Law was used, the validity of which was confirmed by experimental results using 100% cotton plain knitted fabrics (4). Karaguzel calculated values of pore size and pore volume for plain knitted fabrics. Those of the pore size were measured with image analysis and fluid extrusion procedures. It was found that there was a noticeable difference between the estimated and measured values (1). On the basis of computer image analysis, the surface porosity of knitted fabrics was evaluated for plain double-layered and lining knitted fabrics by Wilbik-Halgas et al. It was found that air permeability, contrary to water vapor permeability, is a function of the thickness and surface porosity of knitted fabrics (5). Benltoufa et al. investigated methods of determining jersey porosity, which proved that geometry modelling is the most suitable and easiest method of determining porosity (2). Dias and Delkumburewatte, created a theoretical model to predict the porosity of a knitted structure. It was determined that porosity depended on fabric parameters and relaxation progression (6). Mavruz and Ogulata, investigated air permeability of cotton knitted fabrics. Before manufacturing the fabrics the equation of regression was used to predict air permeability, depending on some fabric properties (7). Vassiliadis et al., used the Computational Fluid Mechanics methods for the air permeability of the woven fabrics (8).

There is only limited number of studies in literature using CFD technique applied to knitted fabrics. Mullings et al., was developed a geometric model of a knitted metal filter. The geometric model outputs can then be coupled with a novel CFD model for fibrous filtration. The CFD results were compared to classical single fiber efficiency theory for conventional fibrous filters. The CFD results showed increased capture efficiency and pressure drop compared to fibrous filter theory (9).

In the study of Cimilli et al., the natural convective heat transfer coefficient for plain knitted fabric is estimated by numerical modeling, and the applicability of commercial software using the finite volume method (FVM) to textile problems was investigated (10).

In the current study, air permeability of knitted fabrics was determined by means of computational fluid dynamics. And numerical results were compared with the experimental results.

2. MATERIALS AND METHODS

2.1. Materials

In order to compare the values of air permeability from using CFD technique and that using experimental and theoretical air permeability, we carried out 12 different knitted samples with various knitting parameters. The yarns were made of cotton fibers and the knitting type of each sample was plain. Plain knitted fabrics were knitted with three different tightness (slack, medium and tight) on a circular knitting machine using ring and compact yarns.

Knitted samples were conditioned for 48 hours in the atmospheric conditions of temperature 20±2ºC and relative humidity 65±2 %, before the tests were taken. Air permeability of the samples ($cm^3/cm^2.sec$) was measured via standard TS 391 EN ISO 9237 method (11), using the Textest FX 3300 air permeability tester. The measurements performed at a constant pressure drop of 100 Pa (20 cm^2 test area). Also, loop length, wales per cm, courses per cm, thickness and weight of the fabrics were measured according to the relevant standards (12-15) (Table 1).

2.2. Methods

<u>**Theory**</u>

The calculation method of air permeability of knitted fabrics by means of Darcy's Law was explained previously as follow: (4).

A knitted fabric consists of one or more looped yarns. Plain knitted fabric, which is illustrated in Figure 1, is one structure of knitted fabrics. W and C represent the wales spacing and course spacing whereas w and c correspond to the number of wales per cm and number of courses per cm respectively (16). (Wales per cm; the number of visible loops per unit length (cm) measured along a course. Courses per cm; the number of visible loops per unit length (cm) measured along a wale. Stitch length; the length of yarn in a knitted loop).

The pressure gradient through a textile is a function of viscosity, density, rate of fluid flow and porosity, just as in the case of flow through a pipe (17).

The dependence of the friction coefficient f on the Reynolds Number Re for laminar and turbulent flow is described by the Blasius equation:

Table 1. Fabric properties

Sample number	Yarn number (Ne)	Loop length (cm)	Course count per cm	Wale count per cm	Thickness (cm)	Mass per unit area (g/m^2)	Experimental air permeability ($cm^3/cm^2.sec$)
1	30	0.255	23.0	12.3	0.0069	161.38	119.3
2	30	0.320	16.0	12.1	0.0068	136.90	156.2
3	30	0.330	15.0	13.0	0.0062	134.22	194.8
4	40	0.256	24.0	12.2	0.0063	120.88	202.0
5	40	0.320	15.0	12.0	0.0052	87.22	305.9
6	40	0.280	18.0	13.0	0.0060	118.24	296.6
7	30	0.285	18.0	12.3	0.0057	136.78	156.2
8	40	0.284	19.0	12.0	0.0059	105.72	207.7
9	40	0.250	15.0	13.0	0.0065	107.16	370.8
10	30	0.286	19.0	13.0	0.0058	143.72	164.7
11	40	0.261	24.0	13.0	0.0059	126.10	245.9
12	30	0.260	24.0	13.0	0.0060	159.48	153.2

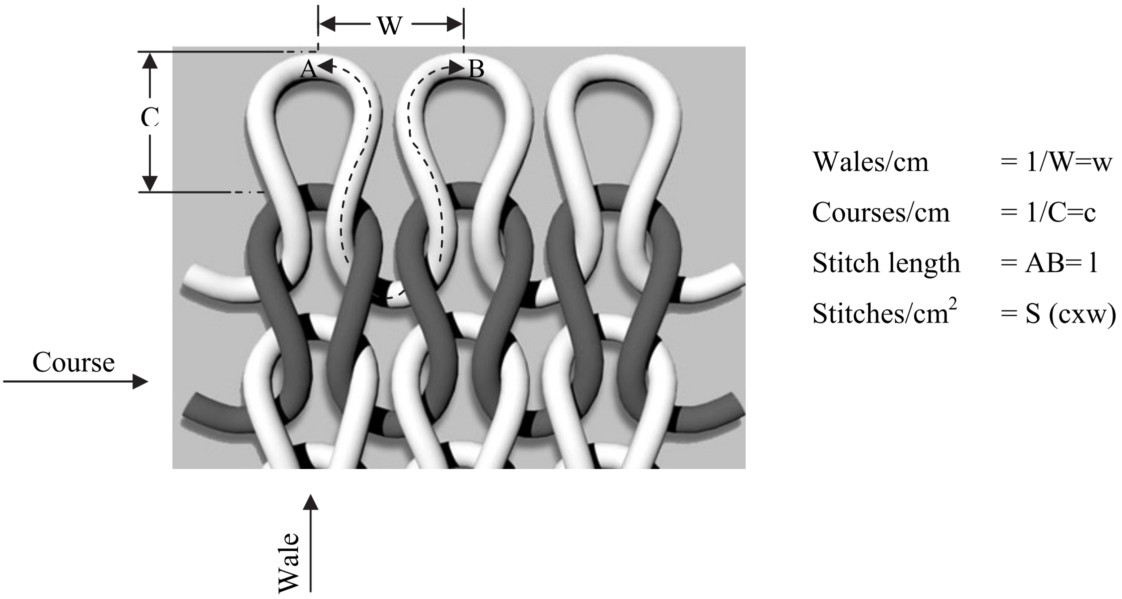


Figure 1. Representation of a plain knitted fabric

$$f = \lambda . \mathrm{Re}^{-n} \tag{1}$$

where λ is the coefficient of laminar or turbulent flow, n is a coefficient indicating the flow regime.

Laminar flow : λ= 64, n=1

Turbulent flow : λ= 0,3164, n=0,25

The type of flow depends on Reynolds number. The Reynolds number represents the ratio of inertia force to viscous force (18).

The Reynolds number is calculated as:

$$\mathrm{Re} = \frac{U_m . d_h}{\nu} \tag{2}$$

where U_m is the mean flow velocity, d_h is the hydraulic diameter of a pore, ν is the kinematic viscosity of the air (18, 19).

The pressure drop of the flow through a duct over the thickness of the fabric is related to the friction factor f by the Darcy's formulation.

$$\Delta P = f \frac{t}{d_h} \rho \frac{U_m^2}{2} \tag{3}$$

where t is the thickness of the fabric, ρ is the air density (20).

The knitted fabric is porous structure. For this reason, the air velocity in pores must be taken into consideration.

$$U = \frac{U_m}{\varepsilon} \tag{4}$$

where U is the air velocity through pores, ε is rate of void area (porosity) (18).

Figure 2 shows the pore within a loop. Our theoretical model was created by considering one repeating unit cell of the knitted structure. By determining the course (c) per cm, wale (w) per cm, thickness (t), yarn diameter (d_y) and loop length (l), the porosity is as follows (2):

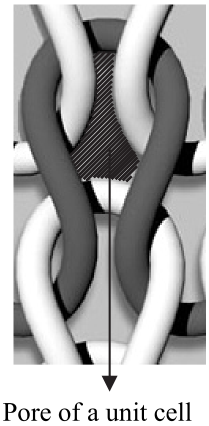


Figure 2. Stitch diagram of a plain knitted structure

$$\varepsilon = 1 - \frac{\text{Yarn volume}}{\text{Total volume}} \tag{5}$$

$$\text{Yarn volume} = \frac{\pi d_y^2 2l}{4} = \frac{\pi d_y^2 l}{2} \tag{6}$$

$$\text{Total volume} = \frac{1}{c}\frac{1}{w} t = \frac{t}{cw} \tag{7}$$

Finally,

$$\varepsilon = 1 - \frac{\pi d_y^2 lcw}{2t} \tag{8}$$

The air velocity through pores of the fabric has not usually a high value. Therefore, the fluid flow in the pores is laminar flow. For the kinetic theory, if the Reynolds number is below 2320, the flow in the tube is laminar (18, 19). For this reason, the mean air velocity through one pore can be expressed as:

$$U_m = \left(\frac{d_h^2}{32\eta t} \right) \Delta P \tag{9}$$

The flow rate of the air for the fabric with porous material Q becomes:

$$Q = m.A_1.U \tag{10}$$

where m is the number of pores, A_1 is the cross-sectional area of pore (18)

$$A_1 = \pi \frac{d_p^2}{4} \tag{11}$$

where, d_p is pore diameter (In this study, the loops are assumed to be composed of ideal yarns which are circular in cross-section and have a constant diameter throughout their length, yarn deformation at crossover points is omitted, so, it is accepted $d_p = d_h$).

Thus, equation (10) can be written as follow:

$$Q = \frac{m}{\varepsilon} \pi \frac{d_p^4}{128\eta t} 10^{-6} \Delta P \text{ (m}^3\text{/s)} \tag{12}$$

The value of air permeability (R) is calculated according to the following equation

$$R = \frac{Q}{A_t} \tag{13}$$

where A_t is the tested fabric area (11).

Air permeability values of the samples, calculated theoretically and measured experimentally can be seen in Table 2.

Table 2. Air permeability values of the samples, calculated theoretically and measured experimentally (4).

Sample number	Experimental air permeability (cm^3/cm^2.sec)	Theoretical air permeability (cm^3/cm^2.sec)
1	119,3	127,4
2	156,2	162,7
3	194,8	202,4
4	202,0	208,7
5	305,9	392,6
6	296,6	297,1
7	156,2	180,5
8	207,7	295,2
9	370,8	319,6
10	164,7	181,0
11	245,9	210,8
12	153,2	147,2

Computational Fluid Dynamics (CFD)

Computational fluid dynamics, usually abbreviated as CFD, is a branch of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. With high-speed supercomputers, better solutions can be achieved.

In the study, for the numerical simulation, FLUENT® program was employed. FLUENT® is a CFD program that analyzing flow in/around complex geometries and heat transfer. The first stage in CFD analysis is to generate a 3D mesh structure and the next is to solve the flow equations numerically between the mesh elements (21, 22).

A powerful approach to obtain insight into momentum transport within textiles is based on CFD. With this methodology it is in principal possible to predict details regarding the distribution of pressure and velocities of fluid momentum in textiles to any desired accuracy. However, limitations are still imposed by computer hardware and associated requirements for time consuming computations. Moreover, CFD calculations always based on specific assumptions; hence in order to be meaningful they need to be validated by experiments (23).

Main steps of the study are as follows;

1. Design of 3D geometric model
2. Grid generation
3. Assignment of boundary conditions
4. Running the analysis.
5. Post processing

2 parameters have significance during mesh generation. These are, number of grid element and grid density. Employing a high-density grid in critical regions, while using a coarse grid in other regions, provides a lower number of element and optimum times for the solution.

CFD Modeling of Knitted Fabrics

When considering the fluid flow through textiles, the shape arrangement and size distribution of voids through, which the fluid flows, has a great importance. Fabric thickness and differential pressure between the two surfaces of a fabric are the other dominant factors that affect permeability (17).

In this study, the loops were assumed to be composed of ideal yarns, which were circular in cross-section and have a constant diameter throughout their length; yarn deformation at crossover points was omitted. So, Figure 3 illustrates, the interstices between the threads can be depicted as circular shapes by referencing the theoretical approach explained previously (4).

In the current study, the preliminaries conducted and results obtained for sample 1 will be explained and discussed in detail, analysis results of the rest of the samples will be provided in the results section briefly.

Flow passages over the sample 1 can be assumed that a cylinder having dimensions 0,68 mm diameter and 0,069 mm height by referencing the study of Ogulata and Mavruz, 2010 (4).

Angelova et al. 2011 (3) investigated 3X3, 4X4, 5X5 and 6X6 cylinder systems in their study and stated that, a 4X4 cylinder system is enough to simulate the 3D flow through a single layer fabric to save simulation cost and CPU time. In our study since we have a powerful workstation, having 12 dual core 2,67 GHz processors and 12 GB of RAM. And also the geometry analyzed is so simple. There is no problem related with the simulation time. By considering these situations, in order to stay in the safe side and to get more reliable results we added 2 extra rows (Left and right) and 2 columns (Top and bottom). And a 6X6 cylinder system was designed (Figure 3). A 6X6 cylinder system can be analyzed under a 5mm by 5 mm area. So, analysis was run over a 5X5 mm region of the fabric assumed that having 36 cylindrical pores. Dimensions and the distribution of the pores of this region can be seen in Figure 4.

Quality of a grid is the most important part of a CFD Analysis. In this study, 3D geometric model of the fabric structure was created by using 3D CAD program CATIA. In general, if this kind of geometries is modeled in a single volume, triangular elements providing less precision is generated. So, in order to create a high quality grid, flow domain must be sub-divided into simple geometries like cylinders and rectangular cross-section bars. The main purpose of dividing the main body into simple parts is to provide a flow domain that can be meshed with rectangular elements, which provides a high quality and more precise results, instead of triangular elements. So, since the flow domain consists of inlet channel, outlet channel and 36 pieces of cylinders representing the pores in the fabric. The flow domain created in 38 distinct bodies. As a result of this, quadrilateral grid element providing more precise results can be generated.

Length of the inlet channel and outlet channel was determined by referencing the study conducted by Leisen et al. 2005 (23). In that study, a ratio was determined by normalizing the inlet channel length with fabric thickness as about 138 (460/3,34). In the current study, according to this ratio, the length of inlet channel was calculated as 0,069*138=9,52 mm. To be in the safe side and create a smooth mesh, length of inlet channel was rounded to 10 mm.

Similarly again by normalizing the outlet channel length with fabric thickness with the values in the same manuscript (22), (135/3,34=40). By using this ratio the length of outlet channel was determined as 40*0,069=2,76 mm and finally by increasing the ratio to be in the safe side, the final outlet channel length was determined as 3 mm.

By considering inlet/outlet channels' lengths and 0,069 mm of fabric thickness, the length of the flow domain was calculated as 13,069 mm (The total length of the flow domain is summation of inlet channel, outlet channel and fabric thickness).

The flow domain can be seen in Figure 5.

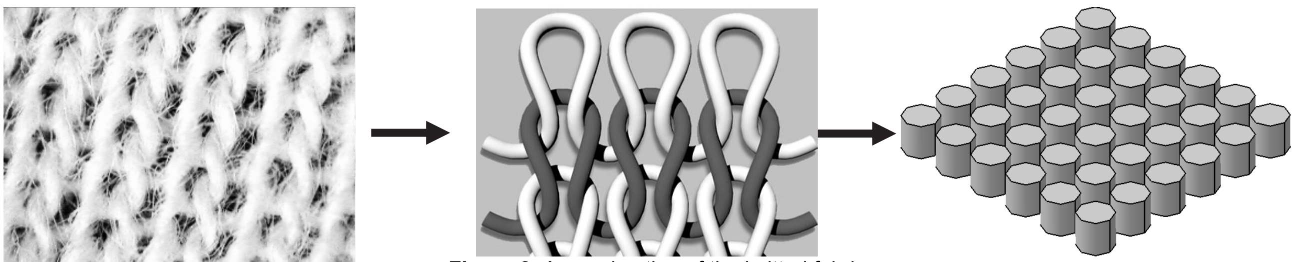


Figure 3. Approximation of the knitted fabric

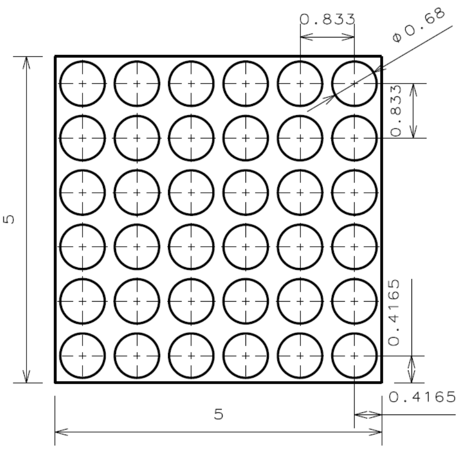


Figure 4. Flow domain (Section view)

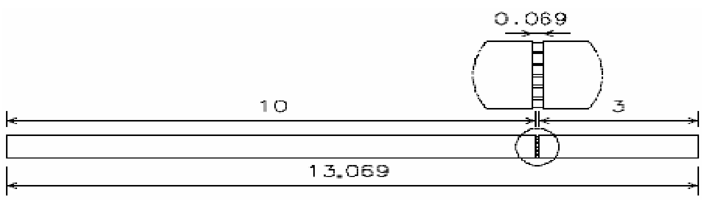


Figure 5. Flow domain (Dimensions in mm)

After designing 3D geometric model of the flow domain, grid generation process, which is the next step of CFD analysis, was carried out by employing GAMBIT® program (25).

While creating models with CFD codes, it is important to check whether the solution is independent of the grid. One way to perform this study is to increase the number of grids in the simulation till that accuracy is reached. The solution from two models of different grid densities is compared. One or several such comparisons can be done to ensure grid independency. If the solutions of the highest two grids densities are within a sufficiently small predetermined tolerance, the final grid density is considered sufficiently accurate for engineering purposes (26).

The effect of grid density on the results for the current simulations was determined by performing a grid independency study.

In the current study, grid density of each of the parts (inlet/outlet channels and cylinders) forming the flow domain was changed and the effect of change was examined. For this purpose 4 different meshes with different density and number of elements were generated and analyzed under the same conditions. Resultant values of element numbers and worst element's equisize skewness of inlet, outlet channels and pores of flow domain can be seen in the following Table 3.

Table 3. Number of element and equisize skewness of grids

	Grid 1	Grid 2	Grid 3	Grid 4
Inlet Channel	62.500	250.000	375.000	500.000
Outlet Channels	18.750	75.000	112.500	150.000
Pores	101.520	101.520	203.040	203.040
Total Element Number	182.770	426.520	690.540	853.040
Worst Element	0,402	0,402	0,397	0,397

These 4 grids having different mesh densities were analyzed under the same conditions and the results of calculated air permeability values can be seen in Table 4;

Table 4. Values of air permeability with different grids

	Grid 1	Grid 2	Grid 3	Grid 4
Air permeability ($cm^3/cm^2.sec$)	153,2	138,0	127,5	125,3

In order to investigate in detail and see clearly the results, air permeability values obtained from each of the grids were graphed in Figure 6.

When we investigate the result Table 4 and graph in Figure 6, it is seen that in transition from GRID 1, which is the coarsest, to GRID 2, which is finer than GRID 1, results has big changes respectively (approximately 11%). Similar situation can also be observed in transition from GRID 2 to GRID 3 (approximately 8%). However, the amount of changes in transition from GRID 3 to GRID 4, which is the finest grid, is very small and it is below 2 %.

By evaluating the tables and graphics mentioned above, it is clearly seen that the GRID 4, which is the finest grid with 853.040 elements, gives the most suitable results and the solution can be accepted as independent from the grid. So, for the following analyses, grid will be generated by employing the properties of GRID 4.

The section view of the grid of flow domain can be seen in Figure 7.

As a result of all these processes, a grid containing 853.040 elements, 2.721.786 surfaces and 910.134 nodes was generated. The quality of the mesh was checked by GAMBIT® program with respect to minimum value of the equisize skewness, which was computed 0,397 for this grid. This equisize skewness value indicates that the grid generated is very high quality.

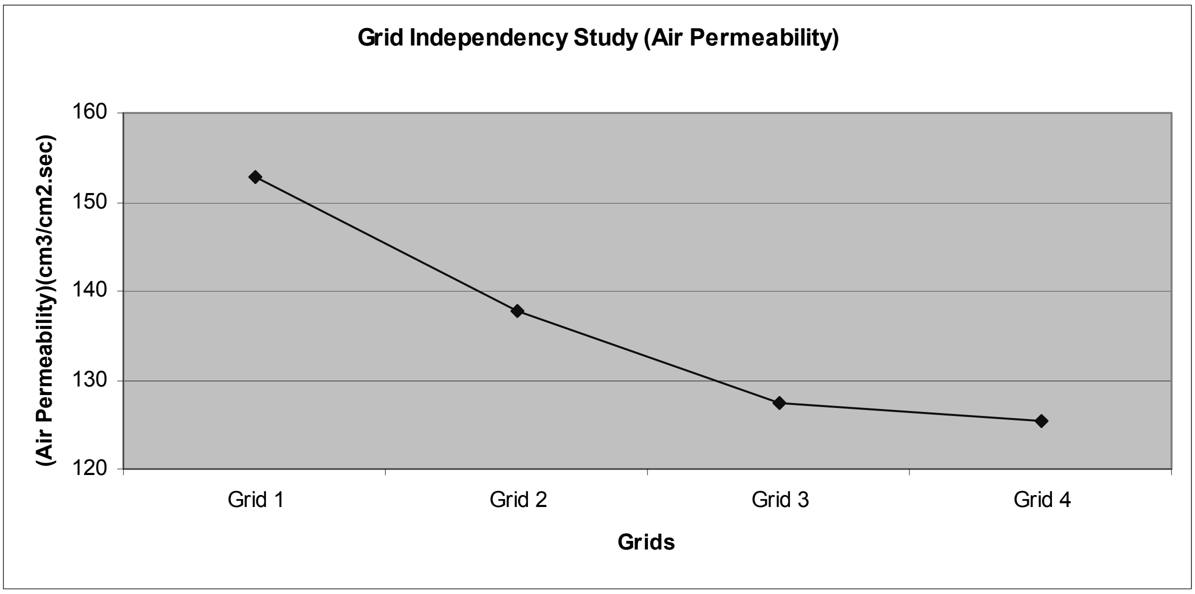


Figure 6. Grid independency study

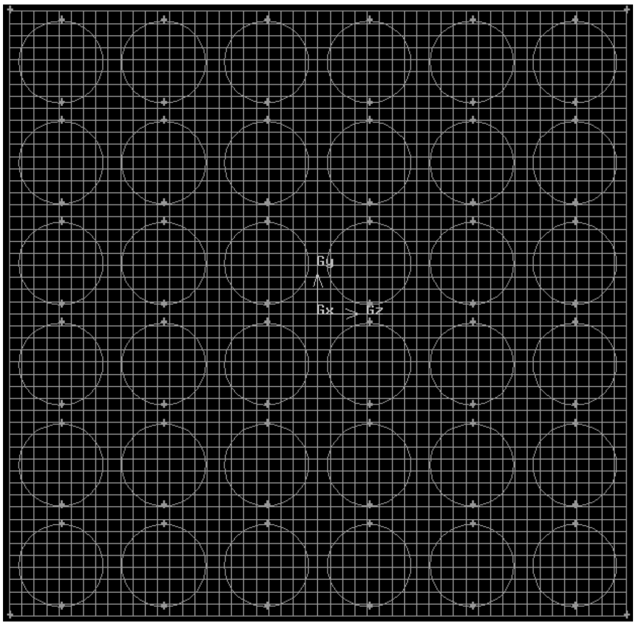


Figure 7. Section view of the flow domain in YZ plane, which is perpendicular to the flow direction.

The view of the fabric's mesh structure can be seen in Figure 8.

After completing the grid generation processes, boundary condition identifications were done by means of GAMBIT® program for each of the faces and volumes generating the flow domain. According to the measurement of air permeability test standard (TS 391 EN ISO 9237), while one of the faces of the fabric must be subjected to 100 Pa pressure, the other face of the fabric must be open to atmosphere. By considering the information above, the boundary conditions were determined and set as follows;

Boundary Conditions

Inlet Condition: According to the measurement of air permeability of fabrics test standard (TS 391 EN ISO 9237), it is set as "Pressure Inlet" with a value of 100 Pa (Gauge).

Outlet Condition: Since the outlet surface of the fabric is open to the atmosphere, it is set as "Pressure Outlet".

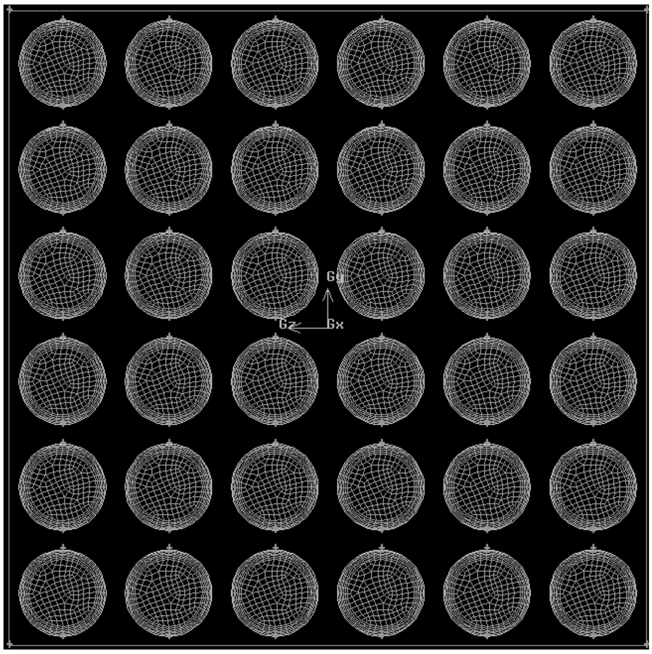


Figure 8. View of the fabric's mesh structure in plane perpendicular to the flow direction.

Walls: All the surfaces building up the flow domain, except inlet and outlet surfaces are set as "wall" with no-slip condition.

Interface: Boundary conditions of the interacted surfaces of divided volumes are set as "interface" in GAMBIT® program and the connection of these surfaces are built up in FLUENT® media.

Analysis Processes

The mesh generated with GAMBIT® program was opened in FLUENT® and the iterations were performed under specifications listed in Table 5, until the residuals were converged up to 10^{-5} level. During the iterations, default under relaxation factors recommended by Fluent for laminar flow was employed.

Table 5. Analysis values

Solver	:	Pressure Based, Implicit, Steady, 3D				
Model	:	Laminar				
Discretization	:	First Order Upwind				
Boundary Conditions	:	Pressure Inlet	:	Pressure Magnitude	:	100 Pa (Gauge)
			:	Hydraulic Diameter	:	5 mm
		Pressure Outlet	:	Pressure Magnitude	:	0 Pa (Gauge)
			:	Hydraulic Diameter	:	5 mm
		Wall	:	No slip condition		
Operating Conditions	:	Fluid Material	:	Air		
		Operating Pressure	:	101.325 Pa		
		Gravity	:	No		

3. RESULTS AND DISCUSSIONS

Velocity contours on surface of the fabric can be seen in Figure 9.

It is observed that the flow is concentrated in the center of the 5X5 mm fabric surface, which is analyzed. And it is seen that the big portion of the air passes through the center of the fabric. Area average velocity value in the outlet surface of the fabric was determined as 125.26 cm^3/cm^2.sec and the mass flow rate in that region was calculated as $38,4x10^{-6}$ kg/s.

Velocity contours away from the fabric surfaces with different distances can be seen in Figure 10.

The increasing velocity distribution at the center of the fabric can be seen in Figures 10. As going away from the center, the average velocity is getting smaller.

As a result, air permeability value of the fabric sample 1 was determined as 125,26 cm^3/cm^2.sec by means of CFD. And the experimental value for the same sample was 119,3 cm^3/cm^2.sec.

By following the same procedures for each of the other 11 samples, Air permeability values of the sample fabrics were determined by means of CFD. Results determined by numerically, theoretically and experimentally were listed in Table 6.

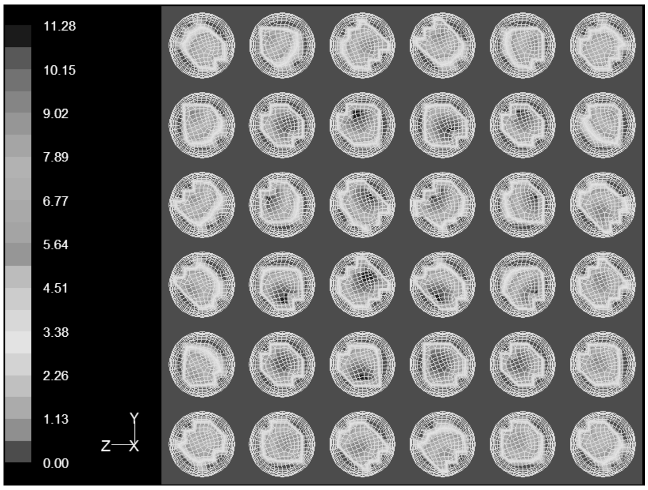
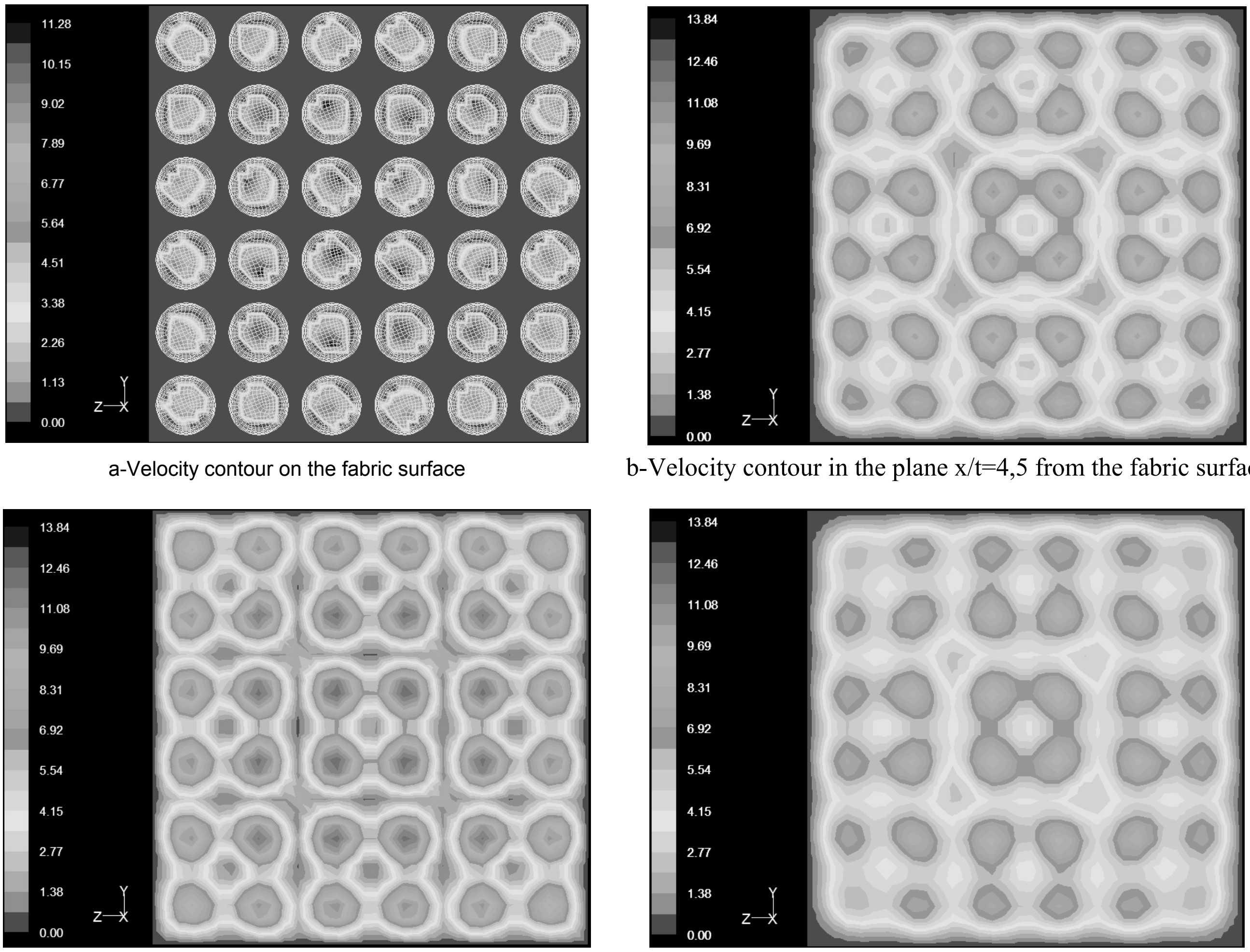


Figure 9. Velocity contour on surface of the fabric (Average Velocity: 125,26 cm/s)



a-Velocity contour on the fabric surface

b-Velocity contour in the plane x/t=4,5 from the fabric surface

c-Velocity contour in the plane x/t=1,5 from the fabric surface

d-Velocity contour in the plane x/t=7,5 from the fabric surface

Figure 10. Velocity contours away from the fabric surfaces with different distances (x) normalized by fabric thickness (t)

Table 6. Air permeability values for theoretical, measured and calculated with CFD

Sample number	Theoretical air permeability (cm^3/cm^2.sec)	Calculated air permeability with CFD (cm^3/cm^2.sec)	Measured air permeability (cm^3/cm^2.sec)
1	127,4	125,3	119,3
2	162,7	187,4	156,2
3	202,4	218,2	194,8
4	208,7	242,4	202,0
5	392,6	336,5	305,9
6	297,1	344,1	296,6
7	180,5	171,8	156,2
8	295,2	209,8	207,7
9	319,6	519,1	370,8
10	181,0	186,1	164,7
11	210,8	280,3	245,9
12	147,2	199,2	153,2

Comparing the method of CFD model and that using experimental air permeability values, we obtained the result demonstrated in Figure 11.

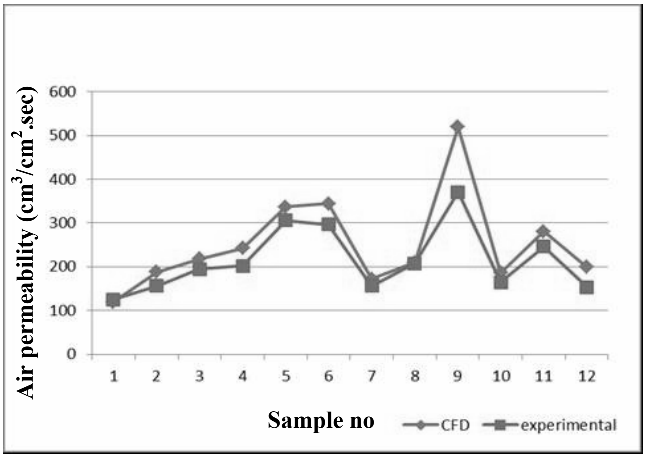


Figure 11. Air permeability values according to the experimental and CFD models

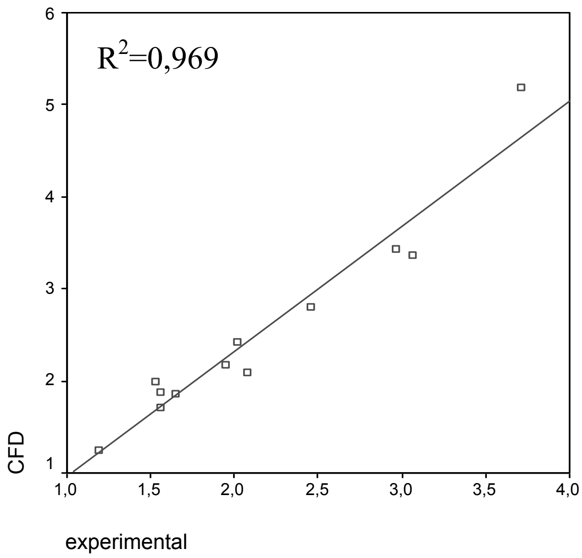


Figure 12. Correlation plots for predicted values with CFD and measured values

Correlation between the numerical and experimental values can be seen in Figure 12. (x axis-experimental values, y axis-predicted values with CFD). The match is close which is also indicated by the high values of correlation coefficients, R^2=0,969 obtained from the statistical analysis.

4. CONCLUSIONS

In this study, Computational Fluid Dynamics (CFD), which is a powerful tool, was used to predict the value of air permeability of plain knitted fabrics by referencing the previously developed theoretical model to determine air permeability by Ogulata and Mavruz (2010).

Air permeability of different knitted fabrics was determined by means of CFD and numerical results were compared with the experimental results. Due to the differences between ideal and real geometry and the random variation of the fabric structure, there are no exact dependences between experimental and predicted air permeability values with CFD. However, closeness of the results of the predictions based on CFD analyses and experimental values show that CFD analyses with our assumptions can be successfully used for prediction of the air permeability of knitted fabrics before manufacturing.

While the results of most of the samples calculated and measured are very close to each other some has rather big difference like sample 9. When the air permeability result of sample 9 was investigated, it is seen that the amount of difference between the calculated and measured values is rather big compared to other samples. It is thought that the source of this difference on sample 9 is the irregularities on the surface of the yarn. In CFD analyses all structural properties of the fabric and yarn assumed as ideal, on the other hand, since real yarns of sample 9 have much more irregularities than the other samples, although it was produced with compact yarn, the difference between calculated and measured values is rather big compared to other samples.

Since the experimental results are highly compatible with the numerical CFD results, it can be said that FLUENT® Package program can be used to simulate the 3D flow through pores of a knitted fabric.

Since the experimentally measured values are very close to theoretically calculated and CFD results by assuming the flow laminar, the flow characteristics of the flow through the knitted fabrics can be assumed as laminar.

REFERENCES

1. Karaguzel, B., 2004, “Characterization and Role of Porosity in Knitted Fabrics”, MSc Thesis, North Carolina State University, Department of Textile Engineering, Chemistry and Science, p.132.
2. Benltoufa, S., Fayala, F., Cheikhrouhou, M., and Ben Nasrallah, S., 2007, “Porosity Determination of Jersey Structure”, *AUTEX Research Journal,* Vol:7, No:1, pp:63-69.
3. Angelova, R.A., Stankov, P., Simova, I., and Aragon, I., 2011, “Three Dimensional Simulation of Air Permeability of Single Layer Woven Structures”, *Central European Journal of Engineering,* 1(4), pp:430-435.
4. Ogulata, R.T, Mavruz, S., 2010, “Investigation of Porosity and Air Permeability Values of Plain Knitted Fabrics”, *Fibres & Textiles in Eastern Europe*, Vol.18 No.5 (82), pp.71-75.
5. Wilbik-Halgas, B., Danych, R., Wiecek, B., and Kowalski, K., 2006, “Air and Water Vapour Permeability in Double-Layered Knitted Fabrics with Different Raw Materials”, *Fibres & Textiles in Eastern Europe,* Vol:14, No:3(57), pp: 77-80.
6. Dias, T., and Delkumburewatte, G.B., 2008, “Changing Porosity of Knitted Structures by Changing Tightness”, *Fibers and Polymers*, Vol:9, No:1, pp:76-79.
7. Mavruz, S., and Oğulata, R.T., 2009, “Investigation and Statistical Prediction of Air Permeability of Cotton Knitted Fabrics”, *Tekstil ve Konfeksiyon*, Vol:19(1), pp:29-38.
8. Vassiliadis, S., Kallivretaki, A., Cay, A., Dimitrofski, K., 2013, “Computational Modeling of the Air Permeability of Fabrics”,5th International Conference of Applied Research in Textile, CIRAT-5, Monastir, Tunisia, pp:12-13.
9. Mullins, B.J., King, A.J.C., and Braddock, R.D., 2011, “Modelling the Influence of Filter Structure on Efficiency and Pressure Drop in Knitted Filters”, 19th International Congress on Modelling and Simulation, Perth, Australia, pp:7.
10. Cimilli, S.D., Deniz, E., Candan, C., and Nergis, B.U., 2012, “Determination of Natural Convective Heat Transfer Coefficient for Plain Knitted Fabric via CFD Modeling”, *Fibres & Textiles in Eastern Europe*, Vol.20 No.1 (90), pp.42-46.
11. TS 391 EN ISO 9237, 1999, Textiles-Determination of the Permeability of Fabrics to Air, Turkish Standards Institution, Ankara.
12. TS EN 14970, 2006, Textiles - Knitted fabrics - Determination of Stitch Length and Yarn Linear Density in Weft Knitted Fabrics, Turkish Standards Institution, Ankara.
13. TS EN 14971, 2006, Textiles - Knitted fabrics - Determination of Number of Stitches per Unit Length and Unit Area, Turkish Standards Institution, Ankara.
14. TS 7128 EN ISO 5084, 1998, Textiles-Determination of Thickness of Textiles and Textile Products, Turkish Standards Institution, Ankara.
15. TS 251, 1991, Determination of Mass per Unit Length and Mass per Unit Area, Turkish Standards Institution, Ankara.
16. Booth, J.E., 1977, Textile Mathematics, The Textile Institute, ISBN 0 900739 24X, p.514.
17. Cay, A., Vassiliadis, S., Rangoussi, M., and Tarakcioglu, I., 2004, “On the Use of Image Processing Techniques for the Estimation of the Porosity of Textile Fabrics”, *International Journal of Signal Processing,* Vol:1(1), pp:51-54.
18. Ogulata, R.T., 2006, “Air Permeability of Woven Fabrics”, *Journal of Textile and Apparel, Technology and Management*, Volume 5, Issue 2, 1-10.
19. Xu, G., Wang, F., 2005, “Prediction of the Permeability of Woven Fabrics”, *Journal of Industrial Textiles*, Vol.34, No:4, 243-254.
20. Holman, J.P., 1992, Heat Transfer, Seventh Edition, McGraw-Hill Book Company, 1992.
21. http://www.ixforten.com/cfd.htm, Computer Fluid Dynamics, (accessed December, 2013).
22. Fluent 6.3.26, 2006, User’s Guide. Fluent Inc.
23. Leisen, J., Beckham, H., Farber, P., 2005, “Micro-Flow in Textiles“, NTC Project:F04-GT05, pp.10.
24. Bulut, S., Ünveren, M., Arısoy, A., Böke, Y.E., 2011, “CFD Analiz Yöntemiyle Klima Santrallerinde İç Kayıpların Azaltılması”, X. Ulusal Tesisat Mühendisliği Kongresi, Nisan, İzmir, pp.291-326.
25. GAMBIT 2.4.6. Software program, 2007.
26. Moujaes, S., Gundavelli, R., 2012, “CFD Simulation of Leak in Residential HVAC Ducts”, *Energy and Buildings* 54 (2012), 534–539.