(REFEREED RESEARCH)

INFLUENCE OF AIR FLOW DIRECTION ON THERMAL RESISTANCE AND WATER VAPOR PERMEABILITY OF RIB KNIT FABRICS

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ABSTRACT

Thermal resistance and water vapor permeability play a critical role in thermo-physiological comfort. There are many factors, which can have influence on the thermal resistance and the water vapor permeability; one of them is airflow direction. This study is aimed to effort to identify the impact of airflow direction on thermal resistance and the water vapor permeability when forced convection heat transfer is used. 18 samples of rib knit fabrics made from the same polyester yarn were prepared. Rib direction on the surface of rib knit fabrics provides a channel for airflow. The thermal resistance and the water vapor permeability in two directions of ribs against the airflow, perpendicular and parallel, was measured. It was found that there is the impact of rib directions on the thermal resistance and on the water vapor permeability. Results indicates that the thermal resistance increases when the ribs lies parallel with the direction of airflow and the water vapor permeability has the tendency to decrease when the ribs lies parallel with the direction of airflow.

Keywords: Thermal resistance, water vapor permeability, air flow, physiological comfort, rib knit fabric

1. INTRODUCTION

One of the main characteristics of clothing is to provide protection from environment and provision of balance between human body and environment. Textile Industry is exploiting various techniques and methods to improve functioning of clothing. One of the methods is to make changes in the structure of textile fabrics. One example is rib knit fabric, which has ribs on the surface. These ribs provides channel for airflow on the surface of the fabric (Figure 1).

Literature provides a number of studies conducted to evaluate impact of airflow direction on heat flow. These studies conclude that there is a significant impact of airflow direction on heat transfer. But there is a lack of study to find the impact of airflow direction on moisture transfer. There are three main ways of heat transfer; conduction, convention and radiation. Heat transfer through conduction depends upon the area of contact, temperature gradient and thermal conductivity of the material. Equation 1 describes the heat flow through conduction.

$$q = -\lambda \frac{\Delta T}{\Delta x} \qquad (1)$$

Equation 1 is based on Fourier's law to describe heat flow in one direction of a plate having variation in temperature on ends. In Equation 1, q indicates heat flow [Wm^{-2}], λ is used for thermal conductivity [Wm^{-1}K^{-1}], ΔT is the temperature difference [K] between two surfaces separated by a distance Δx [m]. Many studies have confirmed the importance of heat transfer is through conduction [1-7]. Nevertheless, it is quite hard to identify the exact share conduction, radiation and convection during heat passing through fabric. In our study, we assume that there is no impact of changing of direction of ribs (wales) on heat transfer by conduction because change in direction does not affect the area and thermal conductivity of material.

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Figure 1. Rib knit fabrics in different width of wales

Heat transfer by radiation is the second way of heat transfer. Heat transfer by radiation depends upon differences of Kelvin temperatures of the studied objects elevated on forth power and emissivity of the related materials. It is important to note, that heat flow transferred through textile fabrics by radiation generally does not exceed 10% of the total heat flow and in our case this mechanisms of heat transfer will be neglected.

Third way of heat transfer is by convection. It depends upon the flow of fluid (air or liquid) on the surface of the hot plate. Eqn. 2 describes the role of different factors in heat transfer by convection and this one is also called Newton law of cooling:

$$q = \alpha \Delta T \tag{2}$$

Where q indicates the heat flow [Wm^{-2}], α is heat transfer coefficient [Wm^{-2}K^{-1}], ΔT in this case presents the temperature difference between the fabric surface and the outside fluid [K].

2. AIRFLOW DIRECTION AND HEAT TRANSFER COEFFICIENT

Rib knit fabrics has wales (ribs) on its surface. The height of rib is about 50% of the total thickness of a fabric. The height varies from 0.9 to 1.1 mm in our samples. Moreover, the width of the rib varies depending upon the type of knitting (Table 1).

2.1. Heat and mass transfer caused by free convection

Thermal resistance and relative water vapor permeability were measured in two directions when putting knitted rib in parallel and perpendicular directions in relation to the airflow direction, see Figure 2. This simulates real situations of wearing style where the ribs can be oriented in various directions.

We can make clothing having perpendicular ribs (top to bottom direction) and parallel direction (from right to left) see Figure 2. Due to the free convection principle, the warm air due its lower density raises from the bottom to the top of the clothing wearer, thus increasing the vertical velocity of the air passing close to outer surface of fabric worn by a wearer and may increase heat and mass transfer between the environment and the wearer. Consequently, the effect of this free convection transfer may will improve thermo-physiological comfort of the wearer. From the common considerations follows, that the rib orientation in relation to the air flow direction should influence the resulting heat and mass transfer between the clothed body and environment.

However, for standing or sitting person, the prevailing air flow direction is the vertical one, caused by free convection. The air flow velocities in this case are low, less then 0,5 m/s, hence, the effect of rib orientation can be slow. Nevertheless, this situation will be discussed in the next chapter.

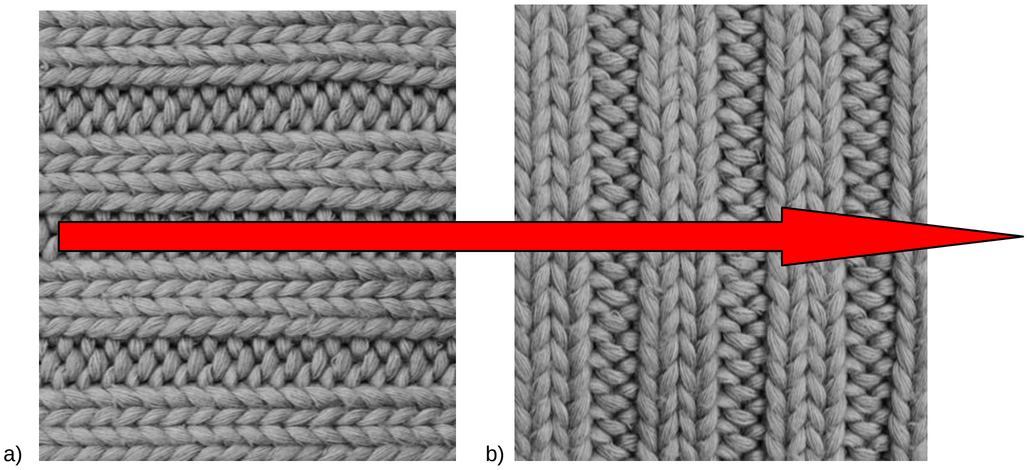

Figure 2. Ribs vs. airflow – a) parallel, b) perpendicular

Kast and Klan [9] have referred work of Churchill and Chu related to natural convection adjacent to perpendicular planes. Equation 3, 4 describes the role of vertical planes for both laminar (Eq. 3) and turbulent flow (Eq. 4):

$$\alpha = \frac{\lambda}{L}\left(0.825 + \frac{0.387\ Ra_L^{\frac{1}{6}}}{\left(1+\left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}}\right) \tag{3}$$

$$\alpha = \frac{\lambda}{L}\left(0.68 + \frac{0.67\ Ra_L^{\frac{1}{4}}}{\left(1+\left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}}\right) Ra_L 10^9 \tag{4}$$

where α is heat transfer coefficient [$Wm^{-2}K^{-1}$], L is length with respect to gravity, Ra_L is the dimensionless Rayleigh number, Pr means Prandtl number, λ presents thermal conductivity [$Wm^{-1}K^{-1}$]. The above discussion shows that there is a change in heat transfer coefficient α due to change in direction. Kast and Klan [9] have also discussed external flow and horizontal plates discussed by McAdams. McAdams have suggested the following equation to calculate heat transfer coefficient in case the hot surface facing up or down:

$$\alpha = \frac{\lambda 0.54 Ra_L^{\frac{1}{4}}}{L}, \qquad 10^5 \le Ra_L \le 2.10^7 \tag{5}$$

$$\alpha = \frac{\lambda 0.14 Ra_L^{\frac{1}{3}}}{L}, \qquad 2 * 10^7 \le Ra_L \le 3.10^{10} \tag{6}$$

However, the mentioned equations 3-6 are valid only for smooth surfaces and for rib knitted fabrics have limited use.

2.2. Heat and mass transfer caused by forced convection

In the case that the wearer of the rib fabric is walking or running, the air direction will change. Its direction will be mostly horizontal (parallel to the ground) and its velocity v will exceed 1 m/s. Thus, the convection heat and mass transfer from the outer clothing will be forced, mostly laminar. For the calculation of the heat transfer coefficient the experimental relationship for plane with the length L can be used. Based on dimensionless numbers Nusselt Nu and Reynolds Re ($Re = vL/v$, where v means the kinematic viscosity of the fluid), the heat transfer coefficient between air and solid object can be determined from the experimental relationship:

$$\alpha = 0.572 Re^{0.5} \tag{7}$$

The determined heat transfer coefficients then serve for calculation of the total thermal resistance between the wearer´s clothing and the environment. This total thermal resistance then consists of thermal resistance of the fabric and thermal resistance of the boundary layer. Here, thermal resistance of the boundary layer R_{bl} is given by the inverted values of the previously determined heat transfer coefficients, in means $R_{bl} = 1/\alpha$.

Heat transfer coefficient α for natural and forced convection heat transfer was investigated by Ucar and Yilmaz [13] for rib knit fabrics. Their experiment led to the conclusions that tightness of rib knits has influence on the heat transfer coefficient α for both situation as for natural as for forced convection heat transfer and forced convection led to higher heat transfer coefficient α respectively to lowering of thermal resistance R.

In this paper, an effort was focused on the investigation of the effect of the air flow direction (perpendicular or parallel) in relation to the orientation of the ribs on thermal resistance and water vapor permeability when forced convection heat transfer is used.

The measurements were carried out by means of the small Skin model tester called PERMETEST. This instrument is a product of SENSORA Czech Republic and widely used for measuring of water vapor permeability and thermal resistance

The PERMETEST instrument measures in the first step thermal resistance of the boundary layer, and in the second step the sum of thermal resistance of the fabric and thermal resistance of the boundary layer. In the third step, the PERMETEST program deduces the result of the first step from the result in the second step, thus receiving thermal resistance of the fabric only. Unfortunately, the thickness of the boundary layer on the PERMETEST, when there is no fabric (smooth surface, the first measurement step on the PERMETEST), is thinner than in the case when there is the fabric with the ribs parallel (thicker the boundary layer) or perpendicular (probable the thickest the boundary layer).

All above discussion shows that literature provides many studies related to direction of fluid and its impact on end results but there is a lack of systemic measurement of correlation between airflow direction and thermal resistance along with water vapor permeability.

3. EXPERIMENTAL PART

3.1. Material

18 samples of rib knit fabrics using 100% polyester yarn were manufactured on a double knit flat knitting machine. The samples arrangement is presented in Table 1 and more details are can be seen in Table 2. All samples were dyed simultaneously and no finishing was used here in order to eliminate the impact of any foreign material. Standard knits means here is that they are knit with gauge 12 but tightly knit means here is that they are knit bit higher gauge 16

By using different rib type can be reached very wide range of distances between two ribs which represents width of channel, see Table 1. The relative contact area was calculated using Formula

$$RCA = \frac{We}{We + Wc} \text{ X } 100 \tag{8}$$

Table 1. Rib knit fabrics used in experimental

Standard					
1x1	2x1	3x1	4x1	5x1	6x1
1x2	2x2		4x2		
	2x3	3x3	4x3		
		3x4	4x4		
Tightly					
1x1	2x1	3x1	4x1		

Where *RCA* means relative contact area, *we* is the width of elevated wales (ribs) and *Wc* is width of the channel among the ribs enabling the parallel air flow.

3.2. Testing Equipment

The instrument PERMETEST was used for measuring thermal resistance and water vapor permeability. All samples were put in the testing laboratory, where relative humidity was between 20-22% and temperature was in the range of 24-26 °C. All samples were dried at 105 °C to remove all moisture present. Each sample was tested three times to calculate the mean values.

The amount of heat which passes through the thermal model of human skin (the principle, see Figure 3) is measured on the PERMETEST instrument. For testing purpose, samples are put on measuring head, which is covered with a semi-permeable foil. After putting sample, it is exposed to parallel air flow. Velocity of air is 1 ms^{-1}. All measurements are carried out under controlled thermal conditions (23.0 ±0.5 °C). The PERMETEST instrument is connected with a computer, on which the results of the evaporative resistance (*Ret*), thermal resistance (*R*) and relative water vapor permeability (*RWVP*) of fabric following the modified ISO 11092 standards are displayed. The higher *RWVP* means that lower *Ret* is and it means better thermo-physiological comfort. *RWVP* (%) is calculated using the following equation

$$RWVP = \frac{q_s}{q_o} 100 \qquad (9)$$

Here q_s presents the heat flow determined by the instrument when the sample is placed on the measuring head of the instrument, and q_o is the heat flow measured without the sample.

Table 1. Properties of the fabric samples

Sample No	Rib types		Width of elevated wales (*We*) [mm]	Width of channel for air flow (*Wc*)	Square mass [g/m2]	Relative contact area (RCA) [%]
1	**1x1**	standard	1.5	1.0	378	60.0
2	**2x1**	standard	3.2	1.3	422	71.1
3	**3x1**	standard	4.7	1.1	447	81.0
4	**4x1**	standard	0.7	5.8	474	10.8
5	**5x1**	standard	1.2	6.9	501	14.8
6	**6x1**	standard	1.2	8.1	470	12.9
7	**1x2**	standard	1.8	2.2	400	45.0
8	**2x2**	standard	3.4	2.4	560	58.6
9	**2x3**	standard	3.4	3.3	462	50.7
10	**3x3**	standard	4.9	3.1	477	61.2
11	**3x4**	standard	5.2	4.3	471	54.7
12	**4x2**	standard	6.0	1.6	548	78.9
13	**4x3**	standard	4.7	2.0	540	70.1
14	**4x4**	standard	6.3	2.0	540	75.9
15	**1x1**	tightly	4.9	3.1	481	61.2
16	**2x1**	tightly	3.2	1.3	541	71.1
17	**3x1**	tightly	4.0	1.2	523	77.0
18	**4x1**	tightly	1.3	6.1	485	17.6

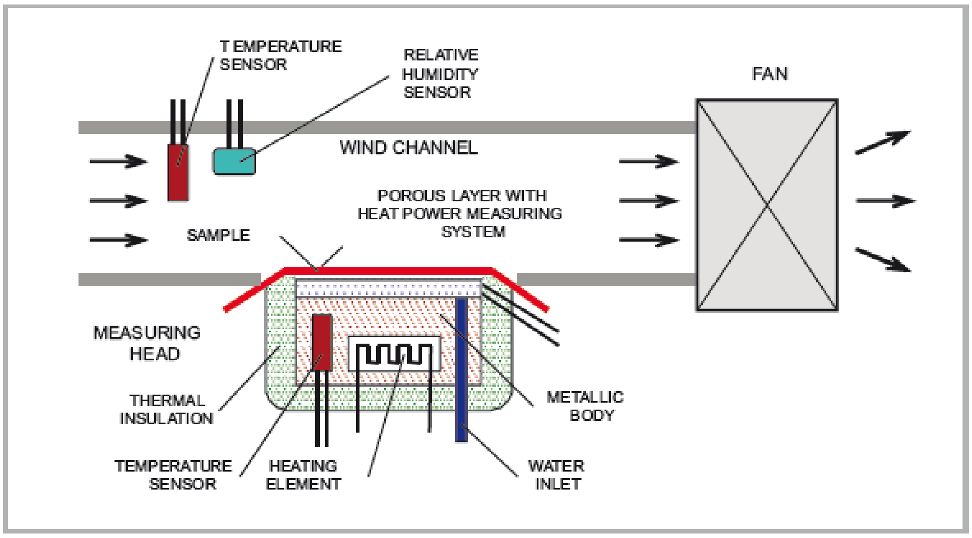

Figure 3. Principle of the PERMETEST Skin model

4. RESULTS AND DISCUSSION

The measurements of thermal resistance and the relative water vapor permeability of 18 samples in perpendicular and parallel direction were realized three times. The resulted mean values are presented in Table 3. The changes in results for both properties are expressed as ratios parallel/perpendicular (see eqns. 10a, 10b) and the columns are marked as ratio in the Table 3. Variation coefficients not exceed 5% at all samples.

$$R_{rat} = \frac{R_{par}}{R_{per}} \tag{10a}$$

$$RWVP_{rat} = \frac{RWVP_{par}}{RWVP_{per}} \tag{10b}$$

The results of ratios show that the parallel arrangement of ribs against the airflow leads mostly to the higher thermal resistance and lower relative water vapor permeability in respect to the perpendicular arrangement.

The relations among all properties are shown by means Spearman rank correlation coefficients and partial correlation coefficients. As it is shown in Figure 4 the histograms indicates that normal distributions cannot be used for modeling a therefore Spearman rank correlation coefficients was applied. The results are shown in Table 3 above the main diagonal. The results of the partial correlation coefficients are presented under the main diagonal. This correlation coefficient is used in situation for elucidade false correlations [14]. The bold type in Table 3 means that correlation coefficients are statistically significant at significance level α=0.05. As it flows from results in Table 3 no dependencies were found among the design parameters and measured properties. It can be explained by combination of the design parameters of the rib knit fabrics, it means, the width of elevated wales, the width of channel for air flow and if the knits were prepared as standard or tightly.

Table 2 Thermal resistance (*R*) and relative water vapor permeability (*RWVP*)

Sample No	Thermal resistance (*R*)			Relative water vapor permeability (*RWVP*)		
	Parallel	Perpendicular	Ratio (R_{rat})	Parallel	Perpendicular	Ratio
	(R_{par})	(R_{per})		($RWVP_{per}$)	($RWVP_{par}$)	($RWVP_{rat}$)
1	0.0367	0.0333	1.10	50.7	51.8	0.98
2	0.0353	0.0306	1.15	48.2	49.6	0.97
3	0.0365	0.0321	1.14	51.2	51.0	1.00
4	0.0382	0.0356	1.07	49.6	51.3	0.97
5	0.0337	0.0349	0.97	56.2	56.8	0.99
6	0.0391	0.0356	1.10	49.9	49.2	1.01
7	0.0365	0.0337	1.08	48.5	51.4	0.94
8	0.0412	0.0349	1.18	50.2	51.0	0.98
9	0.0375	0.0364	1.03	51.6	53.6	0.96
10	0.0321	0.0317	1.01	42.6	48.4	0.88
11	0.0376	0.0358	1.05	53.0	54.2	0.98
12	0.0383	0.0331	1.16	50.2	50.1	1.00
13	0.0392	0.0370	1.06	51.0	53.0	0.96
14	0.0390	0.0366	1.07	53.2	53.6	0.99
15	0.0309	0.0307	1.01	53.4	54.6	0.98
16	0.0395	0.0366	1.08	53.4	52.2	1.02
17	0.0375	0.0353	1.06	53.2	53.8	0.99
18	0.0326	0.0302	1.08	47.6	49.6	0.96
Min	*0.0309*	*0.0302*	*0.97*	*42.6*	*48.4*	*0.88*
Max	*0.0412*	*0.0370*	*1.18*	*56.2*	*56.8*	*1.02*

Table 3. Spearman rank correlation coefficients (above the main diagonal) and partial correlation coefficients (under the main diagonal)

	t	*Wc*	*W*	*RCA*	R_{par}	R_{pen}	R_{rat}	$RWVP_{par}$	$RWVP_{per}$	$RWVP_{rat}$
t	–	-0.33	0,38	**0,7**	0,09	0,09	-0,11	0,28	0,23	0,13
Wc	**0,8**	–	0,05	**-0,81**	-0,12	0,07	-0,42	-0,09	0,04	-0,18
W	0,37	-0,02	–	0,29	**0,49**	0,3	0,03	0,33	0,18	0,42
RCA	**0,91**	**-0,96**	-0,14	–	0,13	-0,05	0,27	0,27	0,03	0,39
R_{par}	-0,14	-0,09	0,27	0,01	–	**0,76**	0,43	0,2	0,01	**0,5**
R_{pen}	0,15	0,09	-0,26	-0,01	**0,99**	–	-0,17	**0,48**	0,44	0,24
R_{rat}	0,18	0,04	-0,27	-0,05	**0,99**	**-0,99**	–	-0,35	**-0,59**	0,38
$RWVP_{par}$	-0,35	0,24	0,32	0,35	-0,37	0,38	0,38	–	**0,86**	**0,54**
$RWVP_{per}$	0,39	-0,29	-0,32	-0,38	0,35	-0,36	-0,36	**0,99**	–	0,13

$RWVP_{rat}$	0,29	-0,17	-0,3	-0,28	0,35	-0,36	-0,35	**0,99**	**-0,98**	–

The more detailed analysis was realized, too. For the analyses the chosen rib knit fabrics were divided to following groups:

a) standard: 1x1, 2x1, 3x1, 4x1, 5x1, 6x1

b) standard: 1x1, 2x2, 3x3, 4x4

c) standard: 1x1, 2x1, 3x1, 4x1 versus tightly: 1x1, 2x1, 3x1, 4x1

Some trend was found for the thermal resistance at group c) where the ratios was higher for standard rib knit fabrics 1x1, 2x1 and 3x1 than the analogical tightly rib knit fabrics, however at knits 4x4 such result was not found. At other groups no significant trends were determined.

5. CONCLUSIONS

An effort of this study was focused to behavior of the water vapor permeability and thermal resistance of rib knit fabrics when the orientation of ribs considering the airflow direction was given in the parallel and perpendicular way. For testing purposes, 18 rib knit fabrics were produced and water vapor permeability and thermal resistance were measured using PERMETEST instrument. The ratio parallel/perpendicular of the orientation of ribs in respect to airflow was used for evaluation. It was found that the thermal resistance was higher for the parallel orientation for 17 from 18 samples and at 6 (33%) samples the increase reached at least 10% than at perpendicular orientation of ribs with respect to the airflow. On the other hand, at relative water vapor permeability the ratio was lower than 1 at 14 samples. It means that parallel arrangement of ribs leads to the decrease relative water vapor permeability. However, the difference higher than 10% was only at one sample. Therefore, orientation of ribs in respect to the airflow does not play so big role for relative water vapor permeability as at the thermal resistance. It was found that the orientation of ribs can play sure role for thermo-physiological comfort.

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