DOI: 10.2478/ata-2018-0025

Acta Technologica Agriculturae 4
Nitra, Slovaca Universitas Agriculturae Nitriae, 2018, pp. 136–140

DETERMINATION OF MELTING UNIT PRODUCTIVITY IN SYNTHETIC FIBROUS MATERIALS PRODUCTION BY VERTICAL BLOWING METHOD

Vladislav SVIATSKII[1]*, Pavol BOŽEK[2], Mikhail SOKOLOV[3]

[1]*Technology of Mechanical Engineering and Instrument Making, Votkinsk Branch of Kalashnikov Izhevsk State Technical University, Russia
[2]Institute of Applied Informatics, Automation and Mechatronics, Slovak University of Technology, Slovakia
[3]Computer-Integrated Systems in Mechanical Engineering, Tambov State Technical University, Russia

This paper presents the technology of production of synthetic fibrous materials from PET-raw by vertical blowing method. Fibre production by vertical blowing method is accompanied by complex and specific phenomena; therefore, development of new progressive technologies, high-performance machines and units for producing such materials is impossible without process modelling, which can significantly reduce the number of natural tests, cost and designing time and select optimal operating modes. Molten material motion in the melting unit of the hydrostatic type is determined by means of Poiseuille formula. Furthermore, the paper has proven that the melting unit has the greatest impact on process productivity by means of outlet radius and the pressure change of compressed air acting on the molten material surface. Increase in the height of the molten material column in the main cylindrical chamber of melting unit also leads to an increase in process productivity.

Keywords: secondary granulated PET-material; raw material melting; blow head; fibre blowing; elementary fibres

Synthetic fibrous materials made of PET raw materials are widely used in various fields of human activity. They are used in engineering, aircraft building, oil and gas, instrument engineering, electrical and radio engineering, electronics, construction, agriculture, medicine, sports, and household products (Krishna Murthy and Mandal, 2016; Sentyakov et al., 2010).

Traditional technological scheme for synthetic fibre production based on melt extrusion through the thin holes of the spinneret in the form of jets and their subsequent pulling by the receiving device is complicated (Papkov, 1988; Lestyánszka Škůrková and Kudičová, 2015.); moreover, cost of production is high. In addition to this, traditional method is focused on processing high-quality primary industrial materials of a certain composition (Charvet et al., 2018). When household and industrial wastes of heterogeneous composition and containing foreign inclusions are used as a material, final product has lower viscosity, melting temperature, as well as low mechanical characteristics, which do not allow for the usage of winding devices. For this reason, it is not possible to obtain a fibrous non-woven material from this kind of material by means of the traditional method (Sentyakov et al., 2014).

Results of works on designing of a new technology for fibrous materials production made of molten thermoplastics by means of vertical blowing of molten material in a jet flowing from the spinneret confirmed its positive qualities, including a significant reduction in the production costs of such fibre in comparison with traditional technology (Balog and Maľcovský, 2015). Moreover, such technological scheme for fibrous material production is simple and one-step method, since the entire feedstock transition process to the finished material is carried out by a single unit. Initial raw material is a harmless primary or secondary thermoplastic used for making food plastic dishes. The finished product is a staple fibre obtained from a primary or secondary thermoplastic, e.g. crushed plastic bottles (Sentyakov and Timofeev, 2004). Such fibre can be obtained in the form of cotton wool or canvases, in which elementary fibres are held together by either natural bonding forces or by gluing a fibre portion using temperature effect (Perton et al., 2018). Average diameter of the elementary fibres ranges from 1 to 100 mkm and average length of these fibres extends from 1 to 500 mm. Density of cotton wool or canvases ranges from 10 to 100 $kg \cdot m^{-3}$. Material is of low hygroscopicity, high strength and elasticity; content of acids, alkalis, acetone, dichloroethane is stable. It is not susceptible to the action of microorganisms. Operating temperature ranges from -60 to 170 °C and its coefficient of thermal conductivity is 0.037–0.040 W/(m·K) (Papkov, 1988).

Scheme for obtaining fibrous materials by the blowing method – by blowing a vertically falling molten thermoplastic jet with a compressed air stream is shown in Fig. 1. Apparatus for synthetic fibrous material production by vertical blowing method includes a melting unit, a blow head with an annular nozzle, and a conveyor.

Contact address: Vladislav Sviatskii, Technology of Mechanical Engineering and Instrument Making, Votkinsk Branch of Kalashnikov Izhevsk State Technical University, Russia, e-mail: svlad-2000@yandex.ru

Material and methods

In relation to designing the units for production of fibrous materials by vertical blowing, one of the most important tasks is the calculation of expected process performance. In one type of these units, feeding of molten polymer into the working zone of the pneumatic blow head is provided by electric melting unit, calculation scheme of which is shown in Fig. 1.

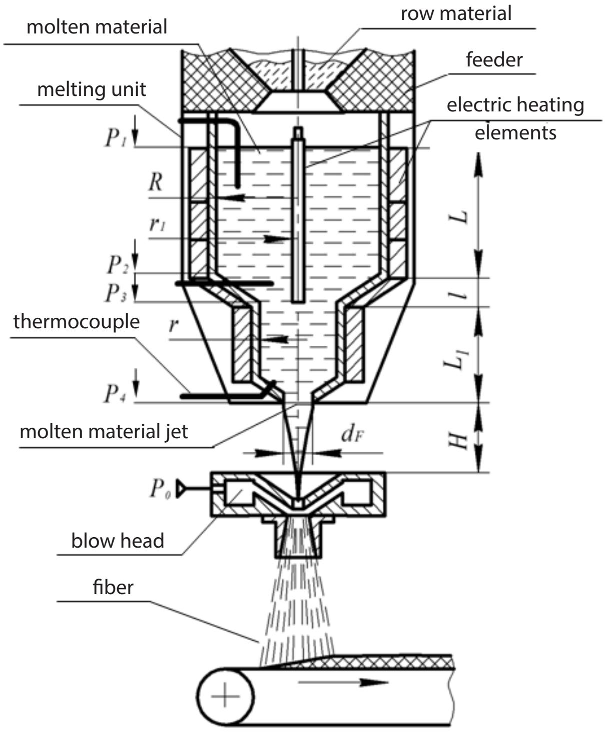

Fig. 1 Calculation scheme of melting unit for production of fibre materials made of thermoplastic

Melting unit (Fig. 1) consists of a vertically located main cylindrical chamber, on the outer surface of which electric heating elements are placed. In the central part of this chamber, there is an electric heating element. Main chamber is also connected to a small cylindrical chamber that is also equipped with an electric heating element and has an outlet for the molten thermoplastic exit into the atmosphere, placed coaxially with the central channel of the blow head. The upper part of chamber is covered with a lid with a conical valve of the input feeder and connected to a pneumatic oscillation generator (Pan and Zhao, 2018). Such construction of melting unit provides evenly staged heating and melting of raw materials at temperature of 250–280 °C (Božek and Turygin, 2014).

Automation of loading and control of the material amount in the main cylindrical chamber can be evaluated by the pneumatic oscillation frequency generated by the volume sensor. Molten thermoplastic expulsion through the outlet hole occurs under the influence of hydrostatic pressure and pulsating air pressure produced by the pneumatic oscillation generator (not conditionally shown) (Sentyakov et al., 2014).

In contrast to the most common type of extruder units (Sviatskii et al., 2015), the main difficulty of theoretical productivity calculation of such melting units lies in the fact that the working fluid is a molten thermoplastic that can be significantly uneven in terms of viscosity at both height and radius of the inner surface. In order to reduce this unevenness, the unit's inner surface is divided into two chambers with individual heating elements and an additional heating element is installed in the central part of the main chamber. During designing the internal unit surface, smooth conic and radial transitions from one part of the surface to the other are provided, what also helps to reduce the viscosity gradient. This technical solution allows for an assumption that the molten thermoplastic is a viscous incompressible fluid. It was also observed that flow of molten material, even in the smallest flow sections, is laminar – with very small values of the Reynolds criterion – what also simplifies the solution of the problem (Apel and Dmitriev, 2004).

Considering the molten material motion in each of four geometric elements of the aforementioned melting unit, its motion in the main cylindrical chamber can be determined from the Poiseuille formula:

$$P_1 = \frac{8\mu_1 LQ}{\pi\left(R - r_1\right)^4} \tag{1}$$

where:

μ_1 – coefficient of dynamic viscosity of molten thermoplastic in the first element, Pa·s

Q – volumetric flow velocity or unit capacity, $m^3 \cdot s^{-1}$

P_1 – air pressure in main cylindrical chamber, Pa

Molten material motion over conical melting unit inner surface is determined by the relation (Gusinsky et al., 1979):

$$P_1 + P_2 = \left(\frac{8\mu_2 lQ}{3\pi r^4}\right)\left(\frac{r}{R} + \left(\frac{r}{R}\right)^2 + \left(\frac{r}{R}\right)^3\right) \tag{2}$$

where:

μ_2 – coefficient of dynamic viscosity of molten thermoplastic in the second element, Pa·s

$P_2 = \rho g L$ – hydrostatic pressure of the second element, Pa (ρ = 1,300 $kg \cdot m^{-3}$) – density of the PET, g = 9.8 $m \cdot s^{-2}$)

Molten material motion through the second cylindrical section of the melting unit is also determined by the Poiseuille formula:

$$P_1 + P_2 + P_3 = \frac{8\mu L_1 Q}{\pi r^4} \tag{3}$$

where:

μ_3 – coefficient of dynamic viscosity of the molten thermoplastic in the second cylindrical section, Pa·s

$P_3 = \rho g l$ – hydrostatic pressure directly above the second cylindrical section, Pa

Flow of a molten thermoplastic from jet outlet into the atmosphere occurs under pressure determined by the following expression (Apel and Dmitriev, 2004):

$$P_1 + P_2 + P_3 + P_4 = \frac{3Q\mu_4}{r_F^3} \tag{4}$$

where:

μ_4 – dynamic viscosity coefficient of the molten thermoplastic at the jet outlet into the atmosphere, Pa·s

$P_4 = \rho g L_1$ – hydrostatic pressure directly above the outlet, Pa

It is necessary to point out that the coefficient of molten thermoplastic dynamic viscosity value varies in different geometric elements of the melting unit internal. In the middle part of melting unit, it is possible to maintain the temperature of the molten material in the required range – from 270 to 280 °C – with $\mu_2 = \mu_3$ = 190–200 Pa·s. In the upper part of melting unit, through which the material is constantly fed, the temperature on the molten material surface is lower, so the dynamic viscosity coefficient is of a larger value $\mu_1 > \mu_2$. At the jet outlet, the material is cooled by atmospheric air, what is also intensified by interaction with the blow head and leads to higher dynamic viscosity coefficient $\mu_4 > \mu_2$.

Considering the Eqs. 1, 2, 3 and 4 obtained above as a system of equations, after the transformations, a formula for determining the volumetric productivity of melting unit is obtained:

$$Q = \frac{\left(4P_1 + 3P_2 + 2P_3 + P_4\right)}{\left(A + B + C + D\right)} \tag{5}$$

$$A = \frac{8\mu_1 L}{\pi}\left(R - r_1\right)^4$$

$$B = \left(\frac{8\mu_2 l}{3\pi r^4}\right)\left(\frac{r}{R} + \left(\frac{r}{R}\right)^2 + \left(\frac{r}{R}\right)^3\right)$$

$$C = \frac{8\mu L_1}{\pi r^4}$$

$$D = \frac{3\mu_4}{r_F^3}$$

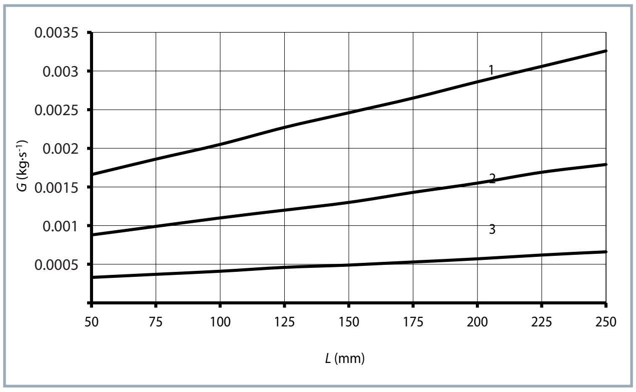

Fig. 2 Dependence of the mass productivity of the melting unit G on the column height of material L in the main cylindrical chamber at different values of the outlet radius r_F
1 – r_F = 2.5 mm; 2 – r_F = 2 mm; 3 – r_F = 1.5 mm

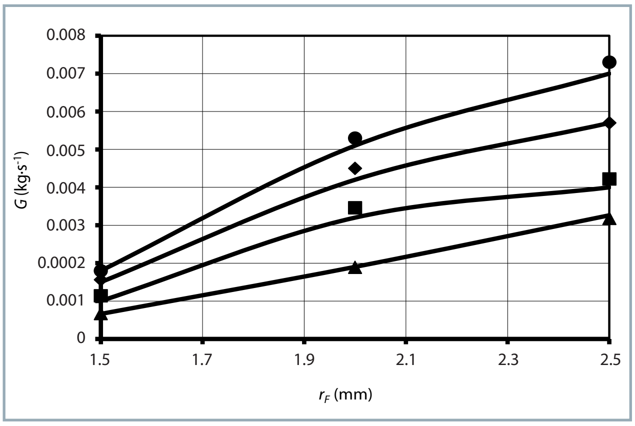

Fig. 3 Dependence of the mass productivity of the melting unit G on the radius of the outlet r_F at different air pressures P_1
Δ – P_1 = 0 kPa; □ – P_1 = 1 kPa; ◊ – P_1 = 10 kPa; ○ – P_1 = 20 kPa

Mass production capacity of the unit G (kg·s^{-1}) is determined using the following formula:

$$G = Q \times \rho \tag{6}$$

Analysis results obtained by means of Eq. 6 are shown in the graphs in Figs. 2 and 3.

Experimental research

A general view of the experimental apparatus (Sentyakov et al., 2014) of a hydrostatic melting unit is shown in Fig. 4. Productivity was calculated by means of Eq. 6, unit had the following geometric parameters: L = 200 mm; R = 40 mm; r_1 = 9 mm; r = 12.5 mm; l = 25 mm; L_1 = 100 mm.

Experimental apparatus works as follows: before the process starts, small and large melting chambers are fed with secondary granular PET raw material. The first feeding load does not exceed ¾ of the maximum volume. Subsequently, all heating elements are switched on and when the temperature reaches 180–200 °C in the small melting chamber, the heating process is switched off. When the temperature in the large melting chamber reaches 250–270 °C, the heating element of the lower melting chamber is switched on. After the molten mass outflow begins, the air supply to the blow head is switched on through the spinneret of the lower melting chamber and the fibre production process begins. Fibre is deposited on a movable conveyor belt, producing a canvas 350 mm wide with a density of approx. 15 kg·m^{-3} (Charvet et al., 2018).

During the experimental apparatus testing, spinnerets of three sizes r_F = 1.5, 2.0 and 2.5 mm were investigated. Flow process out of the melting unit was stable.

Experimental research results of the melting aggregate productivity are presented in Table 1, as well as in Fig. 2. Points of the graph show the average experimental values of the melting unit's output for different sizes of the spinneret outlet and at pressures P_1 on the molten material surface, which were obtained after five experiment repetitions. A confidence interval with a fixed probability of

Table 1 The research results of melting unit productivity

P_1 (kPa)	r_F (mm)	Melting unit productivity G ($kg \cdot s^{-1}$)		Standard deviation σ
		estimated	experimental	
1	2	3	4	5
0	1.5	0.00066	$0.00067 \pm 0.3 \cdot 10^{-4}$	0.00002
	2.0	0.0019	$0.00189 \pm 2.1 \cdot 10^{-4}$	0.00012
	2.5	0.00326	$0.00318 \pm 1.9 \cdot 10^{-4}$	0.00017
1	1.5	0.001	$0.00114 \pm 4.1 \cdot 10^{-4}$	0.00023
	2.0	0.0032	$0.00346 \pm 4 \cdot 10^{-4}$	0.00023
	2.5	0.004	$0.0042 \pm 3.2 \cdot 10^{-4}$	0.00033
10	1.5	0.0015	$0.00156 \pm 3.4 \cdot 10^{-4}$	0.00019
	2.0	0.0042	$0.0045 \pm 3.4 \cdot 10^{-4}$	0.0002
	2.5	0.0057	$0.0057 \pm 10 \cdot 10^{-4}$	0.00056
20	1.5	0.0018	$0.0018 \pm 3.2 \cdot 10^{-4}$	0.00018
	2.0	0.0051	$0.0053 \pm 5 \cdot 10^{-4}$	0.0003
	2.5	0.007	$0.0073 \pm 4.6 \cdot 10^{-4}$	0.00026

$\gamma = 0.95$ (Gusinsky et al., 1979) was determined for the mean experimental values presented in Table 1.

Results and discussion

It was assumed by calculation that $\mu 1 = 250$ Pa·s, $\mu 2 = \mu 3 = 190$ Pa·s, $\mu 4 = 220$ Pa·s (Papkov, 1988).

Graphs of the productivity dependence on these parameters are shown in Figs. 3 and 4. As shown in Fig. 3, an increase in the molten material column height L in the main cylindrical chamber leads to the productivity increase. Furthermore, calculations also showed that the greatest influence on the melting unit productivity is caused by a change in the outlet radius r_F and the change in the

Fig. 4 General view of the experimental apparatus of hydrostatic type melting unit

compressed air pressure acting on the molten material surface P_1.

Difference between the results of the productivity calculation by means of Eq. 6 and the experimental data obtained during the melting unit testing with the aforementioned flow section geometric parameters at radius r_F ranging from 1.5 to 2.5 mm and pressure P_1 ranging from 0 to 20 kPa, using secondary granulated PET material as feedstock, averaged 5%.

In terms of assessment of the described unit together with a blow head with an annular converging nozzle with an average annular gap diameter of 10 mm, it has been found that a reduction in the outlet radius r_F by less than 1.5 mm results in a significant reduction in the radius of the molten material flow and staple fibre production does not take place – a continuous thread is formed with a very low process productivity that is of no practical interest. An increase in r_F by more than 2.5 mm results in a corresponding increase in the radius of the outflowing molten material jet, its consequent contact with the inner surface of the central gap of the blowing head, resulting in termination of the fibre production process. An increase in pressure P_1 by more than 10 kPa leads to an increase in process productivity, however, such increase imposes risks for safety.

Conclusion

Control over the performance of the melting unit is possible without changing its design parameters, but by changing the air pressure P_1 and the height of the column of molten material L in the main cylindrical chamber. Presented method of calculating the melting unit productivity for the production of fibrous materials from a molten thermoplastic by the vertical blowing method allows obtaining calculation formulas for melting units with an arbitrary combination and arrangement of the aforementioned basic geometric elements in their internal cavity.

Acknowledgement

The contribution is sponsored by the project 015STU-4/2018 Specialised laboratory supported by multimedia textbook for subject "Production systems design and operation" for STU Bratislava.

References

APEL, P. YU. – DMITRIEV, S. N. 2004. Optimization of the shape of the pores of track membranes. In Critical Technologies, Membranes, vol. 23, no. 3, pp. 32–37.

BALOG, M. – MAĽCOVSKÝ, M. 2015. Optimization of the production process of the plastic injection molding engineering with the technology of reverse engineering application. In Acta Tecnología – International Scientific Journal about Technologies, vol. 1, no. 2, pp. 9–12.

BOŽEK, P. – TURYGIN, Y. 2014. Measurement of the operating parameters and numerical analysis of the mechanical subsystem. In Measurement Science Review, vol. 14, no. 4, pp. 198–203.

CHARVET, A. – PACAULT, S. – BOURROUS, S. – THOMAS, D. 2018. Association of fibrous filters for aerosol filtration in predominant Brownian diffusion conditions. In Separation and Purification Technology, vol. 207, DOI: December 22, 2018.

GUSINSKY, G. M. – KREMER, E. B. – KREMER, M. I. – MCHEDLISHVILI, B. V. 1979. Determination of the micropores' size of nuclear microfilters with a small diameter. In Engineering and Physics Journal, vol. 37, pp.119–129.

KRISHNA MURTHY, C. S. – MANDAL, B. B. 2016. Biomaterials based on natural and synthetic polymer fibers. In Trends in Biomaterials, pp. 217–174.

LESTYÁNSZKA ŠKŮRKOVÁ, K. – KUDIČOVÁ, J. 2015. Study of injection process capability in production of plastic boxes. In Acta Technologica Agriculturae, vol. 18, no. 2, pp. 54–56.

PAN, Y. – ZHAO, H. A. 2018. Novel blowing agent polyelectrolyte for fabricating intumescent multilayer coating that retards fire on cotton fabric. In Journal of Applied Polymer Science, vol. 135, no. 32, DOI: August 20, 2018.

PAPKOV, S. P. 1988. Theoretical foundations of the production of chemical fibers. Moscow: Chemistry, 272 pp.

PERTON, M. – SPICA, Z. – CAUDRON, C. 2018. Inversion of the horizontal-to-vertical spectral ratio in presence of strong lateral heterogeneity. In Geophysical Journal International, vol. 212, no. 2, pp. 930–941.

SENTYAKOV, B. A. – TIMOFEEV, V. L. 2004. The production technology of heat-insulating materials on the basis of basalt fiber. Izhevsk: Publishing house of ISTU, 232 pp.

SENTYAKOV, B. A. – SHIROBOKOV, K. P. – SVIATSKII, V. M. 2010. Fibrous sorbent for the collection of oil based on polyethylene terephthalate. Prevention of accidents of buildings and structures. In Collection of Scientific Papers, no. 9, Moscow, pp. 631–634.

SENTYAKOV, B. A. – SHIROBOKOV, K. P. – SVIATSKII, V. M. – SVIATSKII, V. M. 2014. Processes of obtaining and practical use of polyethylene terephthalate fiber from secondary raw materials (monograph). Stary Oskol: Publishing house TNT, 162 pp. ISBN 978-5-94178-451-6.

SVIATSKII, V. M. – SENTYAKOV, B. A. – SVIATSKII, M. A. – SENTYAKOV, K. B. – GARAYEV, S. A. 2015. Simulation of the process of fabrication canvas with fibrous materials. In Vestnik ISTU, no. 2, pp. 17–20.