

The special design of extrusion head for manufacturing of polymer pipes with increased mechanical strength

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Abstract: This work presents a proposal of the new design of an extrusion head for polymer pipes manufacturing, especially from polyethylene. The most significant feature of this head is that the conical core of the conical nozzle and the nozzle port of the core have on their surfaces coils made along a helical path which are shifted relatively to each other. As a result, the channel created between these parts contributes to helical twisted polymer flow. Helical flow causes tangential stresses which is a result of the orientation of the macromolecules in the flow direction. This makes that the pipe has increased strength to internal pressure. This current state of knowledge of this kind of extrusion heads and the mathematical interpretation of increasing the strength of the polymer pipes during the extrusion process were also presented. The proposed new extrusion head allows the production of polymer pipes with increased mechanical strength using a very easy and inexpensive method.

Keywords: extrusion process, extrusion head, polymer pipes, polyethylene, mechanical strength.

Konstrukcja głowicy wylączarskiej do wytwarzania rur z tworzyw polimerowych o zwiększonej wytrzymałości mechanicznej

Streszczenie: W pracy przedstawiono projekt nowej konstrukcji głowicy wylączarskiej do wytwarzania rur z tworzyw polimerowych, zwłaszcza z polietylenu. Cechą charakterystyczną opisywanej głowicy jest to, że część stożkowa rdzenia od strony dyszy oraz część stożkowa dyszy od strony rdzenia mają na swych powierzchniach zwoje rozmieszczone wzdłuż linii śrubowej. Zwoje te są przesunięte względem siebie, tworząc kanał kształtujący przepływ strumienia uplastycznionego polimeru. Przepływ w kanałach śrubowych powoduje powstawanie naprężeń stycznych na skutek orientacji makrocząsteczek w kierunku przepływu, co przyczynia się do wzrostu wytrzymałości rur na ciśnienie wewnętrzne. W niniejszym artykule opisano również aktualny stan wiedzy o tego typu głowicach wylączarskich oraz przedstawiono matematyczną interpretację wzrostu wytrzymałości rur polimerowych w procesie wytłaczania. Zaproponowane rozwiązanie konstrukcyjne głowicy umożliwia stosunkowo prosty i tani sposób produkcji rur o zwiększonej wytrzymałości mechanicznej z tworzyw polimerowych.

Słowa kluczowe: wytłaczanie, głowica wylączarska, rury z tworzyw polimerowych, polietylen, wytrzymałość mechaniczna.

INTRODUCTION

The article presents a new design for an extrusion head for polymer pipes, especially from polyethylene. Presented extrusion head allows producing pipes with improved resistance to internal pressure. The pipes used in the construction of pipelines for the gas or water supply systems are exposed to significant tensile stresses due to internal pressure.

The premise for work on the new extrusion head construction was the demand for pipes with high resistance to internal pressure. The idea was to get the increase in strength only in the process of extrusion but not by cross-linking of the polymers as a result of irradiation. An important aspect is the fact that the crosslinked polyethylene (PE) pipes are not suitable for recycling [1].

The present solution takes into account the specific type of polymer flow through the head causing helical flow of polymer and causing the tangential stress. This head enables to produce, in a standard extrusion technological line, pipes with increased mechanical strength.

The results of recent studies show that during the extrusion process of PE pipes, which causes a helicoidal motion to the plasticized layers, an increase in mechanical strength of the pipes can be achieved. High mechanical strength is associated with high resistance of pipes to

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internal pressure. To meet this requirement, a polymer should be subjected to a circumferential stress during a flow through the nozzle channels of the extrusion head. For this purpose, the heads with the rotary shaft or ring are applied. In the literature [2–7] the various constructions of extrusion heads can be found. The work [2] shows an example of a straight rotary head with a conical core driven by an electric motor through a worm gear and clutch torque transmission. The main disadvantage of this solution is the need for a drive in the form of a worm gear and an electric motor for rotating and controlling rotation of the core. Moreover, such a solution makes it necessary to use rotating elements in high operating temperature.

In the solution described in the paper [2], the process of forming a pipe profile in the head is done by rotation of a conical core relatively to a nozzle. As a result of the friction polymer moves along the axis of the head in a helicoidal motion. Axial movement of the plasticized material in the head is the result of the pressure differences in the head. It can be assumed that as a result of the axial displacement of the polymer, axial stresses (σ_x) are formed, and by the rotation of the core circumferential stresses (σ_y) arise. Because of this, the tension of the polymeric material is expressed by the following equation:

$$\sigma = \sqrt{\sigma_x^2 + \sigma_y^2} \quad (1)$$

Radial stresses generated by the different channel diameters can be omitted.

As a result of the helical movement, an arrangement of the polymer structure, its elongation and the tangential stress occur as well as an increase in its mechanical strength. The change in the mechanical strength of a pipe depending on the rotational speed (ω_r) of the core head is shown in Fig. 1 [2].

The higher value of component σ_y corresponds to lower value of component σ_x , i.e. greater strength in the cir-

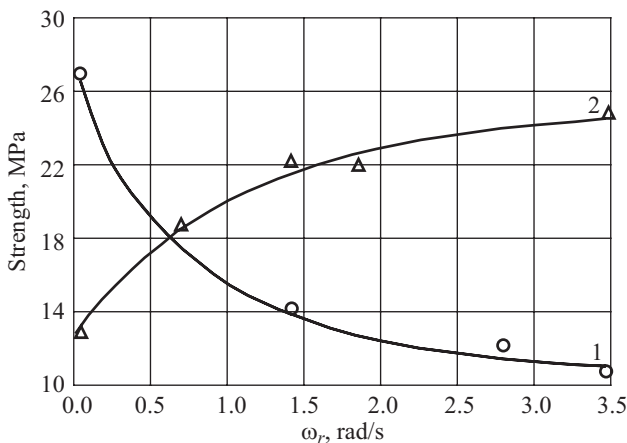


Fig. 1. Dependence of strength of pipe on the rotational speed (ω_r) of the core for a high-density polyethylene (according to [2]): 1 – breaking stress in the circumferential direction, 2 – breaking stress in the axial direction

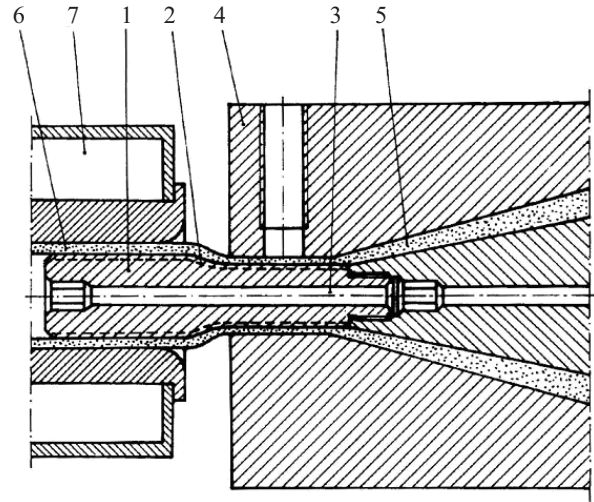


Fig. 2. Extrusion head for pipe manufacturing (according to [3]): 1 – shaped pin, 2 – longitudinal grooves evenly distributed at the circumference of the pin, 3 – cooling aperture, 4 – extrusion head body, 5 – plasticized polymer, 6 – extruded tube, 7 – calibrator

cumferential direction means smaller strength in the axial direction. As it is shown in Fig. 1, an increase in the rotational speed (ω_r) of the core greatly increases the strength in the circumferential direction (curve 1) and decreases the strength in the axial direction (curve 2). An increase in ω_r of the core greatly reduces the tensile relative elongation in the extrusion direction. It increases in the tangential direction as well. In this way, convergence of dependency between destructive stress and relative elongation are revealed as well as between destructive stress and rotation of the core head. Presumably, this can

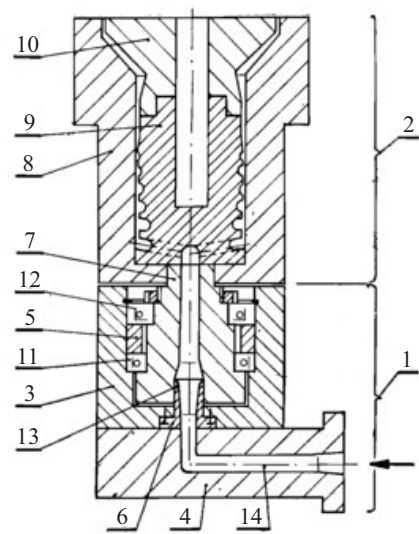


Fig. 3. Extrusion head for pipe manufacturing (according to [4]): 1 – fixed part, 2 – rotating part, 3 – body, 4 – connector, 5 – spacer sleeve, 6 – tubular element, 7 – sleeve, 8 – outer ring, 9 – core, 10 – cone, 11, 12 – ball bearings, 13 – resilient part, 14 – flow channel

be explained by the fact that the axis of the crystallization, which is compatible with the chain of the macromolecule, is aligned along the axis of the crystallization lattice, which in turn coincides with the direction of the total vector of movement of the polymer. This should contribute to the achievement of greater polymer strength in this direction.

The extrusion head for pipe manufacturing from thermoplastic polymers, having a body shaped with a central core cooling hole, is shown in Fig. 2 [3]. In this solution, a shaped core has two outer diameters, with a smooth transition between surfaces which forms the core, and have longitudinal grooves evenly distributed on its circumference, wherein the core forming part of the larger diameter extends beyond the front of the head from a fraction to several diameters. Another solution is the extrusion head [4] which consists of the fixed part and the rotary part, presented in Fig. 3. This head is equipped with the tubular element fixed at one end of the body. The second end is in the shape of a resilient protrusion which is slidably embedded in the polymer flow channel.

THE MATHEMATICAL INTERPRETATION OF AN INCREASE IN THE STRENGTH OF THE POLYMER PIPES

The state of plane stress in the pipes during axial tension with force (Q) and the internal pressure (p) is shown in Fig. 4.

In this state of the pipe load, components of principal stresses are described by the following equations [8, 9]:

$$\sigma_x = \frac{Q}{F} + \frac{pD_{sr}}{4e} \quad (2)$$

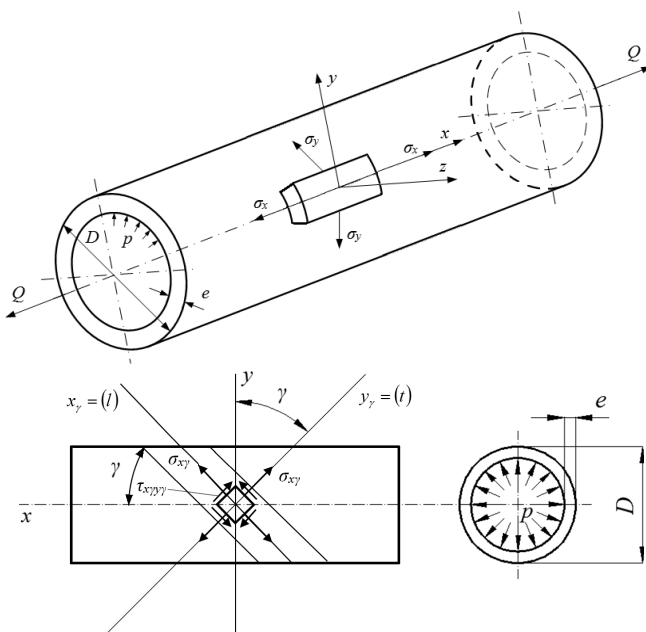


Fig. 4. Diagram of plane stress in an infinitesimal element of the pipe wall at an axial tensile strength of force Q and internal pressure p

$$\sigma_y = \frac{pD_{sr}}{2e} \quad (3)$$

where: D – pipe diameter, e – pipe wall thickness, F – cross-sectional area of the pipe.

The radial stress ($\sigma_z = -p/2$) is omitted because its value is very small, therefore considered plane state of stress.

Assuming that the pipe is only loaded with internal pressures (p) and the axial force is zero ($Q = 0$), the axial and circumferential stresses are related by the relationship:

$$\sigma_y = k\sigma_x = 2\sigma_x \quad (4)$$

The coefficient $k = 2$ is the aspect ratio of stress.

The transformation of the stress tensor principal directions (axis system x, y) in any direction (axis system x_{γ}, y_{γ}), corresponds to the rotation of the polymer band by the angle γ so, that this element is a segment of a polymer band of the pipe wall. The plane stress state can be expressed by general transformational formula [9]:

$$\begin{Bmatrix} \sigma_{x_{\gamma}} \\ \sigma_{y_{\gamma}} \\ \tau_{x_{\gamma} y_{\gamma}} \end{Bmatrix} = \begin{bmatrix} c^2 & s^2 & -2sc \\ s^2 & c^2 & 2sc \\ sc & -sc & c^2 - s^2 \end{bmatrix} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \quad (5)$$

where: $\sigma_{x_{\gamma}}, \sigma_{y_{\gamma}}, \tau_{x_{\gamma} y_{\gamma}}$ – stress in relation to the axes x_{γ}, y_{γ} (in the element rotated by the angle γ); $\sigma_x, \sigma_y, \tau_{xy} = 0$ – stress in relation to the axes x, y (principal stress $\sigma_x = \sigma_{min}, \sigma_y = \sigma_{max}, \tau_{xy} = 0$); c, s, sc – indicate the function of the direction, i.e.: $\cos \gamma, \sin \gamma, \sin \gamma \cdot \cos \gamma$, respectively.

After expanding the eq. (5) the tension in the element rotated by the angle γ have the general form:

$$\sigma_{x_{\gamma}} = \sigma_x \cos^2 \gamma + \sigma_y \sin^2 \gamma - \tau_{xy} 2 \sin \gamma \cos \gamma \quad (5a)$$

$$\sigma_{y_{\gamma}} = \sigma_x \sin^2 \gamma + \sigma_y \cos^2 \gamma - \tau_{xy} 2 \sin \gamma \cos \gamma \quad (5b)$$

$$\tau_{x_{\gamma} y_{\gamma}} = \sigma_x \sin \gamma \cos \gamma + \sigma_y \sin \gamma \cos \gamma + \tau_{xy} (\cos^2 \gamma - \sin^2 \gamma) \quad (5c)$$

After transformation the eqs. (5a), (5b) and (5c) and taking into account that $\tau_{xy} = 0$, the limit values of principal stresses $\sigma_x, \sigma_y = 2\sigma_x$ can be determined depending on the angle of polymer twisted bands of material in the pipe. In determining these stresses, it is assumed that the maximum tensile stress value in the band for the longitudinal $x_{\gamma} = l - \sigma_{x_{\gamma}}$ and transverse direction $y_{\gamma} = t - \sigma_{y_{\gamma}}$ will be equal to the corresponding yield stress $\sigma_{yield(l)}$ and $\sigma_{yield(t)}$ for the directions [$\sigma_{x_{\gamma}} = \sigma_{yield(l)}$ and $\sigma_{x_{\gamma}} = \sigma_{yield(t)}$] as well. The shear stress $\tau_{x_{\gamma} y_{\gamma}}$ reaches the value of the shear strength τ_s ($\tau_{x_{\gamma} y_{\gamma}} = \tau_s$). Therefore, the value of the axial stress σ_x (at circumferential stress $\sigma_y = 2\sigma_x$) should meet all the following conditions:

$$\sigma_x \leq \frac{\sigma_{yield(l)}}{\cos^2 \gamma + 2 \sin^2 \gamma} \quad (6a)$$

$$\sigma_x \leq \frac{\sigma_{yield(t)}}{2 \cos^2 \gamma + \sin^2 \gamma} \quad (6b)$$

$$\sigma_x \leq \frac{\tau_s}{\sin \gamma + \cos \gamma} \quad (6c)$$

The test results of samples, cut from pipes of the outer diameter 160 mm and wall thickness of 14.6 mm, which were made of polyethylene PE-HD (PE 80) with a straight

extrusion head (with a straight outflow channel), showed that the yield stress in the wall of the middle layer was the largest and almost equal to the stress in longitudinal direction of the tube axis, $\sigma_{yield(l)} = 13.8$ MPa and across to it, $\sigma_{yield(t)} = 13.7$ MPa [10]. Although the yield stress value is equal $\sigma_{yield(l)} = \sigma_{yield(t)} = 13.5$ MPa, it is still somewhat lower in the middle layer of the pipe wall. However, the yield strength of the outer layer in the transversal direction $\sigma_{yield(t)} = 12.7$ MPa was about 6 % lower than for the longitudinal direction $\sigma_{yield(l)} = 13.5$ MPa [10].

To determine the limit of the axial stress (σ_x) depending on the angle of helically oriented polymer bands of polymer in an extruded tube from PE 80, using the proposed extrusion head, the same yield strength range for both directions (longitudinal and transverse) $\sigma_{yield(l)} = \sigma_{yield(t)} = 13.5$ MPa [10] was adopted. According to the hypothesis of Misses-Huber for the pure shear stress, shear strength of polyethylene is described by the formula [11]:

$$\tau_s = 0.578 \cdot \sigma_{yield} = 0.578 \cdot 13.5 = 7.803 \text{ MPa} \quad (7)$$

The calculation results presented in Fig. 5 indicate that the strength of the tube determines the limit values of the stresses σ_x , which is determined on the basis of yield stress and plastic point in both directions (longitudinal and transverse) according to the formulas (6a) and (6b). However, the total elongation yield strength σ_x determined from the shear strength according to eq. (6c), is significantly higher. In the present case, the largest strength of the polymer pipe with twisted polymer bands ($\sigma_x = 9$ MPa) was obtained for the torsion angle of polymer band $\gamma = 45^\circ$. It is greater than the strength of the extruded pipe manufactured with a classical head with a straight outflow channel ($\sigma_x = 6.75$ MPa for $\gamma = 0^\circ$) by approximately 33 %.

The results of calculations of the limit level of axial stress (σ_x) for a pipe made of polyethylene, with regard to tensile yield stress for both directions of twisted polymer

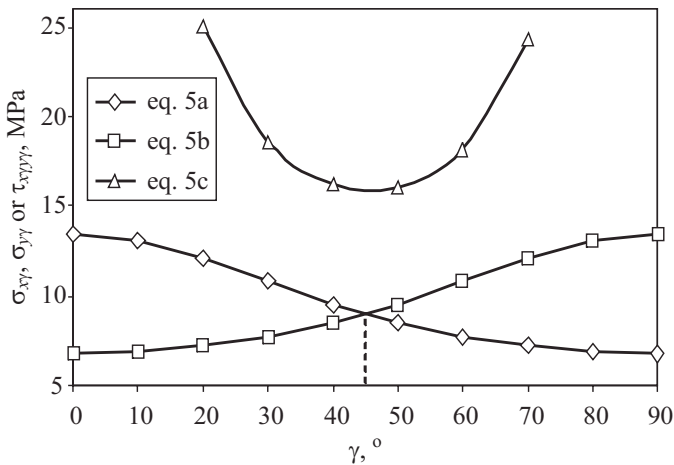


Fig. 5. The limit values of axial stress in the pipe (σ_{xlr} , σ_{yrl} and $\tau_{xrl/yl}$), depending on the angle of torsion of the polymer band (γ) with yield strength $\sigma_{yield(l)} = \sigma_{yield(t)} = 13.5$ MPa

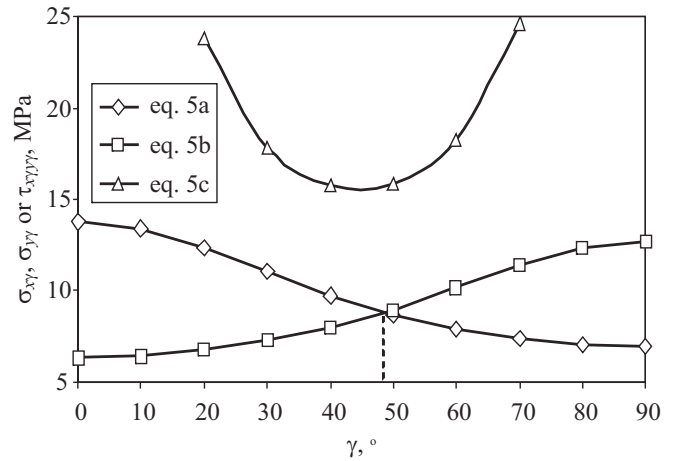


Fig. 6. The limit values of axial stress in the pipe (σ_{xlr} , σ_{yrl} and $\tau_{xrl/yl}$), depending on the angle of torsion of the polymer band (γ) with yield strength $\sigma_{yield(l)} = 13.8$ MPa, $\sigma_{yield(t)} = 12.7$ MPa

bands [$\sigma_{yield(l)} = 13.8$ MPa and $\sigma_{yield(t)} = 12.7$ MPa and $\tau_s = 0.578 \cdot \sigma_{yield(t)} = 7.341$ MPa] is shown on the Fig. 6. It can be seen, that the highest strength of the pipe $\sigma_x = 8.83$ MPa is obtained for the torsion angle $\gamma = 48.58^\circ$ and the lowest $\sigma_x = 6.35$ MPa for $\gamma = 0^\circ$. The increase in strength, resulting from the helically oriented bands of polymer in the pipe (deviated by approximately 39 %), was obtained in this case.

In the pipe made by the extrusion head with twisted channels, considerably higher anisotropy of polymer can be expected. It takes place because the PE flowing from the extrusion head with multiple channels has much smaller cross section than the cross section of the channel (nozzle) in the head with a straight outflow channel. The result is that the orientation of the polymer chains is more consistent with the direction of polymer flow from the channel (nozzle). The related increase in yield stress differs for the two directions of the band. It will result in further increases in the strength of the pipe in relation to the strength of the tube extruded with a standard extrusion head with a straight channel. It should also be noted, that the maximum strength of the pipe occurs at the higher torsion angle of polymer bands which is higher than in the presented case.

Thus, by changing the angle γ , the value of stresses occurring in the wall of the pipe can be changed. This creates a large pipe design options which meet various criteria such as maximum strength with minimum weight. Taking into account the practical aspect of the pipe extrusion, using the new design of extrusion head, the angle of about 45° of bands of material in the pipe should be obtained. This will increase the resistance to internal pressure in the pipe by about 30 %.

THE NEW EXTRUSION HEAD DESIGN

The analysis of the discussed solutions and presented mathematical considerations contribute to a proposal of a

different solution design that allows the helical flow of plasticized polymer in the extrusion head. Polymer flow in the helical channel causes tangential stresses due to the orientation of the macromolecules in the flow direction which is the reason for the increase in the strength of the pipe internal pressure. As a result of the helical movement, arrangement of the polymer structure occurs which causes its elongation and twisting. As a result of such orientation of the extrudate stream, the orientation of the macromolecules along the helical path occurs. It can be concluded that the orientation of the macromolecules in the extrudate might contribute to the greater strength of the pipe to internal pressure [2].

The new extrusion head design presented in this article is shown in Fig. 7 which shows the extrusion head in the longitudinal section. The illustrative sketch of the head of the helix is shown in Fig. 8. The extrusion head (Fig. 7) has a body (5) ended by the nozzle part (7). Shaped core (2), which ends are in the shape of a cone passing into a cylinder, is located in the nozzle (7). Between the inner surface of the body (5) and the surface of the nozzle (7), and the outer surface of the core (2) plasticized polymer flow channel is located. Conical part of the core (2) from the nozzle site (7) and a conical nozzle (7) from the core site (2) have on its surface coils arranged along a helical path to allow uniform flow of the polymer. These coils are offset by half the height of the helix and their height is $3/4$ of the channel height. It is necessary to adjust the nozzle body (5) in order to maintain the symmetry of the polymer tube. Polymer extruded at the final stage of the flow through the nozzle (7) is oriented and moves helically. It is caused by the shape of helical channel.

The essence of the presented solution is that the conical core on the nozzle part site and the nozzle conical part on the core site have coils on their surfaces. The helix coils are offset relatively to each other. In comparison with known solutions, the designed construction of the extrusion head allows for helical movement of extruded plas-

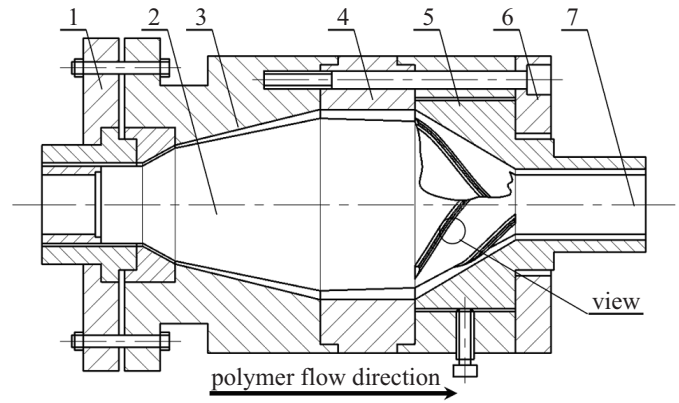


Fig. 7. The extrusion head (longitudinal section, according to [12]): 1 – ring, 2 – conical core with helical line, 3 – body, 4 – connecting ring, 5 – nozzle body, 6 – cover, 7 – part of the nozzle with helical line

tic in the final stage of the flow through the nozzle which is forced by fixed parts of the head.

Coils are located on a helix which is on the extrusion head core and nozzle body which means that it is located on the outer cone and the inner core of the nozzle part site. At the simplest, from the technological point of view, it would be a helix with a constant pitch. However, it does not provide any uniform flow of polymer. According to the authors, it would be a better solution to place coils into a helix of constant length in the stroke range. The cross section is reduced slightly. The outline of helix channels in the cross section is large enough that it does not cause any significant change in the pressure of the flowing polymer. Thus, positioned coils provide a uniform steady flow velocity of liquid polymer in the channel formed by these coils.

The length of the helix in the range of stroke is constant which ensures the continuity of the polymer flow. Feasibility of such a helix line on the conical surface is described, *inter alia* in [13].

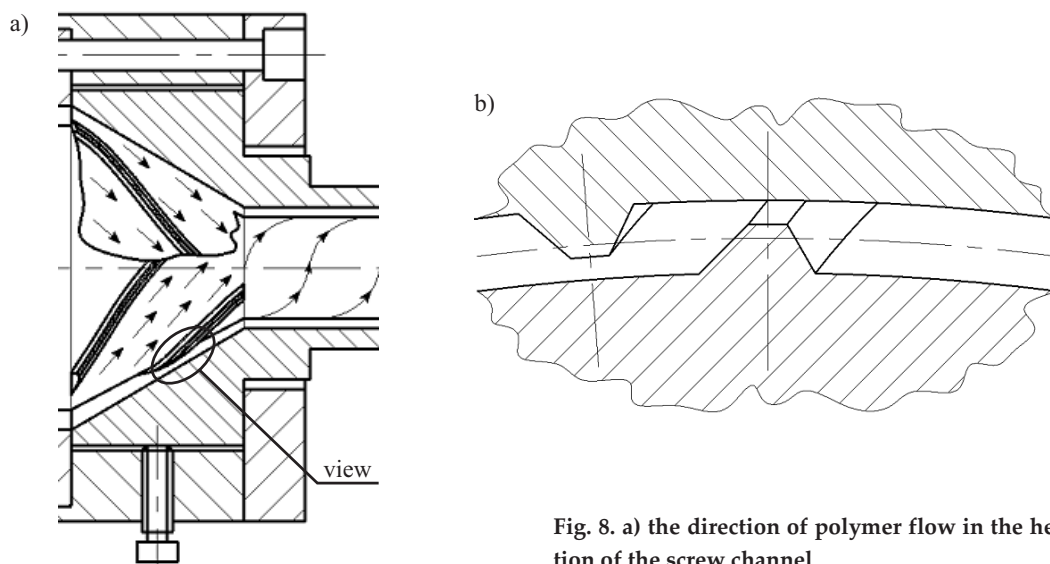


Fig. 8. a) the direction of polymer flow in the head, b) cross-section of the screw channel

CONCLUSIONS

Presented design solution of the extrusion head for PE pipes is the innovative solution that allows the manufacturing of high-strength pipes made of PE with standard extruder lines. Stress state in polymer pipes as well as issues related to their strength were discussed in papers [10, 14–22]. This new design solution of the extrusion head for PE pipes has a very important advantage over other solutions of this type extrusion heads. Namely, it allows the manufacturing of pipes with increased mechanical resistance without any changes and construction technology of extrusion lines. Head design is relatively simple and the main advantage of this solution is also no need for additional moving parts working at high polymer processing temperature. The increase in mechanical strength of the pipes is achieved due to the fact that the liquid polymer in the head has helicoidal motion. The flow in the helical channel causes tangential stresses due to the orientation of the macromolecules. Such arranged polymer microparticles in the wall of the tube provide the appropriate effects. It has been proved theoretically in article [2]. In order to obtain such movement of material on the inner and outer parts of pipe, the conical head helical channels were made. The helix has a constant channel length within the stroke which ensures the continuity and uniformity of the polymer flow. This method enables manufacture of polymer pipes which are characterized by an increased internal pressure resistance by approximately 30 % at relatively low costs of manufacturing and retrofitting pipe manufacturing lines. This solution has been submitted to the Polish Patent Office [12].

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