3.2.5 Example 2: Modelling of Fibre Formation in the Spunbonded Nonwoven Process

The spunbonded nonwoven process represents a typical multifilament spinning process because of its high number of filaments which can be up to a multiple of thousands. Take-up of the filaments is usually achieved by means of air friction, either in an excess-pressure or in an underpressure process, or sometimes a combination of both. Hajji, Misra, Spruiell et al. [263, 264] discussed the application of a modified single filament model to the *Reicofil* spunbonding nonwoven process and found good agreement between experimental and predicted data for their investigation. The following section deals with the application of both single filament and multifilament fibre formation models to the underpressure spunbonding nonwoven process in order to attain high filament velocities and low filament finenesses. The discussion is based on investigations which were carried out by the authors together with the *Saxon Textile Research Institute Chemnitz* [265]. The questions for the investigations were the following: Which dependencies exist for the underpressure process between the filament velocity and the filament fineness on the one hand and the spinning and take-up condition on the other? What are the best energetic conditions for the air suction device? How is the take-up to be designed to enable high filament velocities? Some answers can be given with the help of the applied fibre formation model.

Friction Forced Filament Take-up

The specialty of the process is that the filament take-up is not realised by means of godets or a winder like in the conventional yarn spinning processes but via drag of an air stream in spinning direction (Fig. 3.56). Contrary to the fibre spinning process where the final fibre velocity is fixed, the take-up velocity resulting from air drag force is not known from the beginning and thus cannot be treated as an initial spinning parameter. The higher the velocity of the axial air stream the higher the friction and drag force transferred to the fibre – thus the higher the fibre velocity. Furthermore, the higher the fibre velocity the lower its diameter (at constant mass throughput) and the lower the resulting friction and driving of the fibre. Consequently, the intentional effect will be reduced as the resulting air drag itself depends upon the difference between the velocities of fibre and air and also on the fibre fineness. The final fibre velocity, its fineness and all corresponding properties result from the balance between the air drag transferred to the fibre and the inherent fibre force contributions like the rheological, inertial, and gravitational forces, respectively.

When trying to solve the differential equations of the fibre formation model it becomes obvious that the initial value F_0 for the force at the spinneret is unknown. This causes no difficulties in the case of conventional take-up by means of godets or a winder because the initial rheological force in the

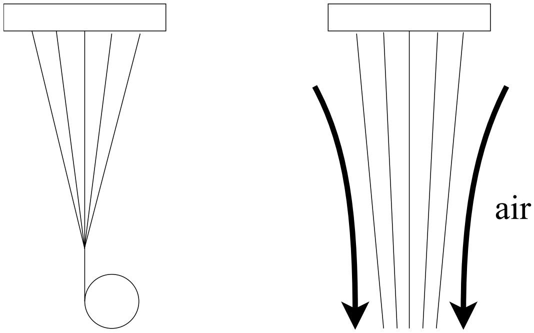

Fig. 3.56. Comparison between conventional yarn melt spinning process (*left*) and nonwoven process with air drag take-up (*right*)

model can be determined via an iteration procedure, that is, until the final take-up velocity is reached within an adequate numerical tolerance. However, the situation regarding the take-up by means of air drag is quite different because the final take-up velocity results from an equilibrium of forces and therefore is unknown from the beginning.

The simplest idea to solve this problem is to assume the initial rheological force is equal to zero $F_0 = F(0) = 0$ [263, 264]. But the problem can be more accurately solved in general by means of an additional iteration if the rheological force is known (or can be estimated) at *any* distance x of the fibre path. Especially the usage of a take-up channel (see below) opens up the possibility to get a much better assumption for the missing boundary value.

Figure 3.57 illustrates the basic idea of modelling the effect of a take-up channel. The possible technical realisation of an underpressure nonwoven equipment is also depicted. The positions of entrance and exit of the take-up channel (measured from the spinneret at $x = 0$) are x_1 and x_2, respectively.

The tensile force F for a single filament at entrance x_1 of the take-up channel is given by (see Eq. 3.11a on page 50 – the force balance)

$$F(x_1) = F_0 + Q \cdot (v(x_1) - v_0) + \int_0^{x_1} \frac{\varrho_{\mathrm{air}}}{2} c_{\mathrm{f}}\, \tilde{v}^2\, \pi\, D\, dx - \int_0^{x_1} \varrho_{\mathrm{p}}\, g\, \frac{\pi}{4}\, D^2\, dx\ , \tag{3.187}$$

where $\tilde{v}$ is the difference between the velocities of fibre and surrounding air, respectively, $\tilde{v} = |v - v_{\mathrm{air}}|$. The tensile force must be equal to the force applied inside the take-up channel:

$$F(x_1) = F_{\mathrm{e}} + \int_{x_1}^{x_2} \frac{\varrho_{\mathrm{air}}}{2}\, c_{\mathrm{f}}\, \tilde{v}^2\, \pi\, D\, dx - \int_{x_1}^{x_2} \varrho_{\mathrm{p}}\, g\, \frac{\pi}{4}\, D^2\, dx\ . \tag{3.188}$$

If the fibre is already solidified at the entrance $x = x_1$ of the channel, which means the fibre velocity and diameter are fixed and the air velocity inside

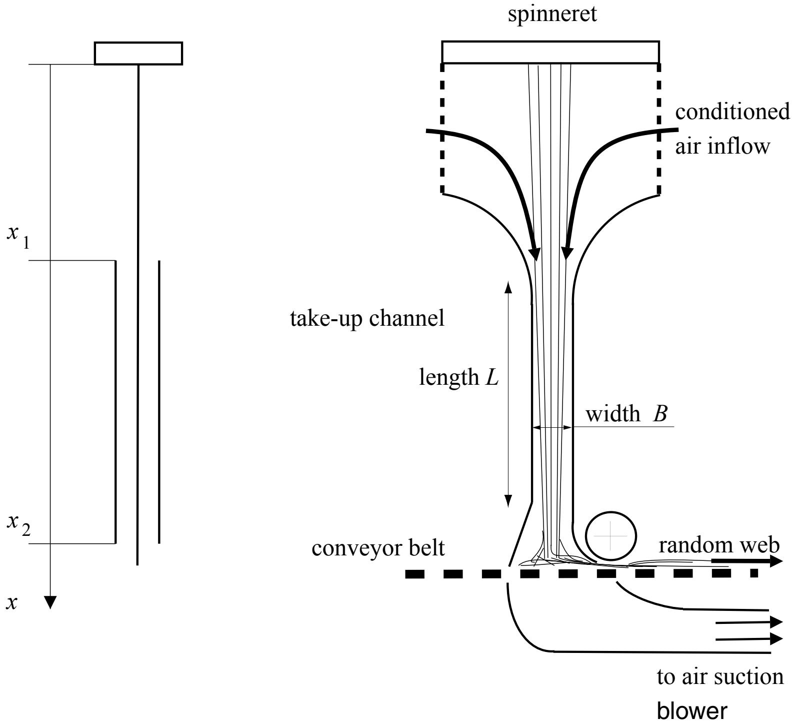

Fig. 3.57. Principle of the take-up channel (*left*) and possible realisation of an underpressure spunbonding nonwoven process (*right*)

the channel can also assumed to be constant, then (3.188) is simplified to

$$F(x_1) = F_\mathrm{e} + L\,\frac{\varrho_\mathrm{air}}{2}\,c_\mathrm{f}\,\tilde{v}^2\,\pi\,D - L\,\varrho_\mathrm{p}\,g\,\frac{\pi}{4}\,D^2\ . \tag{3.189}$$

The term $F_\mathrm{e} = F(x_2)$ is the tensile force at the exit of the channel and $L = x_2 - x_1$ is the channel length. Both equations can be combined together for all distances x. If careful attention is payed to the signs of air friction force contribution inside and outside of the take-up channel follows

$$F(x) = F_0 + Q\cdot(v(x) - v_0) + \Theta\int_0^x \frac{\varrho_\mathrm{air}}{2}\,c_\mathrm{f}\,\tilde{v}^2\,\pi\,D\,dx - \int_0^x \varrho_\mathrm{p}\,g\,\frac{\pi}{4}\,D^2\,dx\ , \tag{3.190}$$

with

$$\Theta = \begin{cases} 1 & \text{for} \quad v(x) > v_\mathrm{air} \\ -1 & \text{for} \quad v(x) < v_\mathrm{air} \end{cases}\ . \tag{3.191}$$

The initial tensile force F_0 correlates with the initial fibre velocity gradient dv/dx at $x = 0$ and therefore determines the final velocity after integration.

The only reasonable assumption for the equilibrium of forces at any distance is that the tensile force vanishes at the exit of the take-up channel

$$F(x_2) = 0 . \tag{3.192}$$

This condition replaces the boundary condition of a fixed take-up velocity. With the air profile $v_{\mathrm{air}}(x)$ given and the equations of fibre modelling, it is now possible to calculate the final fibre velocity and all connected characteristics of fibre formation.

High Filament Velocities – Realised by Means of an Underpressure Spunbonding Nonwoven Process

Subject of the investigations described below is the design of an underpressure spunbonding nonwoven equipment that realises high filament velocities up to 3000 m/min and filament finenesses of 1...2 dtex [265]. Boundary conditions are: the maximum total height of the equipment of less than 3 m and the limited power of the air suction blower. With help from the fibre formation model it was possible to accompany the design process and to give useful hints for the construction.

Inside the upper part of the underpressure spunbonding nonwoven equipment, the air entrance chamber, the air flow behavior should be a symmetrical (Fig. 3.57). Assuming a channel width of $B = 20$ mm, height of entrance chamber of $H = 1$ m, and mean value of the air velocity inside the channel of $v_{\mathrm{channel}} = 3000...6000$ m/min, then follows for the air entrance velocity v_{entr}:

$$v_{\mathrm{entr}} = \frac{B}{H} \cdot v_{\mathrm{channel}} = 1...2 \text{ m/s} .$$

The amount of entrance air velocity is comparable to the quenching air velocity for the staple fibre multifilament spinning example treated in the section before. Therefore the model of symmetrical flow behaviour can be used to calculate the multifilament effects on individual fibre formation, for example to estimate the differences in cooling behaviour of filaments located at the inner and outer side of the bundle, respectively. Figure 3.58 elucidates the application of the model for melt spinning of polypropylene.

For this process it must be assured that the filament temperatures inside the take-up channel are lower than any given critical temperature in that manner, and that no sticking occurs while the filaments touch each other or the walls of the channel. The solidification which represents the end of the fibre formation zone is not fixed because it depends on the spinning conditions, especially on the mass throughput, the melt temperature, and the kind of polymer material (with its property of heat capacity). Additionally, the cooling rate is retarded in the centre of the filament bundle. Therefore each set of spinning conditions determines a minimum distance x_{min} where the temperatures of all filaments is lower than the critical temperature:

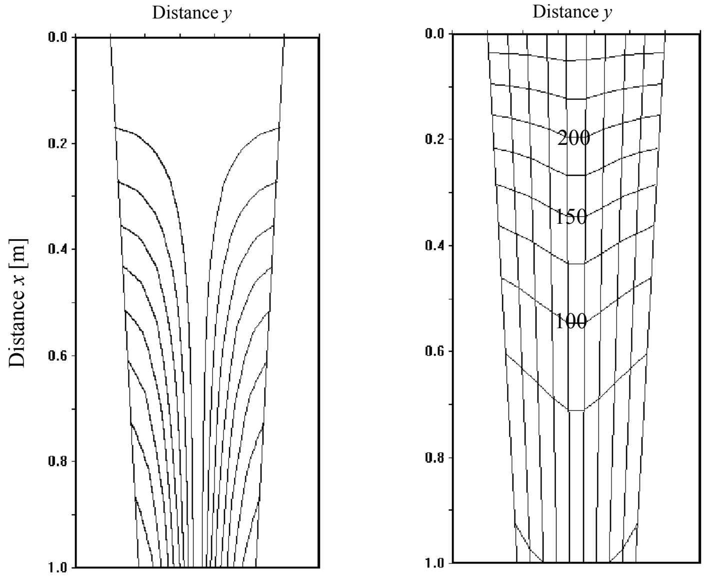

Fig. 3.58. Example of multifilament model application to the underpressure spunbonded nonwoven process. *Left:* streamlines of air, *right:* filament temperatures (isotherms), temperatures in °C indicated

$$T(x_{\min}) < T_{\mathrm{crit}} \ . \tag{3.193}$$

The next figure (Fig. 3.59) shows the distances where the polypropylene filaments reach the temperature of $T_{\mathrm{crit}} = 100\,°\mathrm{C}$ as example.

It can be seen that for the indicated spinning conditions these distances are always lower than 1 m; therefore the minimum distance of $x_{\min} \approx 1$ m according to the mass throughput of $Q = 1$ g/min is a sufficient distance between the spinneret and the entrance of the take-up channel. The calculation also confirms the assumption that the final filament velocity depends nearly linearly on the length L of the take-up channel. The calculation also provides relationships to describe the dependence of final velocity on air velocity inside the channel (see Figs. 3.60, 3.61).

At last the theoretical investigations allow to estimate the pairs of air velocity v_{channel} within the channel and corresponding length L of the channel to reach a destined filament velocity (Fig. 3.62). From the figures it can be seen that the conditions to reach 3000 m/min filament velocity are approximately the following: channel length ≈ 1 m, driving air velocity ≈ 100 m/s.

The task of reaching a defined air velocity inside the take-up channel of a given length and width is due to the power and energetic conditions of the air suction blower and depends upon pressure losses of the channel together with other parts of the spinning device. The longer the channel, the http://www.springer.com/978-3-540-46221-7

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