Zbigniew Lewandowski,
***Andrzej Ziabicki,**
***Leszek Jarecki**

University of Bielsko-Biała,
ul. Willowa 2, 00-000 Bielsko-Biała, Poland

***Institute of Fundamental Technological Research,**
Polish Academy of Science,
ul. Warszawska 111, 00-000 Warsaw, Poland
E-mail: z.lewandowski@wp.pl

The Nonwovens Formation in the Melt-blown Process

Abstract
Melt-blowing is an industrial method for the rapid production of nonwoven fibres. In melt-blowing a polymer is melted and extruded through a capillary while heated air is blown through an air nozzle. The aerodynamic drag of the air jets on the polymer provides the attenuation force that draws the polymer streams into fine diameter fibres. In this paper, the following factors are presented: a modified mathematical model of melt spinning for a pneumatic process accounting for the effects of structural transformation in the viscoelastic behavior of the spun polymer; the application of mathematical modelling to the melt-blown process; a novel method for nonwoven formation in airflow with supersonic velocity.

Key words: *melt-blown process, mathematical modeling, supersonic airflow, nonwoven formation.*

Introduction

Current trends in melt spinning technology involve an increase in production rates and reduction in filament thickness. The available spinning speed and filament thickness strongly depend on the material properties and spinning conditions. Rheological properties of polymer (shear and elongational viscosity, relaxation time) limit spinning speed in classical melt spinning technology and determine the polymer jet disintegration. This phenomenon is a principle of nonwoven formation in melt-blown technology, where non-uniformity is the result of the complex interactions between the air stream and polymer jet.

The outflowing polymer jet, with an initial diameter of approximately 0.4 mm, is blown on by a hot air jet flowing out of two converging slot dies, so that fibres with an average diameter of 1-5μm are achieved.

With knowledge of the polymer output velocity, initial air velocity and the hypothesis, a melt-blown fibre with an average diameter of 2 μm is formed. Furthermore, a stretching ratio of about 5×10^4 can be calculated [1].

Modeling of the air jet dynamics

Accurate reproduction as well as a mathematical model for the formation of the melt-blown fibres has not yet been presented. The application of computer modeling is an alternative for time-consuming and expensive experimental works, allowing to draw technological conclusions.

Ziabicki [2-5], Andrews [6] and Kase [7-9] described scientifically mathematical models for spinning fibres from melted polymers. These works were developed in the following years for different applications [10 - 13].

A mathematical model of melt spinning was modified for the pneumatic process, taking into account the effects of structural transformation in the viscoelastic behavior of spun polymer. Assuming thin stream of the polymer jet, the mathematical model consist of mass, momentum and energy balance equations as well as a constitutive equation of viscoelasticity. Structure development equations – an amorphous orientation equation under uniaxial tensile stress and the kinetic equation of the oriented crystallization of the polymer are also included.

Figure 1 shows a spinning beam in the melt-blown process where a molten stream of polymer is extruded from the die and rapidly attenuated into fine fibres by an air jet at high velocity and high temperature. The air jet also transport fibres along the spinning line to a collector where they bond at fibre-fibre contact points to produce a cohesive nonwoven web.

The velocity and temperature distribution of the polymer and the air are considered as a separate fields, with interactions between them within their boundary conditions. The velocity, temperature, pressure, kinetic energy and energy dissipation distributions of the air blow are predetermined from the set of differential equations for a wide range of the parameters mentioned.

The K-ε (K-epsilon) flow model and a FLUENT 6.2 computer program were applied to make calculations. [14, 15] The following initial air parameters outflowing from an air nozzle were used for simulation:

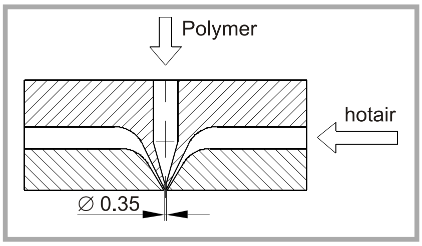

Figure 1. *Spinning beam in melt-blow process.*

- temperature, $T_0 = 573$ K
- pressure, $P_0 = 1{,}015$ bar
- velocity, $U_0 = 30, 50, 75, 100, 200$ and 300 m/s.

The distributions of air velocity and air temperature along the spinning line are displayed in figures 2÷5.

On the basis of these works, one can draw the following conclusions:

- maximum air speed occurs at a distance of a few millimeters from the spinning beam. The maximal air speed is greater than the air outflow because both streams collide with each other. For a speed of 300 m/s, the increase is equal to 40%;
- air temperature decreases monotonically, practically in the same way as in the whole range of initial air velocity;
- these observations have important effects on the aerodynamic conditions of fibre formation.

Modelling of air-driven melt spinning

The modelling of the pneumatic melt spinning of propylene fibres was based

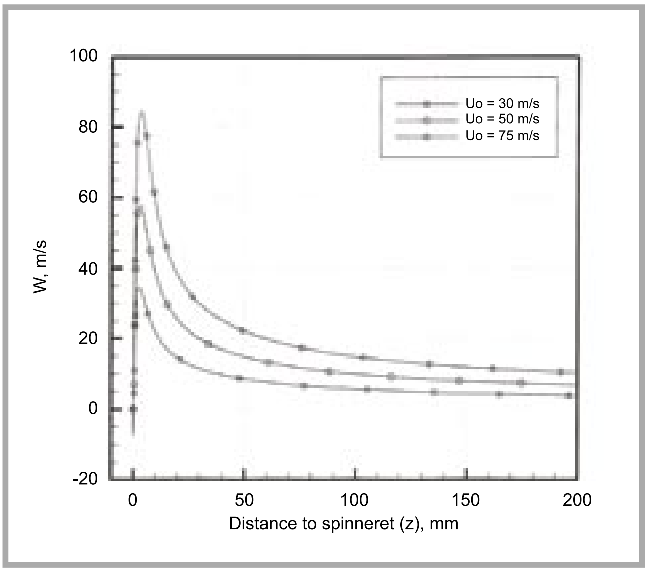

Figure 2. *The distribution of air velocity Win m/s along the spinning line for initial air velocity* $U_0 = 30 \div 75$ *m/s.*

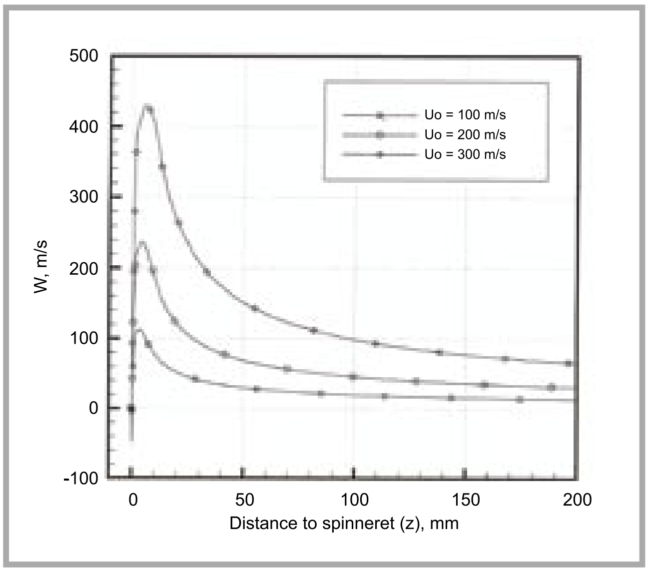

Figure 3. *The distribution of air velocity Win m/s along the spinning line for initial air velocity* $U_0 = 100 \div 300$ *m/s.*

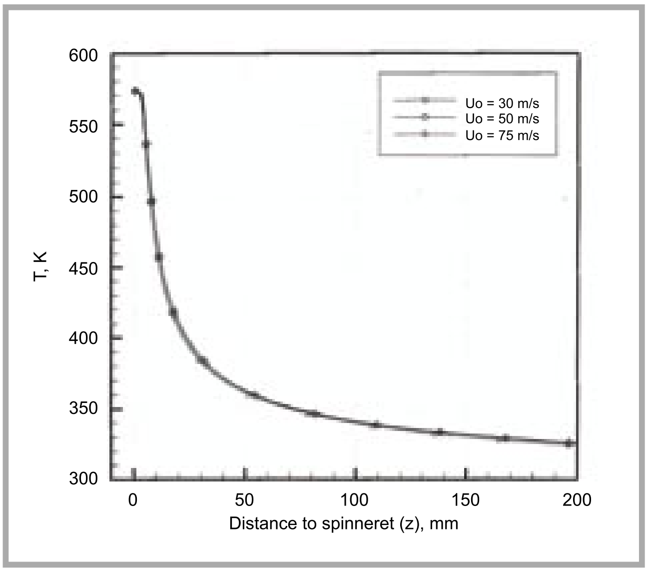

Figure 4. *The distribution of air temperature T in K along the spinning line for initial air velocity* $U_0 = 30 \div 75$ *m/s.*

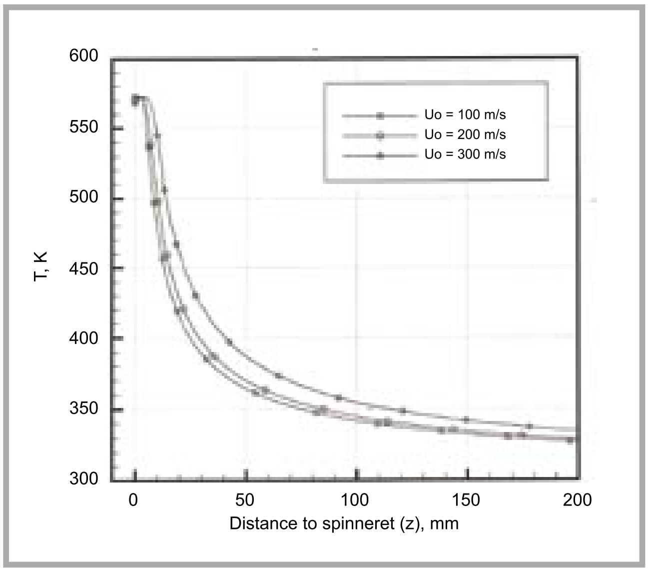

Figure 5. *The distribution of air temperature T in K along the spinning line for initial air velocity* $U_0 = 100 \div 300$ *m/s.*

on thin filament approximation, neglecting radial distribution of kinematic and dynamic characteristic (velocity *V*, temperature *T*, axial tension *F*). Instead of radially differentiated variables, average variables integrated over a filament cross-section were used. This reduces the dynamic equations to one dimension-coordinates, measured along the spinline from the spinneret (spinning beam) to the collector. Approximation is more reasonable as the location of linear orifices in the spinning beam causes only an insignificant influence of the neighbouring polymer streams.

The set of material characteristics and parameters for the simulation of isotactic polypropylene melt spinning is given in Table I.

Axial dynamic profiles computed from the model show a maximum of the tensile force located at the spinneret outflow. Next, the force decreases monotonically along the spinning line and vanishes at the deposition point on the nonwoven plane (Figure 6)

The computed tensile stress is small at the spinneret outflow because of the high initial cross-section of the liquid polymer jet. Despite the decrease in the tensile force, the tensile stress increases along the spun jet, starting from the spinneret outflow, as a result of a strong reduction in the jet diameter. The stress achieves a maximum at a distance of 5 - 6 cm to the spinneret and then reduces to zero at the filament deposition point (Figure 7).

Table 1. *The material characteristics and parameters for simulation of isotactic polipropylene melt spinning.*

Parameter	Value
Average molecular weight, Mw, Da	100,000 ÷ 300,000
Shear viscosity at temp. 300 °C, η_o, Pas	16÷670
Orifice diameter in spinning beam, D_o, mm	0.35
Polymer throughput per orifice, W, g/s	0.01
Initial polymer temp., °C	190; 300
Initial air velocity, m/s	30 ÷ 300
Initial air temp., °C	300

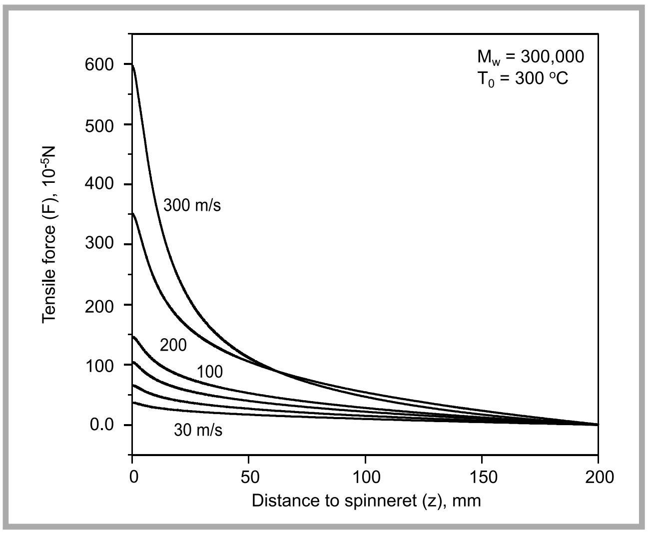

Figure 6. Tensile force as a function of the distance to the spinneret for initial air velocity in the range of 30 ÷ 300 m/s. Polymer molecular weight M_W = 300,000. Initial air temp. T_0 = 300 °C.

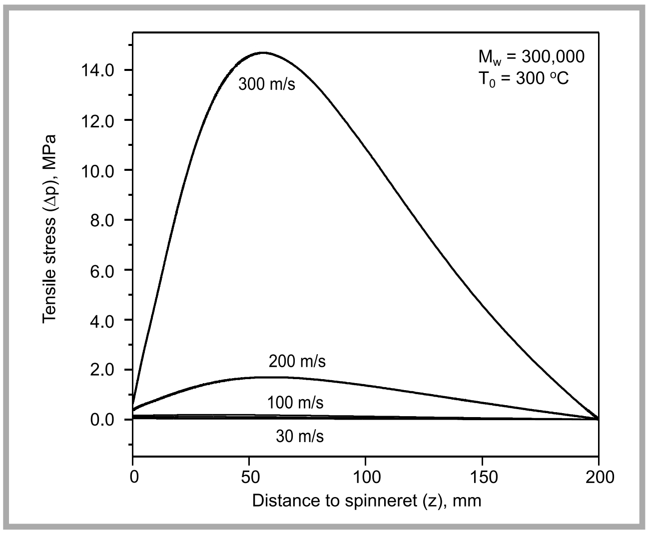

Figure 7. Tensile stress as a function of the distance to the spinneret for initial air velocity in the range of 30 ÷ 300 m/s. Polymer molecular weight M_W = 300,000. Initial air temp. T_0 = 300 °C.

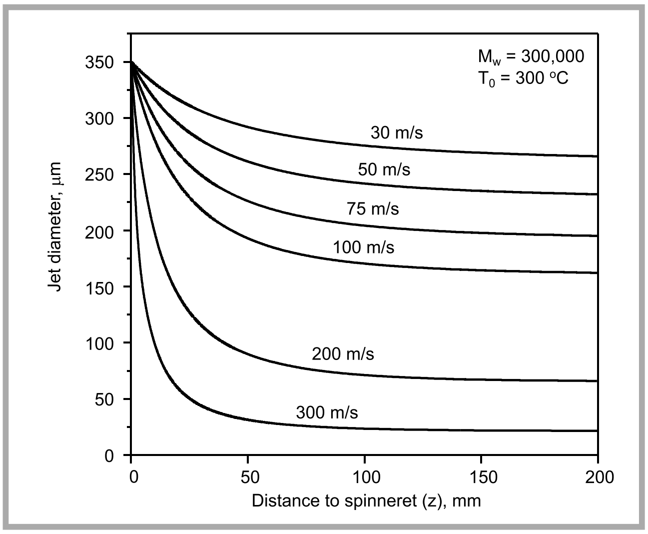

Figure 8. Jet diameter as a function of the distance to the spinneret for initial air velocity in the range of 30 ÷ 300 m/s. Polymer molecular weight M_W = 300,000. Initial air temp. T_0 = 300 °C.

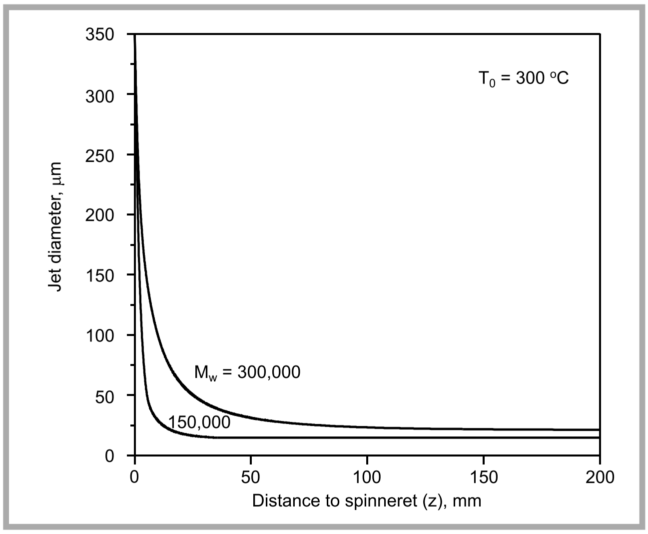

Figure 9. Jet diameter as a function of the distance to the spinneret for initial air velocity of 300 m/s and initial air temp. of 300 °C. Polymer molecular weight M_W = 300,000 and M_W = 150,000.

The computed axial profile of the jet diameter indicate that the fibre formation occurs most intensively at a distance of about 8cm below the spinneret output in the range of the maximum tensile stress (Figure 8).

The elongation rate of the polymer fluid in the fibre formation range significantly increases, resulting in smaller diameter of the nonwoven fibres, higher values of initial air velocity, higher initial temperature of polymer and lower polymer molecular weight.

The influence of polymer molecular weight on fibre diameter is shown in Figure 9.

Decreasing polymer molecular weight leads to obtaining fibres a smaller diameter, what is beneficial for nonwoven properties.

The temperature profiles of the polymer jet with the take-up plane of the nonwoven located 20 cm below the spinneret and with initial temperature of the air blow of 300 °C indicate that the polymer is amorphous in the entire range of the spinning line.

Increasing the initial air velocity and initial temperature of the polymer and decreasing its molecular weight, results in a shortening of the zone of drawing activity of the air blow and shifting of the whirling zone towards the spinneret. In such a case it maybe necessary to shift the nonwoven take-up plane to the zone of drawing activity of the air to avoid whirling the liquid polymer jets in the spinning space before deposition on the take-up plane.

In the case of very high initial air velocity in the range of 200 ÷ 300 m/s, one can predict a reduction in the distance between the spinneret and the whirling instability down to a few centimeters or anywhere from ten to twenty millimeters. Any shift of the take-up plane to such a short distance from the spinneret maybe technically difficult.

To avoid the negative effects of the whirling of liquid jets on nonwoven when applying high velocity (supersonic), air blow a with much lower initial temperature of air should be considered for better cooling and solidification of the polymer jets in a short range before entering the whirling zone.

To avoid interactions of the filament with the construction elements of the spinneret-air blow nozzle system and resulting instabilities of the process, adequate geometry of the symmetric air blown nozzle should be considered.

Experimental part

Experimental investigations of the melt-blown process were conducted using commercial-like line equipped with a one meter long spinning beam containing 1000 orifices with a diameter of 0.35 mm.

A schematic illustration of the melt-blown process is shown in Fig.10. A thermoplastic fibre-forming polymer is/was extruded through small orifices into convergent streams of hot air that rapidly attenuate the extrudate into small diameter fibres.

Major parameters controlling nonwoven formation for polypropylene with melt flow-rate of 25g/10min:

- temperature in extruder melting zone 185÷270°C
- temperature along the spinning beam 300÷320°C
- initial air temperature 320÷340°C
- initial air speed 50÷70m/s.

According to the conclusions of the mathematical model, the distance between the spinneret and the solidification area on the moving screen was changed in the range of 20÷30 cm. Also, the influence of initial air temperature and initial air speed on nonwoven formation was investigated. The experimental works were performed using Moplen HF568X isotatic polypropylene and Malen P polypropylene, S-901 Melt flow rate MFR (230 °C/2.16 kg) for Moplen HF568X – 800 g/10 min, for Malen P, S-901 – 25 g/10 min. These polypropylenes were produced by Basell Polyolefins. The parameters of nonwoven formation for polypropylene with an MFR of 800 g/10 min are the subject of current experiments.

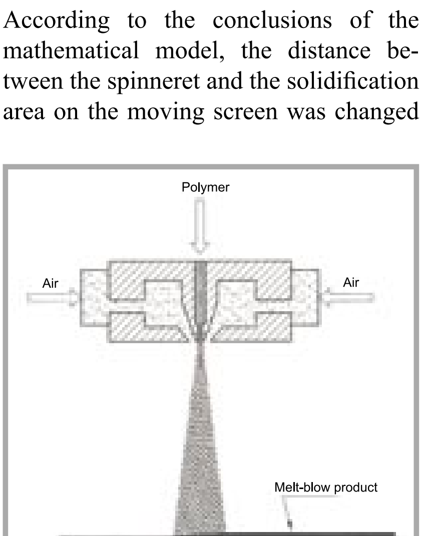

Figure 10. Schematic illustration of the melt-blown process.

In the experiments the following basic criterion were taken into account:

- stability of the nonwoven formation
- quality of the nonwoven web
- physical and mechanical properties of the polymers and filaments
- capacity of the nonwoven line.

The experiments led to the following conclusions:

1. For stable and continuous nonwoven formation, the optimal amount of the air supplying installation was of 0.053 m^3/s, which is related 26 m/s at the level of the air channel outlet. The air speed rapidly decreases along the spinning line, at a distance of 40 mm, which amounts to 17 m/s. This factor influences filament properties as well as its diameter, among others.
2. The quality of a nonwoven web depends on the spinneret distance – the solidification area on a moving screen. At a short distance the web is dense, hard and tightly connected. A too long distance gives a weak web with unconnected fibres.

The best results, as far as web quality is concered, one obtains for a distance of 200 mm.

As the mathematical modeling of pneumatic nonwoven formation indicates, applying high velocity (supersonic) air blow with a much lower initial temperature of air should be considered, allowing for better cooling and solidification of the polymer jets in a short range, before entering the whirling zone.

The behaviour of a liquid viscous filament under the shear forces of a concurrent air stream at its outer surface is the basis of the Nanoval Process [16-18]. This process is comparatively new and works in this field are still being developed.

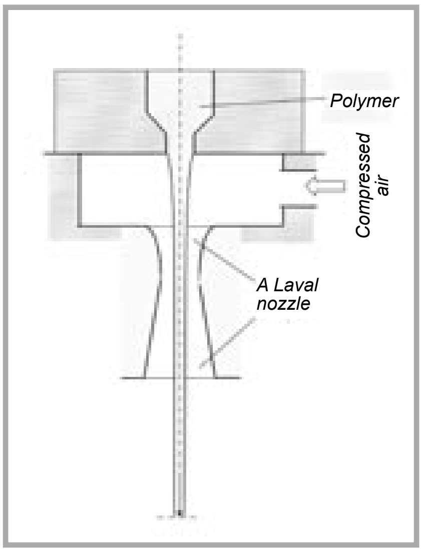

Figure 11. Nonwoven formation in a de Laval nozzle.

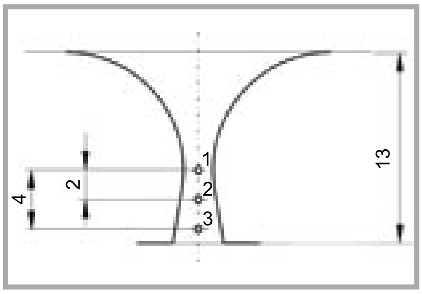

Figure 12. Position of measuring points in de Laval nozzle I.

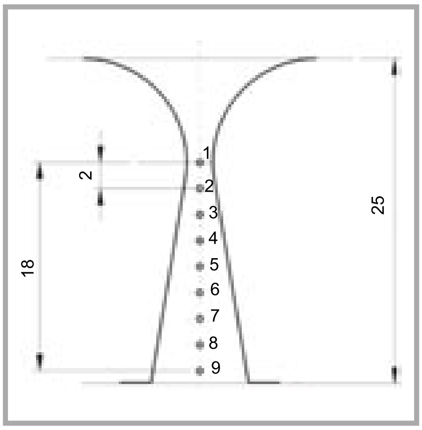

Figure 13. Position of measuring points in de Laval nozzle II.

The basic idea consists in the deformation of melted polymer by a supersonic air stream in a converging – diverging nozzle, called a de Laval nozzle (Figure 11)

The melt leaves the spinneret and is seized by adjacent gas, normally air streams which are accelerated steadily to the gas dynamic rules of theLaval nozzle. The spinneret orifices are arranged linearly, and the extrudeded filaments

Table 2. *Absolute pressure in bar at points 1, 2, 3 for nozzle I and nozzle II. Manometric air pressure = 1 bar.*

Point	1	2	3
Nozzle I	1,011	0,891	0,884
Nozzle II	1,045	0,645	0,614

Table 3. *Air velocity in m/s at points 1, 2, 3 for nozzle I and nozzle II. Manometric air pressure = 1 bar.*

Point	1	2	3
Nozzle I	315	340	342
Nozzle II	310	393	400

Table 4. *Influence of air pressure on fibre diameter.*

Air pressure, bar	Fibers diameter, μm
0.1	14.1
0.2	14.2
0.4	13.1
0.6	12.6
1.0	2.7

transported by the air flow from both sides of the spinneret. The filaments are then joined in the Laval nozzle chamber underneath and deposited on a moving conveyor where a random web is formed. The air flow may reach sonic speed in the narrowest cross section of the Lavala's nozzle. To calculate the air speed in this nozzle, the static pressure at the wall of the nozzle was measured.

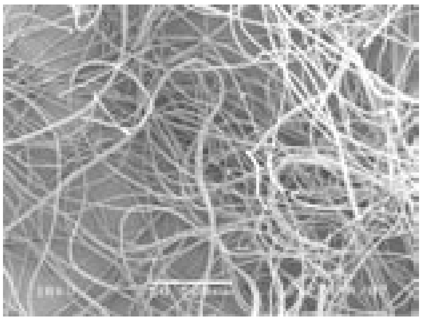

Figure 14. *SEM image of polypropylene nonwovens.*

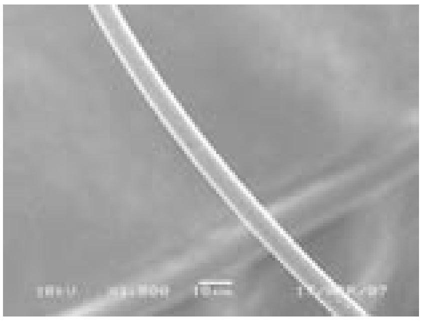

Figure 15. *SEM image of polypropylene filament.*

Figures 12 and 13 show the position of the measuring points. In Table 2 and Table 3 the absolute pressure and air speed at suitable points are given.

The air pressure decreases below the narrowest cross-section, (point 1). At this level, air velocity may reach supersonic speed. Application of longer Laval nozzles is beneficial for spinning because a higher difference of pressures increases the probability of filament splitting.

Pressure inside the filament increases with the degree of attenuation, inversely proportional to filament diameter. The inner pressure controlled by filament attenuation may exceed the air pressure, ultimately leading to the splitting of the filaments.

The problem of splitting is controversial, however [19]. Splitting is a random process and one should expect irregular shapes with a broad diameter distribution. The electronic microscopy studies of polypropylene filaments [Figure 14, Figure 15] do not show any irregularity, cracks or splitting. Further studies are needed to find out whether splitting does occur and, if so, in what conditions.

The attenuation of melt filament in supersonic air flow created by de Laval nozzle is effective for fine fibre production.

The influence of the air pressure feeding the experimental plant on fibre diameter is shown in Table 4.

If air pressure is around 1 bar or more, air velocity reaches supersonic speed. This increases the tensile stress and reduces fibre diameter, which is the desired effect.

Nonwovens consisting of fibres with a diameter of a few micrometers may have a broad technical and medical application.

General conclusions

Mathematical modeling and computer simulation open the possibility of low cost investigation on the pneumatic melt spinning of polypropylene in melt-blown nonwoven formation. The most important factors of nonwoven formation are predetermined from a set of differential equation.

The mathematical model was proved experimentally using a conventional melt-blown process and a new method of nonwoven formation by means of airflow with supersonic speed.

A lot of problems connected with a wide range of factors influencing nonwoven formation are currently solved by means of computer simulation.

Finally, it is possible to manufacte high-quality polypropylene nonwoven in a stable, continuous process for different applications.

Moreover, the process of nonwoven formation in supersonic air velocity can provide next generation products with quite new applications.

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