TECHNIKA TRANSPORTU SZYNOWEGO

Zbigniew PAWELSKI, Mariusz KRAJEWSKI, Janusz JARZĘBOWSKI, Sergiusz ZAKRZEWSKI

UTILISATION OF CFD METHOD OF K-EPSILON FOR MODELLING OF FLOW PHENOMENA OCCURRING DURING PNEUMOSPINNING PROCESS

Abstract

The paper describes the flow phenomena, incorporated in technology of polymer fiber production. It includes detailed description of pneumosppining processes, as well as the influence of values of particular technological parameters on the production process of polymer nonwoven fabics. Also the possibility of utilization of CFD methods, as a tool for modeling flow phenomena existing during pneumosppinig processes, was presented in the paper hereby.

1. INTRODUCTION

The methods of forming polymer fibre in a stream of hot air are one of the most dynamically developing technologies of nonwoven fabrics production. Manufacturing of fabrics by these methods is a complex process. Until now numerous theoretical and empirical models, both for laboratory and industrial applications, have been developed in order to describe it. The structure of fibre-form fleece is being obtained as a function of multiple parameters, altering dynamically in the area in between multi-hole nozzle, feeding spouts of melted polymer, and the condenser on which fabrics is being formed. The parameters include the temperature of a spout, velocity and diameter of a polymer spout, temperature and velocity of air stream, as well as non-stable, tangled character of the fibre sheaf.

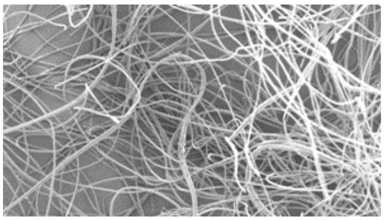

Fig. 1. Image of polypropylene nonwovens

Furthermore, the structure of fibre-form fleece depends directly on velocity of the flow of melted polymer through the holes of the spinning nozzle, distance between the nozzle and the transporter (condensator) and rheological properties of the polymer itself. The geometry of nozzle holes (its diameter and length to diameter ratio), configuration of the conduit feeding compressed, hot air to the nozzle, as well as size of the aperture situated alongside nozzle holes, they all influence the structure of fabric being formed.

Unique properties of nonwoven fabrics are the key factors for their wide area of application e.g. as filtering materials used as cartridges for various filter types, isolators for building and textile industry, single use personal protective suits. The process of fabrics manufacturing enables for addition of various types of additives in order to improve their final characteristics, thus broadening the area of potential use for industrial applications.

Global need for such products is currently extremely high. Polymer fabrics of various properties are being used in agriculture, motor and food industry and most of all in medicine.

2. FLOW PHENOMENA OCCURRING AS A PART OF FABRICS PRODUCTION TECHNOLOGY

The process of fabrics production is considered to be complex, especially due to use of different polymer types of various physical and chemical properties. It requires extremely precise control and operating of complex auxiliary equipment including control and measurement apparatus. The temperature of the mixture of extruded polymer, temperature of air, as well as degree of polymer crystallisation are of great importance. One of the common methods for fabric production is the “melt-blown” method. It is characterized by preserving constant and stable temperature parameters. Temperature of polymer being fed, of the spinning beam, air beam distributing extruded polymer, as well as the temperature of ambient air mixed during the process, are all important parameters. All of them are affected by different factors. The process of blow-separation of melted polymer, forming different types of fabrics, or multilayer composites based on fabrics, requires time-varying set parameters, due to the necessity of maintaining constant conditions of the process at the output of the system, that will not be subjected to variations of ambient temperature, pressure, of irregularity of polymer mass with respect to the width of the beam. Abnormalities of the polymer flow through the extruder and spinning beam are caused directly by the geometry and input parameters’ values.

Fig. 2. Polymer stream flowing out of the spinning beam

They may result in discontinuities of extruded polymer stream from the extruded, or from the spinning beam holes. Raw material, being present inside the system may be overheated, thus causing contamination (burns) unable to be removed without disassembling the machine (spinning beam). The aerodynamic processes of fabrics spinning from polymers mixtures are qualified as double phase systems. The first phase includes stream of liquid polymer, flowing out of the holes of the spinning beam and the second phase includes the compressed air stream from the nozzle, responsible for aerodynamic stretching of the polymer. The stream of polymer flowing out of holes alongside the spinneret are perpendicular to the front face of the spinneret, as well as to plane of formed fabric on the conveyor. The velocity of air stream blowing from extended nozzle is high comparing to velocity of the polymer stream. It blows from both sides of the spinning beam symmetrically affecting the streams of melted polymer, causing its extensions in the first phase and rupturing the strand in the second, before final forming of the fabric on the conveyor. The friction force acting between the blowing air stream and polymer strand, causes its abrupt coercing alongside the spinning axes, thus forming thin fabrics. Pneumatic spinning of fabrics from melted polymer is the basic method for fast industrial production of nonwoven fabrics.

3. COMPLEXITY OF THE NONWOVEN FABRIC PNEUMOSPINNING PROCESS

The process of nonwoven fabric production by available methods of blow-separation of melted polymer, requires pre-serving proper and constant conditions of technological process. Temperature of polymer being fed, temperature of blowing air and temperature of ambient air are of special importance. The temperature of polymer depends on the method of beam heating up to the preset value of temperature. It is realized by appropriate heating zones, equipped most commonly with cartridge heaters of different power. Placement of the heaters is one of the conditions that influences even temperature distribution over the whole length of the beam.

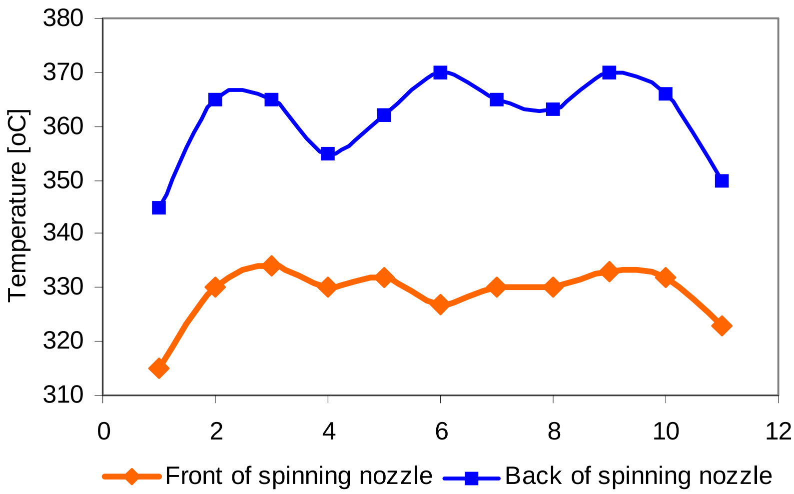

Fig. 3. The expansion of temperature in spinning nozzle

Temperature control of each heating zone is possible thanks to temperature sensors, situated inside the body of the spinning beam. Continuous control of temperature of all heating zones is done with spring regulators, equipped with sensors. Most often self-learning regulators are used. They control the effective power of heaters, thus obtaining expected temperature distribution pattern. Feeding of raw material of accurate properties to worm extruders is another issue. Too high humidity of the raw material causes flow disturbances that in turn leads to instability of the technological process. Humidity released due to increased temperature form the liquid-gaseous mixture that causes non even polymer extrusion from the spinning conduits of the beam. In order to avoid such problems, raw material is subjected to pre-drying in special dryers, assuring proper level of humidity, according to requirements of the particular process. Granulate is being dried by means of circulating air, in the closed circuit of the drying system. The temperature of the air is increased according to the type of polymer. Afterwards the air is dried by the absorber in the cooler, and heated again before it is transferred back to the drying chamber. The air circulating constantly absorbs some of the humidity from the granulate and transfers it to the absorber before reentering the cycle. Dried granulate is put into the worm extruder feeding chamber than it is forced through the extruder cylinder into the polymer pump. The extruder itself is equipped with particular heating zones, that increase the temperature of the worm by means of resistive electrical heaters.

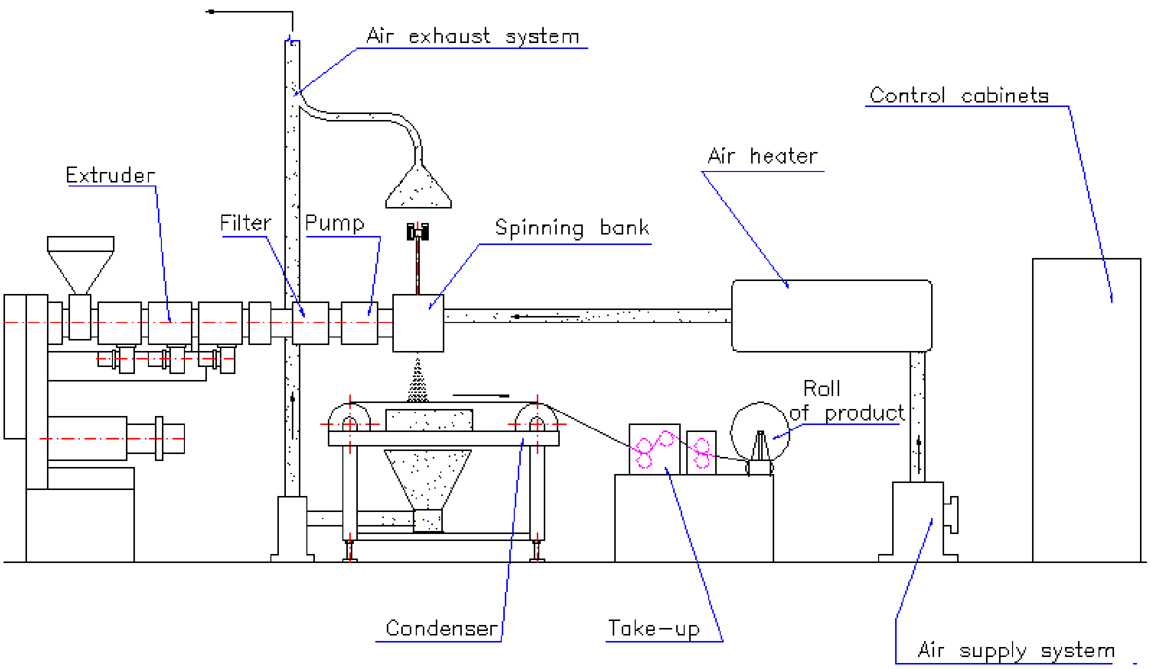

Fig. 4. Line of machinery for manufacturing melt – blown products

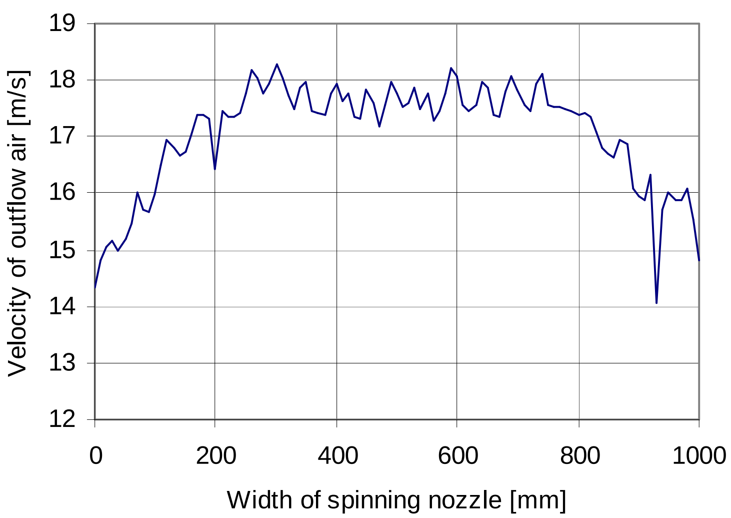

Fig. 5. The expansion of velocity of outflow air in spinning nozzle

The polymer being fed by the worm is intensely mixed and subjected to increased temperature which leads to melting. Then, already in liquid state in, it is transferred through the mesh filter and is fed to the heated spinning beam by the metering pump. The system of shaped conduits inside the spinning beam tunnels melted polymer to the spinneret. The spouts of melted polymer, flowing out of the spinneret through a single, or double row of holes are stretched and torn into particular spouts by parallel streams of hot air, from the nozzles situated alongside polymer holes.

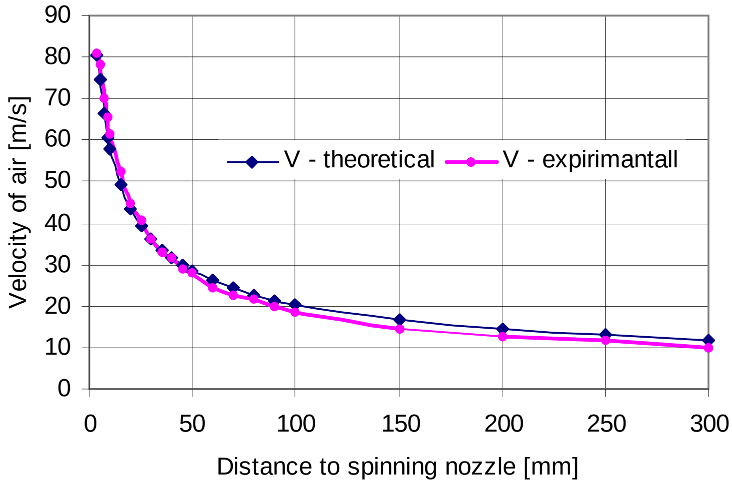

Fig. 6. The velocity in nozzle of spinning beam

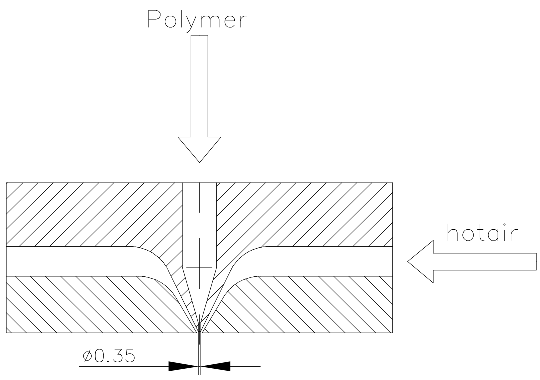

Fig. 7. Spinning beam in melt-blow process

The temperature of particular zones of the cylinder, the spinning beam and air is controlled automatically. The air stream flowing out of the heater deposits formed fabrics on the moving mesh of the conveyor (condenser), on which the fabrics of given width and surface mass is created. Those parameters are dependent directly on the speed of conveyor and efficiency of metering pump situated downstream the extruder. The air from condenser is free of any contaminations and can be transferred directly to the atmosphere. The air used for stretching and tearing the fabric is being compressed through the electric heater and tunnelled by two symmetrical channels up to the spinning beam. The efficiency of the whole system depends on the yield of the polymer metering pump and it is proportional to its rotational speed. Appropriate temperature layout within heating zones of the extruder and spinning beam is selected according to real value of rotational speed of the polymer metering pump. Change of flow rate of the polymer causes change of thermal balance of the system.

4. UTILISATION OF CFD METHOD OF K-EPSILON FOR PNEUMOSPINNING PROCESS

The mathematical basis for the models of nonwoven fabrics spinning with polymers have been already defined in the sixties, by prof. Ziabicki [1]. The models were being intensely developed and elaborated during the years to come. New computation techniques were able to boost the development. However the literature is lacking the detailed analysis of the process, based on simulations using set of equations reflecting the rheological behaviours and structural changes that play significant role for the process dynamics. These are the constitutive equation of viscoelasticity, oriented crystallization kinetics, as well as the influence of crystallization on the rheological properties, i.e. viscosity and relaxation time of the polymer liquid being spinned.

Methods of finite elements enable for numerical computations of any modelled geometrical areas for fluids of different physical properties. Appropriate definition of the geometry of the fluid model constitutes an early stage of analysis of the problem concerning numerical computations of dynamics of air flow through conduits. Elaboration of meshes of finite elements is the following stage of the computation with methods of finite elements (ANSYS environment). In order to achieve it, the 3Dimensional model of fluid is prepared. The process is extremely important and critical for the results of the future simulations. While developing the mesh of finite elements, one must pay attention to the choice of shapes, dimensions, quantity, as well as configuration of elements that will be divided into analysed geometrical models. Correct decisions with respect to mentioned properties will result in the model being as realistic as it is possible. Accurate preparation of the model used during flow analysis with the method of finite elements is vital to resemble the real phenomenon as closely as possible. In order to avoid common mistakes and to perform the analysis correctly, one should follow the scheme as described below: a – geometry generation, b – numerical mesh, c – boundary conditions, d – solver, e – post-processing.

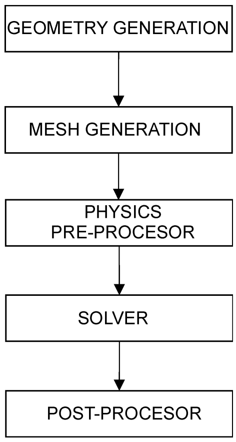

Fig. 8. Structure of numerical computation

The operating principle of the software using CFD methods (ANSYS) is usually based on the finite volumes method. The flow model being investigated is divided into a finite number of small elements that consists of nodes, around which finite volumes are being created. Equations are elaborated for each generated volume. They are based on three basic principles: conservation of mass, conservation of moments and conservation of energy. The equations are being solved in the integral form, by means of flows integration over the external surface of the finite volume. Elaboration of appropriate numerical mesh happens to be troublesome and even more time consuming than the numerical computations themselves. The reason behind is that correct generation of the numerical mesh has crucial impact on the obtained results, as well as run of a computer simulation. Appropriate geometry of the mesh element has to be chosen. The quality of the geometrical models mesh is one of the most important factors that influence results accuracy and computation time. Definition of all possible parameters defining a given continuous environment, as well as providing crucial boundary conditions, is a vital stage after generation of numerical meshes.

In order to generate the mesh of finite elements over the surface of examined flow conduits, one can use e.g. “Triangle” type elements, or “Tetrahedral” type elements. Simulating of real fluids flow in the near-wall areas of the conduit requires increasing density of the mesh, maintaining its regularity at the same time.

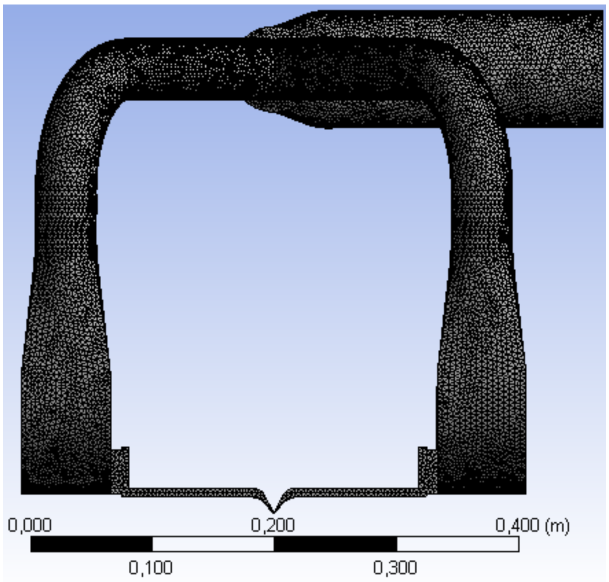

Fig. 9. Finite elements mesh for a part of air conduit

The choice of suitable turbulence model is the most important phase during the selection of analysis type. The default model for flow analysis with the ANSYS CFX is the k-epsilon model.
For this model one defines the momentum equation as follows[1-4]:

$$\rho \cdot U_j \cdot \frac{\partial U_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(t_{ij} - \tau_{ij}\right) + F_i \tag{1}$$

And the continuity equation:

$$\frac{\partial}{\partial x_i}(\rho \cdot U_i) = 0 \tag{2}$$

Where viscous stress is defined as:

$$t_{ij} = \mu \cdot \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{3}$$

where τ_{ij} is the Reynolds stress and equals to:

$$\tau_{ij} = \rho \cdot \nu_T \cdot \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) \tag{4}$$

where: ρ is local air density, U_i – components of the air velocity vector, t_{ij} – viscous stress tensor components, P – the air pressure, τ_{ij} – the Reynolds stress tensor components, μ – viscosity coefficients, and F_i – components of the buoyant force vector.
It is shown that the form of Reynolds’ stress is analogous to viscous stress, where viscosity coefficients of the turbulent form exist [1-4]:

$$\nu_T = C_\mu \frac{k^2}{\varepsilon} \tag{5}$$

where C_μ is a constant, k – the turbulent kinetic energy, and ε – the dissipation rate of the turbulent energy.

It is the standard model used for industrial computations. It can provide correct results for simple flow cases and channels of low geometrical complexity. However for numerical computations by means of this model, the near-wall separation is anticipated too late, which significantly influences the end results. The k-epsilon model cannot be utilized in case of abrupt flows changes, flow through tortuous elements, or in case of spinning active agent. The SST model is able to accurately reflect abrupt flow case, turbulences in the near-wall areas, as well as more complex geometrical architecture of air channels. The model is designed as a composition of the K-epsilon and the K-omega models.

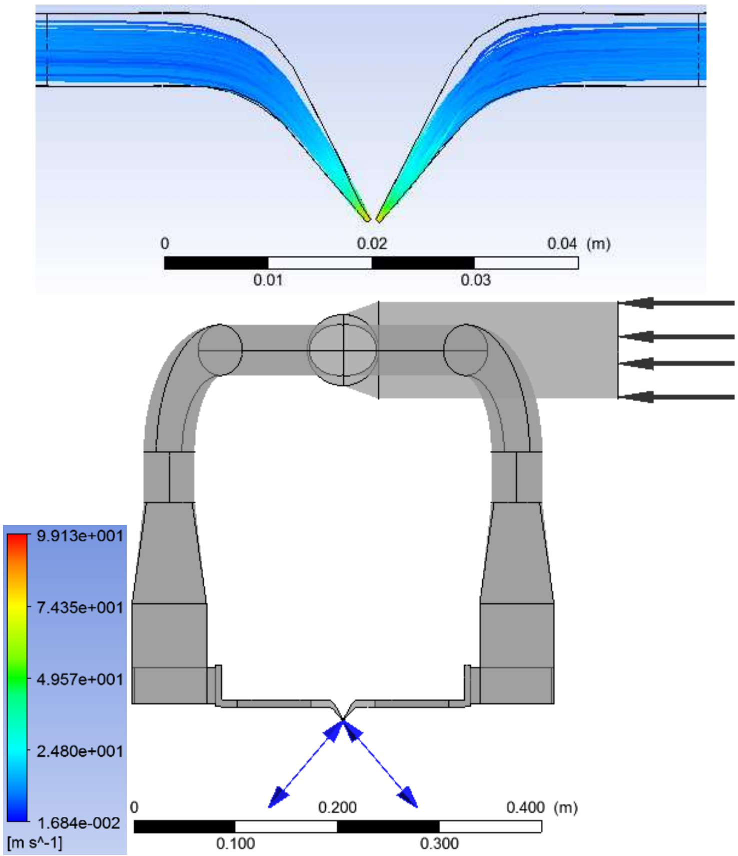

Fig. 10. The paths of hot air current flowing through a channel

For the K-omega model the problem of too late separation of near-wall areas was eliminated. Nevertheless the phenomena occurring in the middle of the stream are not modelled accurately enough.

CONCLUSIONS

Employment of modern computation techniques, based on the finite elements method, or finite volume methods, allows to perform computer simulations and to analyse complex thermo-flow phenomena occurring inside the spinning beam and technological air flow conduits. The computer simulation of the air, or polymer flow inside the sys-tem nodes crucial for the fabric sinning process, allows to shorten the time necessary to determine values of process parameters for different polymers and to develop prototypes of main system nodes. Combination of simulation and optimization methods results in better adaptation of the technological line design for given tasks, lowering of the material consumption index, as well as shortening the time of determining best possible parameters for machine operations. Utilization of modern software to perform simulations allows to decrease the cost of research and modernization of existing process installations.

WYKORZYSTANIE METODY CFD K- EPSILON DO MODELOWANIA ZJAWISK PRZEPŁYWOWYCH WYSTĘPUJĄCYCH W PROCESIE PNEUMOPRZĘDZENIA

Streszczenie

W prezentowanej publikacji opisano zjawiska przepływowe występujące w technologii wytwarzania włóknin polimerowych. Zamieszczono dokładny opis procesów pneumoprzędzenia oraz wpływ parametrów technologicznych na przebieg procesu wytwarzania włóknin polimerowych. W pracy naukowej zaprezentowano również możliwość wykorzystania metody CFD k-epsilon do modelowania zjawisk przepływowych występujących w procesach pneumoprzędzenia.

REFERENCES

1. Zbigniew Lewandowski, Andrzej Ziabicki and Leszek Jarecki: *The Nonwovens Formation in the Melt-blown Proc-ess*. FIBRES & TEXTILES in Eastern Europe, December 2007, Vol. 15, No. 5 - 6 (64 - 65).
2. Leszek Jarecki and Zbigniew Lewandowski*: Mathematical Modelling of Pneumatic Melt Spinning of Isotactic Polypro-pylene. Part I. Modelling of the Air Jet Dynamics*. FIBRES & TEXTILES in Eastern Europe, 2008, Vol. 16, No. 4 (69).
3. Leszek Jarecki and Zbigniew Lewandowski: *Mathematical Modelling of the Pneumatic Melt Spinning of Isotactic Poly-propylene Part II. Dynamic Model of Melt Blowing*. FIBRES & TEXTILES in Eastern Europe, December / A 2008, Vol. 16, No. 5 (70).
4. Leszek Jarecki and Zbigniew Lewandowski: *Mathematical Modelling of the Pneumatic Melt Spinning of Isotactic Poly-propylene.Part III. Computations of the Process Dynamics*. FIBRES & TEXTILES in Eastern Europe, March 2009, Vol. 17, No. 1 (72)

Autorzy:

Prof. dr hab. inż. Zbigniew Pawelski – TECHNICAL UNIVERSITY OF LODZ

dr inż. Mariusz Krajewski – RESEARCH AND DEVELOPMENT CENTRE OF TEXTILE MACHINERY "POLMATEX-CENARO"

inż. Janusz Jarzębowski – RESEARCH AND DEVELOPMENT CENTRE OF TEXTILE MACHINERY "POLMATEX-CENARO"

dr inż. Sergiusz Zakrzewski – TECHNICAL UNIVERSITY OF LODZ