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Study on the Influence of Calendaring Process on Thermal Resistance of Polypropylene Nonwoven Fabric Structure

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Abstract

The purpose of this paper is to investigate the influence of calendering process on polypropylene nonwoven structure and thermal resistance. The study was focused on the influence of mass per unit area, thickness, density, porosity, characteristic opening size and additional thermal bonding by calendering. Thermal resistance of polypropylene nonwoven fabric manufactured using the mechanical carding process and bonding using the needling process, where a part of the samples was additionally bonded by the thermal calendering process, were investigated. The nonwoven fabrics were tested for thermal resistance on the guarded hot plate. Statistical analyses were performed to examine the significance between the observed parameters. Correlation matrix analyses were used to reveal relationship behaviour among the variables. A change in structure of the calendered samples caused a considerably lower thermal resistance i.e. better thermal conductivity. A change of the average value of thermal resistance after calendering related to non-calendered fabric mass between 150 and 500 g/m^2 ranged from 53.9 to 41.0%. With increasing nonwoven fabric mass, the difference between thermal resistances of needled and needled as well as additionally bonded by calendering the nonwoven fabric was reduced.

Keywords: Polypropylene; Needled Nonwoven; Calendaring; Characteristic Opening Size; Guarded Hotplate; Thermal Resistance

1 Introduction

Nonwoven textile is a fabric composed of individual fibres mutually bonded by a certain process. For nonwoven productions different types of fibres are used. The choice of fibre depends on the desired properties of the nonwovens and the cost of the chosen fibres [1, 2]. The three most processed synthetic fibres of world consumption for nonwoven production are polypropylene, polyester and viscose [2]. As previously mentioned, nonwoven fabrics produced of polypropylene were chosen for this study. Needled nonwoven fabrics with different functional properties are used

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in technical applications such as filters, composites, protective clothing, packaging, geotextiles, home furnishing, heat and noise insulating etc. [3].

Thermal properties are important in many textile applications such as apparel, blankets, and sleeping bags, interlinings, building insulation, automobiles, aircraft and industrial process equipment [4]. One of the major nonwoven applications is thermal insulation materials.

Thermal conductivities in steady state condition was investigated by Mohammadi at al. where they concluded that the thermal conductivity of needled nonwoven structures can be predicted with high accuracy using model with fabric thickness, porosity and structure along with applied temperature [5]. Thermal conductivity decreases with increasing material density were concluded by Jirsak et al. [6]. Morris concluded that when two fabrics have equal thicknesses but different densities, fabric with lower density shows greater thermal insulation [7]. Abdel-Rehim et al. studied heat transfer through different fabrics made by polypropylene and polyester mass in a range from 400 to 800 g/m^2 and they concluded that the investigated fabrics have high thermal performance and thermal response as insulators [8]. Saleh investigated properties of needled lining produced from polyester, cotton and recycled fibre and concluded that fabric thickness, mass and fibre type affect the thermal properties of the fabric [9]. In the same study the compressed linings show lower thermal insulation properties compared with non-compressed which was explained by a possible amount of trapped air of non-compressed nonwoven lining which provides greater thermal insulation.

The calendering process gives a more compact structure of nonwoven fabrics, thus resulting in a controlled and predictable compressibility. With calendering needled polypropylene nonwoven fabrics the range of porosity becomes narrow when the characteristic opening sizes is reduced [10].

The influence of the calendering process of polypropylene nonwoven geotextiles on water permeability under different loads, as well as pore characteristics have been recently investigated and it has been concluded that additional bonding with calendering needled polypropylene nonwoven geotextiles provides a more controlled and predictable performance considering only needled geotextiles [11].

Debnath and Madhusoothanan have studied thermal resistance and air permeability of needle punched nonwoven fabric made from jute and polypropylene blends to observe the effect of fabric weight, needling density and blend proportion on thickness, thermal resistance, specific thermal resistance, air permeability and sectional air permeability [1]. They concluded that thermal resistance and thickness increase but air permeability and sectional air permeability decrease significantly with the increase in fabric weight at all levels of jute contents [12].

The reclaimed fibre based non-woven materials, suitable for automotive application, was studied were authors founded that thermal conductivity of reclaimed fibre-based nonwoven materials varies significantly, depending on the type of reclaimed fibres and the resulting bulk density of the materials [13].

Determination of heat transfer by radiation in woven and nonwoven fabrics was investigated were authors concluded that nonwoven fabrics showed substantially higher increase of thermal conductivity with temperature than woven fabrics due to strong free convection effects caused by high temperature drop between the layers [14].

Nonvowen fabrics produced from polypropylene fibers are used in industry as thermal insulators. By development of its applications there is a need for thermal insulators of lower thickness. After calendering needle punched fabrics have a smaller thickness but also a changed structure. The aim of this paper is to investigate the influence of the calendering process on polypropylene nonwoven fabric thermal resistance of different mass ranging from 150 to 500 g/m^2.

2 Experimental

The nonwoven fabric made from polypropylene fibres was manufactured using the mechanical carding process, and bonded using the needling process. A part of the nonwoven fabric was additionally bonded using the thermal calendering process. The main process parameters in needling and calendering were: number of pre-needling strokes per area was 600 strokes/cm^2, depth of needle penetration during pre-needling was 7.5 mm, number of needle strokes per area was 370 strokes/cm^2, depth of needle penetration was 4.0 mm, calendering temperature was 140°C, as well as calendar pressure rollers was 40 daN/cm. The mass for all groups of nonwoven fabric ranged from 150 to 500 g/m^2. For sampling a metal plate size of 60.3 cm × 60.8 cm with holes was used for all nonwoven fabric of the planned testing. The metal plate was moved according to 5-end satin weave with step of 3, in order to avoid repetition of sampling in longitudinal and transverse direction for the same type of testing. The 10% of the nonwoven fabric width from the edges was excluded from sampling (40 cm).

Mass was tested according to the standard ISO 9073-1:1989 Textiles - Test methods for nonwovens - Part 1: Determination of mass per unit area [15], whereas thickness was tested according to the standard for nonwoven textile ISO 9073-2:1995 [16]. Density of nonwoven textiles was calculated from mass per unit area and thickness values, using the following equation:

$$\rho_{\text{geo.}} = \frac{M}{t} \tag{1}$$

where ρ is the density (g/cm^3), M is the mass (g/cm^2) and t is the fabric thickness (cm).

Porosity of nonwoven fabric was calculated from the ratio of nonwoven fabric density and fibre density expressed in percentage.

$$P = 1 - \frac{\rho_{\text{nonw.}}}{\rho_{\text{fib.}}} \tag{2}$$

where P is porosity of nonwoven fabric (%), $\rho_{\text{nonw.}}$ is the density of nonwoven fabric (g/cm^3) and $\rho_{\text{fib.}}$ is density of fibre (g/cm^3), whereas polypropylene fibre density is 0.91 (g/cm^3).

Thermal conductivity is property of a material to conduct heat and it was calculated from the ratio of nonwoven fabric thickness and thermal resistance of nonwoven fabric.

$$\lambda = \frac{t}{R_{\text{ct}}} \tag{3}$$

where λ is the thermal conductivity of nonwoven fabric (W/mK), t is the thickness (m) and R_{ct} is the thermal resistance (m^{2}K/W).

The characteristic opening size of nonwoven fabric was tested according to ISO 12956:2001 [17] whereas thermal resistance was tested according to ISO 11092 [18] using sweating guarded hot plate. Tested properties are given in Table 1.

Table 1: Properties of the nonwoven fabric

Samples	Designation	Mass (g/m^2)	STD (g/m^2)
Polypropylene needled nonwoven fabric	PP150	155	0.119
	PP200	199	0.142
	PP250	234	0.133
	PP300	276	0.190
	PP400	367	0.293
	PP500	417	0.234
Polypropylene needled, additionally bonded by calendaring nonwoven fabric	PPC150	174	0.091
	PPC200	218	0.164
	PPC250	275	0.287
	PPC300	309	0.142
	PPC400	380	0.253
	PPC500	465	0.368

2.1 Characteristic Opening Size — AOS

The principle of measuring the characteristic opening size of fabrics is based on the particles size distribution of different grades of granular material (usually glass pellet or sand) after sieving through a fabric without applying the load. The characteristic opening pore size corresponds to the specific size of granular material passed through the fabric after sewing. This method gives approximate values of the maximum diameter of the samples pore through which soil particles can pass [19]. Value O_{90} is the size of the opening that allows particle sizes d_{90} to pass through the fabric. d_{90} is a particle size, where 90% of the particle mass pass through sieve meshes. The cumulative percentage of sieving material is used as a function of sieve sizes, and it presents graphically the sieving curve of the determinate O_{90}. The distribution of individual curves of the pore sizes and the mean curve (calculated) of needled polypropylene nonwoven fabrics with 500 g/m^2 are shown in Fig. 1. The individual curves present cumulative percentage of sieving material as a function of sieve sizes. Curve O_{90} was determined from the mean.

At the point, where the horizontal line of 90% of passage of grain through a sieve and the vertical line of sieve size intersect the mean curve, the characteristic opening size is read [20, 21].

2.2 Method of Thermal Resistance Measurement under Steady-state Conditions

The sample to be tested is placed on the heated plate with conditioned air ducted to flow across and parallel to its upper surface. For the determination of thermal resistance, the heat flux through the nonwoven fabric to be tested is measured after steady-state conditions have been reached.

For the determination of thermal resistance (R_{ct}) the temperature of the measuring unit needs to be set at 35 °C, air temperature at 20 °C, relative humidity of 65% and air speed at 1 m/s. After reaching the test conditions and steady–state the recording of values can be started.

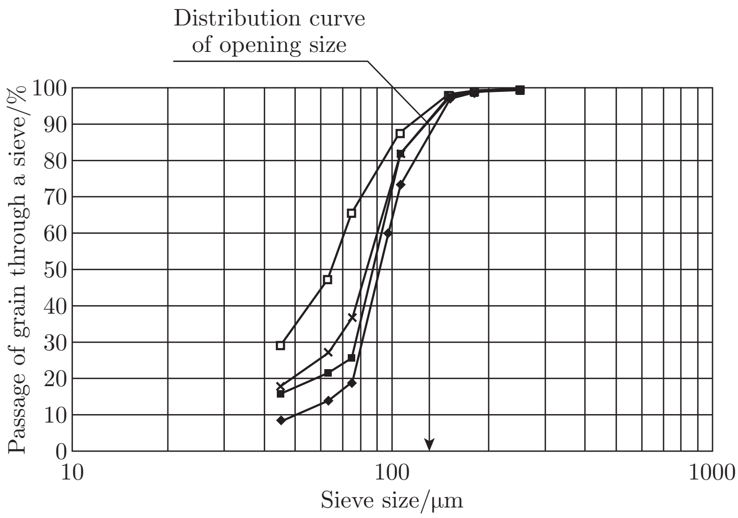

Fig. 1: Distribution curve as well as mean curve of characteristic opening size of needled polypropylene nonwoven fabric with 500 g/m^2

The thermal resistance is calculated according to the following equation:

$$R_{\mathrm{ct}} = \frac{(T_m - T_a) \cdot A}{H - \Delta H_c} - R_{\mathrm{ct0}} \tag{4}$$

where R_{ct} is the thermal resistance (m^{2}K/W), Tm is temperature of measuring unit (°C), T_a is the air temperature during testing (°C), A is the area of the measuring unit (m^2), H is the heating power supplied to the measuring unit (W), ΔH_c is the correction term for heating power for the measurement of thermal resistance and R_{ct0} is the apparatus constant for the measurement of thermal resistance (m^{2}K/W).

Thermal resistance R_{ct} of the tested material is the arithmetic mean of the three individual measurements.

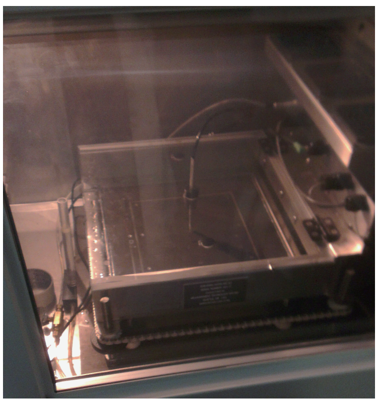

Fig. 2: Sweating guarded hot plate Measurement Technology Northwest

3 Results and Discussion

The structure parameter values of nonwoven fabric and thermal resistance determined using sweating guarded hot plate and thermal conductivity calculated using Equation (3) are given in Tables 2 and 3.

Table 2: Structure parameters of nonwoven fabrics

Sample designation		t (mm)				ρ_{geo} (g/cm^3)				P (%)			
		$\bar{x}$	CV	SD	SEM	$\bar{x}$	CV	SD	SEM	$\bar{x}$	CV	SD	SEM
PP	150	2.97	0.024	0.156	0.049	0.053	3×10^{-5}	0.005	0.002	0.94	4×10^{-5}	0.006	0.002
	200	3.19	0.029	0.170	0.054	0.062	3×10^{-5}	0.005	0.002	0.93	4×10^{-5}	0.006	0.002
	250	3.56	0.017	0.131	0.042	0.066	2×10^{-5}	0.004	0.001	0.93	2×10^{-5}	0.005	0.002
	300	3.82	0.039	0.199	0.063	0.074	1×10^{-4}	0.010	0.003	0.92	1×10^{-4}	0.011	0.004
	400	4.46	0.032	0.178	0.056	0.083	6×10^{-5}	0.008	0.002	0.91	7×10^{-5}	0.008	0.003
	500	4.44	0.019	0.139	0.044	0.094	2×10^{-5}	0.004	0.001	0.90	2×10^{-5}	0.005	0.002
PPC	150	1.01	0.005	0.073	0.023	0.173	2×10^{-4}	0.014	0.005	0.81	3×10^{-4}	0.016	0.005
	200	1.15	0.008	0.087	0.027	0.191	2×10^{-4}	0.015	0.005	0.79	3×10^{-4}	0.017	0.005
	250	1.42	0.003	0.052	0.016	0.194	4×10^{-4}	0.020	0.006	0.79	5×10^{-4}	0.022	0.007
	300	1.59	0.012	0.108	0.034	0.195	2×10^{-4}	0.014	0.004	0.79	2×10^{-4}	0.015	0.005
	400	1.92	0.012	0.109	0.034	0.198	2×10^{-4}	0.013	0.004	0.78	2×10^{-4}	0.014	0.004
	500	2.31	0.010	0.098	0.031	0.201	2×10^{-4}	0.013	0.004	0.78	2×10^{-4}	0.015	0.005

where: t – Thickness (mm), ρ_{geo} – Density (g/cm^3), P – Porosity (%), $\bar{x}$ – Mean value, CV – Coefficient of variation (%); SD – Standard deviation, SEM – Standard error.

Table 3: Thermal parameters of nonwoven fabrics

Sample designation		R_{ct} (m^{2}K/W)				λ (W/mK)			
		$\bar{x}$	CV	SD	SEM	$\bar{x}$	CV	SD	SEM
PP	150	0.0882	1×10^{-5}	3×10^{-3}	2×10^{-3}	0, 0337	2×10^{-6}	1×10^{-3}	8×10^{-4}
	200	0.0997	6×10^{-7}	8×10^{-4}	4×10^{-4}	0.0321	6×10^{-8}	2×10^{-4}	1×10^{-4}
	250	0.1026	1×10^{-5}	3×10^{-3}	1×10^{-3}	0.0347	1×10^{-6}	1×10^{-3}	6×10^{-4}
	300	0.1019	1×10^{-5}	3×10^{-3}	2×10^{-3}	0.0375	2×10^{-6}	1×10^{-3}	7×10^{-4}
	400	0.1046	1×10^{-7}	6×10^{-3}	3×10^{-3}	0.0427	7×10^{-6}	3×10^{-3}	2×10^{-3}
	500	0.1141	9×10^{-6}	3×10^{-3}	2×10^{-3}	0.0389	1×10^{-6}	1×10^{-3}	6×10^{-4}
PPC	150	0.0407	2×10^{-6}	3×10^{-3}	2×10^{-3}	0.0271	5×10^{-6}	2×10^{-3}	1×10^{-3}
	200	0.0463	4×10^{-6}	2×10^{-3}	1×10^{-3}	0.0259	1×10^{-6}	1×10^{-3}	6×10^{-4}
	250	0.0470	3×10^{-5}	5×10^{-3}	3×10^{-3}	0.0305	1×10^{-5}	4×10^{-3}	2×10^{-3}
	300	0.0492	7×10^{-6}	3×10^{-3}	2×10^{-3}	0.0323	3×10^{-6}	2×10^{-3}	1×10^{-3}
	400	0.0575	7×10^{-5}	8×10^{-3}	8×10^{-3}	0.0339	2×10^{-5}	5×10^{-3}	3×10^{-3}
	500	0.0673	2×10^{-6}	1×10^{-3}	8×10^{-4}	0.0343	5×10^{-7}	7×10^{-4}	4×10^{-4}

where: R_{ct} – Thermal resistance (m^{2}K/W), λ – Thermal conductivity (W/mK), $\bar{x}$ – Mean value, CV – Coefficient of variation; SD – Standard deviation, SEM – Standard error

The relationships between nonwoven fabric thermal resistance and their structure parameters (mass, thickness, density, porosity and characteristic opening pore size) with associate linear regression line and R-squared value are shown in Figures (Fig. 1, Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6).

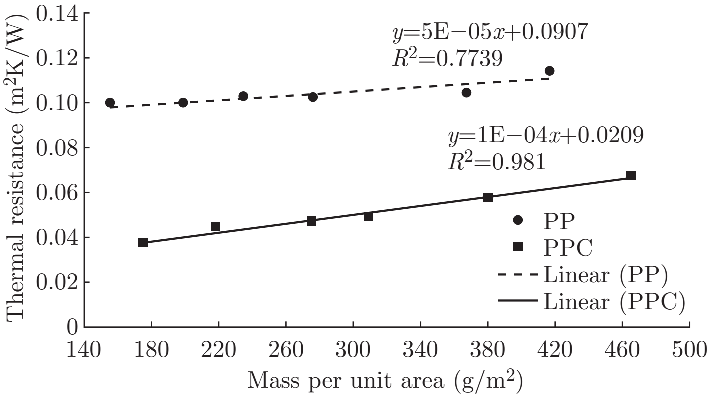

Fig. 3: Relation between thermal resistance and mass of nonwoven fabric

The values of the thermal resistance of the nonwoven fabric ranged from 0.0882 to 0.1141 only for the needled fabric while for the needled and additionally bonded fabric by calendering ranged from 0.0407 to 0.0673 (Table 2 and 3, Fig. 2-6) respectively. It is noticeable that the nonwoven fabric additionally bonded by calendering on an average had a significantly lower thermal resistance than the nonwoven fabric only bonded by needling. The results of t-test confirmed the statement that there are significant differences between thermal resistance of needled nonwoven fabrics and needled nonwoven fabric additionally bonded by calendering (t(12)=0.17, 6.67×10^{-6}). It can be concluded that calendering changes thermal resistance since it uses pressure and heat for bonding. This process causes an increase in the density of the nonwoven fabric that is evident in increasing its mass. Changes in the average value of thermal resistance after calendering related to the non-calendered fabric are as follows: for a mass of 150 g/m^2 it is 53.9%, for a mass of 200 g/m^2 it is 53.6%, for a mass of 250 g/m^2 it is 54.2%, for a mass of 300 g/m^2 it is 51.7%, for a mass of 400 g/m^2 it is 45.0% as well as for a mass of 500 g/m^2 it is lowest and amounts to 41.0%. As a result of calendering changes occur in structure and consequently properties of the calendered nonwoven fabric change. Compressed structures of calendered nonwoven fabrics have a lower amount of trapped air within layers which reduces thermal resistance.

The needled polypropylene nonwoven fabrics have greater thickness and density (Table 2, Fig. 4 and 5). The reduction of the average thickness related to the non-calendered fabric for a mass of 150 g/m^2 is 66.0%, for a mass of 200 g/m^2 it is 64.0%, for a mass of 250 g/m^2 it is 60.1%, for a mass of 300 g/m^2 it is 58.4% for a mass of 400 g/m^2 it is 27.0% as well as for a mass of 500 g/m^2 it is 48.0%. It is noticeable that when the mass of the nonwoven fabric increases a change in thickness due to the calendering process decreases. Consequently, with decrease in fabric thickness of the nonwoven fabric density also decreases.as follows: for a mass of 150 g/m^2 it is 226.4%, for a mass of 200 g/m^2 it is 208.1%, for a mass of 250 g/m^2 it is 193.9%, for mass a of 300 g/m^2 it is 163.5%, for a mass of 400 g/m^2 it is 138.6% and for a mass of 500 g/m^2 it is 113.8%. The standard error bars shows that there are no significant deviations from the empirical regression values of thermal resistance depending on thickness and density.

The calendering process uses temperature and pressure for additional bonding resulting in a more compact structure of the calendered fabric. The porosity of the calendered nonwoven fabric

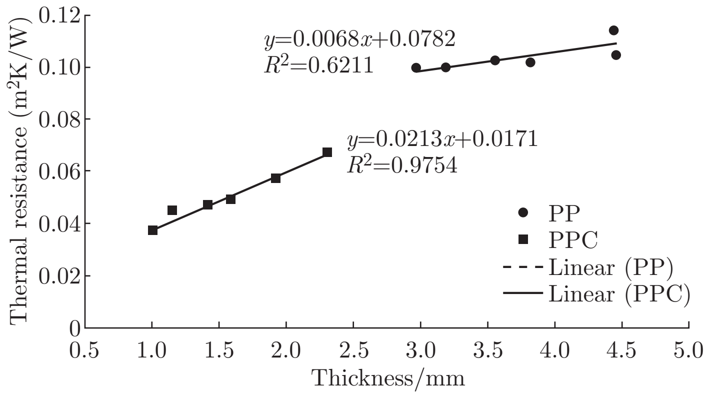

Fig. 4: Relation between thermal resistance and thickness of nonwoven fabric

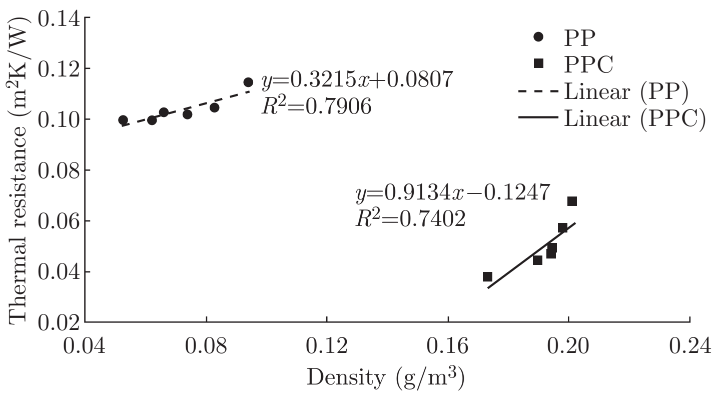

Fig. 5: Relation between thermal resistance and density of nonwoven fabric

is lower as compared with only the needled fabric (Table 2, Fig. 6). The average porosity of the calendered nonwoven fabric is up to 14.3% lower than for the nonwoven fabric bonded only by needling. The standard error bars show that there are no significant deviations from the empirical regression values of thermal resistance depending on porosity.

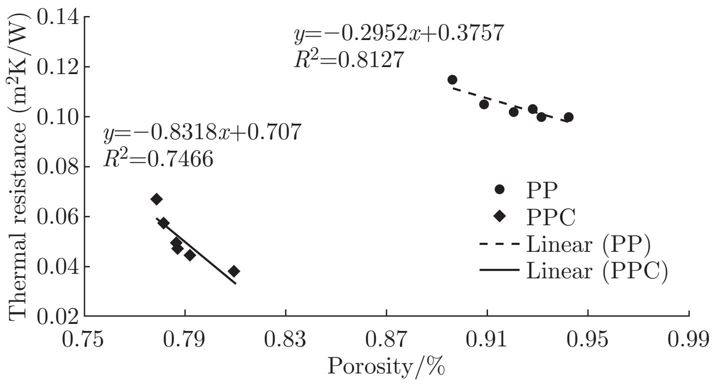

Fig. 6: Relation between thermal resistance and porosity of nonwoven fabric

Calendering causes a significant reduction of the characteristic opening pore size (Table 4, Fig. 7) that results in a reduction of thermal resistance. Considering that the thermal conductivity of polypropylene is higher (0.10 – 0.22 W/m K) than that of air (0.02 W/m K), the reduction of the thermal resistance of the calendered nonwoven fabric can be explained as a consequence of a lower amount of trapped air in calendered structures.

Table 4: Characteristic opening pore size of nonwoven fabric

Sample designation	PP						PPC					
	150	200	250	300	400	500	150	200	250	300	400	500
O_{90} (μm)	172	163	135	135	121	126	123	121	115	112	100	90
STD (μm)	17.01	1.73	7.64	32.08	14.01	10.50	23.46	3.61	26.84	26.58	4.00	28.62

where: O_{90} – Characteristic opening pore size (μm)

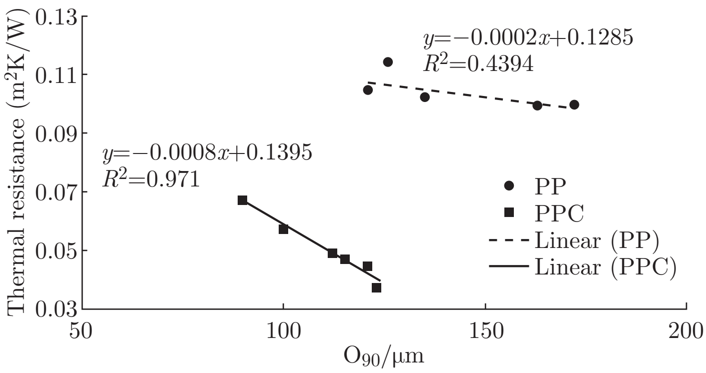

Fig. 7: Relation between thermal resistance and characteristic opening pore size of nonwoven fabric

Considering the regression analyses carried out, it can be concluded that the relationship between the parameters of the needled nonwoven fabric (mass, thickness, density, porosity, characteristic opening pore size, thermal resistance and thermal conductivity) mutually correlate with the high regression coefficient that ranges from 0.66 to 0.99 (with the significance of the correlation ranges from 7×10^{-5} to 0.8) while the nonwoven fabric additionally bonded by calendering ranges from 0.78 to 0.99 (with the significance of the correlation ranges from 7×10^{-5} to 0.9) (Table 5 and 6).

Table 5: Correlation matrix of the nonwoven fabric parameters

	M_A		t		ρ_{geo}		P		O_{90}		R_{ct}		λ	
	PP	PPC	PP	PPC	PP	PPC	PP	PPC	PP	PPC	PP	PPC	PP	PPC
M_A	1	1	0.98	0.99	0.99	0.86	−0.99	−0.87	−0.88	−0.99	0.88	0.99	0.85	0.92
t	0.98	0.99	1	1	0.96	0.84	−0.96	−0.84	−0.94	−0.99	0.79	0.99	0.92	0.99
ρ_{geo}	0.99	0.86	0.96	0.84	1	1	−0.99	−0.99	−0.87	−0.79	0.89	0.86	0.80	0.78
P	−0.99	−0.87	−0.96	−0.84	−0.99	−0.99	1	1	0.85	0.80	−0.90	−0.86	−0.79	−0.79
O_{90}	−0.88	−0.99	−0.94	−0.99	−0.87	−0.79	0.85	0.80	1	1	−0.66	−0.99	−0.85	−0.90
R_{ct}	0.88	0.99	0.79	0.99	0.89	0.86	−0.90	−0.86	−0.66	−0.99	1	1	0.56	0.86
λ	0.85	0.92	0.92	0.99	0.80	0.78	−0.79	−0.79	−0.85	−0.90	0.56	0.86	1	1

Table 6: P values of correlation matrix of the nonwoven fabric parameters

	M_A		t		ρ_{geo}		P		O_{90}		R_{ct}		λ	
	PP	PPC	PP	PPC	PP	PPC	PP	PPC	PP	PPC	PP	PPC	PP	PPC
M_A	-	-	5×10^{-4}	2×10^{-5}	7×10^{-5}	0.03	7×10^{-5}	0.03	0.02	2×10^{-4}	0.02	1×10^{-4}	0.8	0.9
t	5×10^{-4}	2×10^{-5}	-	-	2×10^{-3}	0.04	3×10^{-3}	0.03	6×10^{-3}	7×10^{-5}	0.03	2×10^{-4}	9×10^{-3}	9×10^{-3}
ρ_{geo}	7×10^{-5}	0.03	2×10^{-3}	0.04	-	-	2×10^{-5}	2×10^{-5}	0.02	0.07	7×10^{-3}	0.03	0.06	0.08
P	7×10^{-5}	0.03	3×10^{-3}	0.03	2×10^{-5}	2×10^{-5}	-	-	0.03	0.06	7×10^{-3}	0.03	0.06	0.06
O_{90}	0.02	2×10^{-4}	6×10^{-3}	7×10^{-5}	0.02	0.07	0.03	0.06	-	-	0.04	3×10^{-4}	0.03	0.02
R_{ct}	0.02	1×10^{-4}	0.03	2×10^{-4}	7×10^{-3}	0.03	7×10^{-3}	0.03	0.04	3×10^{-4}	-	-	0.2	0.03
λ	0.8	0.9	9×10^{-3}	9×10^{-3}	0.06	0.08	0.06	0.06	0.03	0.02	0.2	0.03	-	-

4 Conclusion

The calendered nonwoven fabric has lower thickness, porosity and characteristic opening pore size with regard to only the needled nonwoven fabric. The density of the calendered nonwoven fabric is greater than that of the needled nonwoven fabrics. The calendered nonwoven fabric has significantly lower thermal resistance, i.e. better thermal conductivity than only the needled one and it ranges from 53.9% to 41.0%. By increasing the fabric mass, the difference between the thermal resistances of the needled and the needled and additionally calendering bonded nonwoven fabric decreases. The average porosity of the nonwoven fabric additionally bonded by calendering is up to 14.3% lower than that of the nonwoven fabric only bonded by needling. Calendering causes a significant decrease of the characteristic opening pore size that results in decrease of thermal resistance. Since the thermal conductivity of polypropylene is higher than that of air, the reduction of thermal resistance of additionally calendered nonwoven fabric can be explained by a lower amount of trapped air in its structure. The relationships between the parameters of the needled nonwoven fabric have a high coefficient of correlation (ranging from 0.66 to 0.99). The coefficient of correlation between the parameters of the additionally bonded nonwoven fabric by calendering ranges from 0.78 to 0.99.

In relation to the aim of this paper it could be concluded that by calendering the needled, punched polypropylene fabric, a fabric with significantly smaller thickness and sufficient thermal resistance values was obtained that can be used as a thermal insulator.

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