Designs and Methods of Calculation for Acoustic Extrusion Heads for the Manufacturing of Profile-Pogonage Polymeric Products

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Currently, there is theoretical and experimental research[1,3] confirming that, by influencing the stream of a melt of periodic deformation, rotation, and vibration, we can increase the throughput of a channel, reduce its resistance in units of the forming tool, and conduct extrusion at lower temperatures.[2] On the basis of these studies, extrusion heads with rotating central bars and various mechanical elements have been designed.[2,3] However, the use of ultrasonic fluctuations is more economic, presenting an opportunity to simplify the design of extrusion heads and to reduce the energy costs because of the absence of moving elements. Ultrasound allows us to reduce the formation temperature, to raise the extrusion speed, and to reduce the postextrusion swelling of products, and this results in increased productivity.

In the study of melt polymer currents with ultrasonic fluctuations, until now, round and slot-hole channels have usually been used. The applications of such channels are limited, unlike those of channels of complex configurations, the use of which can lead to various kinds of polymeric products of complex profiles.[2,3] In this respect, the perfection of calculation methods and the creation of new designs of extrusion heads for the manufacture of products of complex structures with the use of ultrasound are problems.

The analysis of designs and methods of calculation for thin-plane and trumpet acoustic heads[2–4] allows us to draw the following conclusion: in choosing the type of radiator, we should prefer magnetostrictive radiators, instead of piezoceramic ones, as they are more effective. Among magnetostrictive radiators, it is more expedient to use designs built inside the head extruder. The installation of a vibrator on the case of the forming tool reduces the efficiency of penetration of ultrasonic fluctuations in the melt polymer mass because the wall of the case has a significant thickness. Therefore, a decrease in the melt viscosity of the forewall layer occurs to an insignificant degree and has little influence on the improvement of the quality of the product surface; the cooling system of an active element of a radiator of ultrasonic fluctuations is obligatory for work under conditions of elevated temperatures. The number of industrial acoustic heads is limited now in comparison with forming tools working without ultrasound, despite their higher efficiency. Moreover, the existing designs allow us to make only films, sheets, and pipes, although the demand for high-quality products of complex structures is great.

Working in the field of extrusion head designs with elements of complex profiles and studying the rheological characteristics of polymer melts with ultrasound, we have proposed the design of multilane extrusion heads for manufacturing profile-pogonage polymeric products with the application of ultrasonic fluctuations (Fig. 1), which can improve the quality of profile-pogonage products and raise the productivity of extrusion installations.[4]

Despite the importance of the problem of ultrasonic vibrations during the processing of polymers, it has been investigated insufficiently until now,[3] and the majority of the publications, including the latest, concern the influence of ultrasound on the currents of polymer melts only in round and thin-plane channels.

On the basis of equations describing the pressure currents of liquids in thin-plane and cylindrical channels under the influence of ultrasound,[2] the dependence of the expenditure of liquids in profile channels of acoustic extrusion heads is described:

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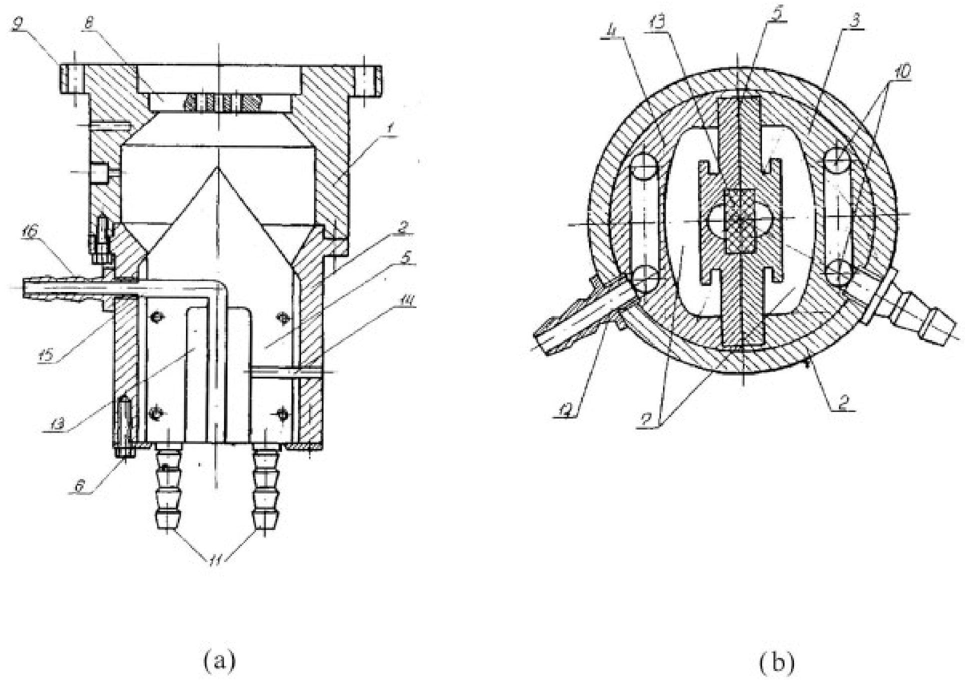

Figure 1 Multilane extrusion head for the manufacturing of profile-pogonage polymeric products with the application of ultrasound: (1) the case, (2) a holder, (3,4) semicylindrical sections, (5) the central bar, (6) a washer, (7) the profile channel, (8) a lattice, (9,16) a flange, (10,16) channels for cooling, (11,12) unions, (13) a magnetostrictive radiator, and (14) the channel connecting thesources of ultrasonic fluctuations. (a) A longitudinal section and (b) a transverse incision are shown.

$$Q = -\frac{a\rho S}{\tau_0^R}\left\{\int_0^{\tau_1}\frac{k_1\tau^B(R_r-\delta)}{\eta_{\text{eff}}}d\tau + \int_{\tau_1}^{\tau_0}\frac{k_2\tau^B\delta}{\eta_\omega}d\tau\right\} \tag{1}$$

where Q is the mass expenditure of the polymer (kg/s), a and b are form factors, ρ is the melt density (kg/m^3), S is the area of the cross section of the channel (m^2), τ_0 is the average pressure of a shift at the wall of the channel (Pa), R_r is the hydraulic radius of the channel (m), σ is the depth of ultrasound penetration (m), η_{eff} is the effective viscosity (Pa s^{-1}), η_ω is the viscosity of the polymer influenced by ultrasound (Pa s^{-1}), and k_1 and k_2 are correction coefficients.

For the estimation of the increase in the productivity of the extrusion process with the use of acoustic forming tools, it is possible to describe the dependence of the capacity of ultrasonic fluctuations (N_ω):

$$N_\omega = 0.25\text{k}_1\text{PL}\rho A^2\omega^2 c \tag{2}$$

where P is the perimeter of the channel (m), L is the length of the channel (m), A is the amplitude of the fluctuations, ω is the angular frequency of the ultrasonic fluctuations (s^{-1}), and c is the speed of sound in the polymer mass (m/s).

For the estimation of the adequacy of the mathematical dependencies and the opportunities of their applications in concrete engineering calculations, a number of experiments have been carried out. An industrial extruder (ATL-45) has been used with the following characteristics: screw length = 0.8 m and diameter = 4 $\times$ 10^{-2} m. The extrusion installation includes a forming knot consisting of a forming head, which is 0.045 mm $\times$ 0.045 m. For the creation of ultrasonic fluctuations (UZG1-4) on the forming head, two magnetostrictive converters have been used (e.g., PMS-6-22), connected to a generator.

Channels of complex profiles have been used. The rheological properties of the polymer melts and their dependence on the temperature, extrusion pressure, ultrasound frequencies, channel design, capacity for ultrasonic fluctuations of the polymer, channel geometry, and ultrasound parameters have been studied.

Equation (1), used for the estimation of the throughput of the channel at extrusion, includes coefficients depending on the form of the channel section. Their calculation is usually very difficult because it is necessary to initially know the true speed of the melt current in the channel, which is difficult to define and to know the dependence of the change in the fluidity of the melt from the shift pressure. Therefore, for the definition of coefficients a and b, a more convenient method in the practical attitude membrane analogies,[2] which allows us to

TABLE I
Values of the Coefficients

Parameter	Π figurative	Γ figurative	Triangular	Ш figurative
	Product Section			
$R_r \times 10^3$ (m)	1.81	1.88	1.52	0.96
a	1.348	1.645	2.208	1.209
b	1.989	1.996	2.573	1.985

estimate form factors for four kinds of channel sections (Table I), has been used.

Three kinds of polymers have been chosen: poly(vinyl chloride) (cable; GOST 5960), polystyrene (PS-S; GOST 20282), and polythene (high-pressure; GOST 150802).

Polymer melts chosen for experimental research are typical representatives of viscoelastic liquids, and their physical and chemical properties have been well investigated and are described in the literature.[1–3,5]

For the confirmation of the validity of eq. (1), research, using the definition of the dependence of the mass expenditure polymer melt from the pressure gradient in the researched channel, has been carried out. The currents of polymer melts in channels of complex profiles of different lengths for each of the four sections has been studied. Thus, experimental data have been obtained for 12 channels and three kinds of polymers [polythene, polystyrene, and poly(vinyl chloride)] at temperatures of 403–453 K, at extrusion pressures of up to 6 MPa, and at various ultrasound frequencies (18.5, 20.5, 21.6, 22.1, and 23.5 kHz).

An analysis of the results shows that in all cases with ultrasonic fluctuations, there is an increase in the mass expenditure of polymers for all channel forms. The greatest increase in the expenditure of polymer products is observed for poly(vinyl chloride) (20–25%), and the least is observed for polystyrene (10–15%). The greatest effect of ultrasound is observed for a triangular channel, and the is observed least for the channel Ш form. With the temperature increasing in a zone of a polymer melt during extrusion, the effect of ultrasound is reduced. A frequency of 21.6 kHz is optimal.

In addition to the account characteristics, the study of the dependence of the capacity of ultrasonic fluctuations from a polymer with respect to channel geometry is of interest. In light of the importance of eq. (2) in practice, the appropriate calculations, the results of which are given in Table II, have been carried out.

An analysis of the experimental results shows that the greatest capacity for radiation absorption by a polymer is characteristic of poly(vinyl chloride). This polymer has a higher density and a lower viscosity than polystyrene and polythene. The speed of sound is 1650 m/s for poly(vinyl chloride), 1500 m/s for polystyrene, and 1600 m/s for high-pressure for polythene. With an increase in the temperature, the capacity for ultrasonic fluctuations decreases as the density of the polymeric products decreases, and so the greatest capacity is found with a triangular channel, and the least is found for channel Ш forms. In the first case, ultrasonic fluctuations operate with greater efficiency throughout the entire perimeter of the channel in the extruder, whereas in the latter case, they operate only

TABLE II
Results of the Calculation of the Capacity of Ultrasonic Fluctuations (W)

Frequency ultrasound (kHz)	Triangular		Γ figurative		Π figurative		Ш figurative	
	Channel							
Poly(vinyl chloride) (413 K)								
18.5	438	435	400	402	419	421	364	367
20.5	846	840	772	770	809	806	699	703
21.6	1345	1346	1229	1232	1287	1282	1111	1115
22.1	1409	1403	1286	1290	1348	1349	1165	1161
23.5	1107	1105	1276	1277	1059	1056	914	918
Polystyrene (438 K)								
18.5	282	285	258	260	270	267	233	235
20.5	543	539	497	495	520	521	449	447
21.6	865	866	790	794	827	829	715	718
22.1	711	710	574	571	602	606	520	523
23.5	455	458	416	417	436	432	376	377
Polythene (403 K)								
18.5	283	280	259	258	271	266	234	236
20.5	546	546	502	498	523	527	451	453
21.6	869	872	793	791	831	832	717	713
22.1	632	630	577	572	604	609	522	520
23.5	457	452	418	416	438	433	378	375

TABLE III
Recommended Modes in an Extruder for forming Profile-Pogonage Products

Researched polymer	Extrusion temperature	Extrusion pressure (MPa)	Viscosity (10^{-4} Pas)	Optimum frequency (kHz)
Poly(vinyl chloride) (GOST 5960)	403–423	4.0–4.5	0.024–0.35	21.6
Polystyrene (GOST 20282)	438–453	4.0–5.0	0.028–0.35	21.6
High-pressure polythene (GOST 150802)	388–418	3.5–4.0	0.013–0.35	21.6

in part of the channel because of the peculiarities of the design of the channel and the dissipation energy.

Optimal frequencies of ultrasonic radiation (21.6–22.1 kHz) for poly(vinyl chloride), polystyrene, and polythene have been found. Thus, the greatest amplitude is 6 μm.

Therefore, the calculation of eq. (2) can be coordinated with the experimental values of the throughput of the channel of the extrusion head under ultrasonic influence, that is, the productivity of the extruder.

The recommended extrusion modes of the researched polymers, determined experimentally, are listed in Table III.

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