Chemical and Petroleum Engineering, Vol. 47, Nos. 11–12, March, 2012 (Russian Original Nos. 11–12, Nov.–Dec., 2011)

EFFICIENCY OF ENERGY CONSUMED BY HYDRAULIC-PRESS DRIVES DURING MOLDING OF COMBINED ARTICLES IN A CLOSED DIE

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This paper presents a procedure for calculation of the work of external forces during the molding of combined multi-component articles formed from disperse materials in a closed die, which includes calculation of the work in overcoming contact-friction forces, and the work required to deform the material in the die, as well as calculation of the effectiveness of the energy consumed by the drive of the hydraulic press. Diagrams of the molding pressure of certain disperse materials versus the working throw of the upper die are presented, as well as experimental data.

A basic criterion for evaluation of the efficiency of the energy consumed by the drive of a hydraulic press, which determines selection of the type of hydraulic equipment, is the degree of fullness of the force diagram [1]:

$$\varphi = \frac{\int_0^{S_w} P dS}{P_{max} S_w},$$

where P is the molding force, P_{max} is the maximum molding force, S is the displacement of the moving traverse of the press, and S_w is the working throw of the press.

If it is assumed that the working throw of the press is equal to the difference in the height of article prior to and after molding (H_0 and H, respectively), the degree of fullness of the force diagram can be represented as

$$\varphi = \frac{\int_0^{H_0 - H} P du}{P_{max}(H_0 - H)}, \tag{1}$$

where u is the displacement of the upper die during the molding.

The integral in the numerator of expression (1) represents the work performed by external forces in molding the article:

$$A = \int_0^{H_0 - H} P du.$$

The force $\boldsymbol{P}$ on the upper die created by the press during molding is summed from the contact-friction forces $\boldsymbol{T}$ and the forces of the material's resistance to deformation $\boldsymbol{F}$:

$$\boldsymbol{P} = \boldsymbol{T} + \boldsymbol{F}.$$

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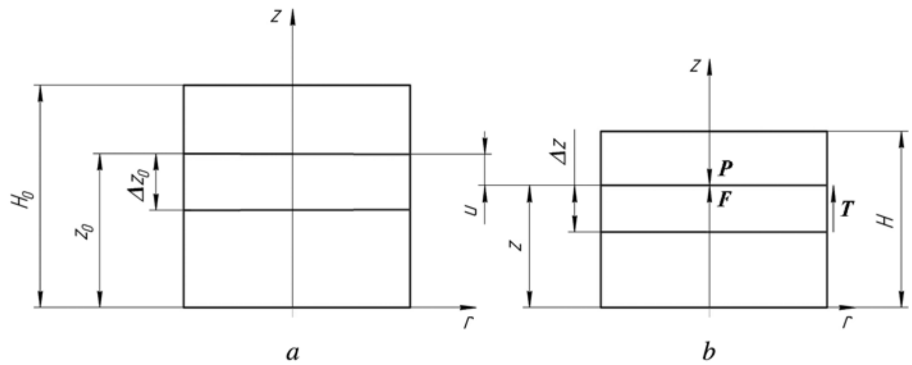

Fig. 1. Diagram showing movement of element of medium during one-sided molding in closed die:
a) prior to start of molding; *b*) after completion of molding.

During molding of the material in a closed die, the work of the external forces consists in the work performed in overcoming the contact-friction forces, and the work required to deform the material in the die [2]:

$$A = A_{\mathrm{f}} + A_{\mathrm{d}}, \tag{2}$$

where A is the work of the external forces, A_{f} is the work of the contact-friction forces, and A_{d} is the work required to deform the material in the die.

The elementary work of the contact-friction forces is

$$\Delta A_{\mathrm{f}} = \Delta T u,$$

where $\Delta T = 2\pi\tau r\Delta z$ is the force of friction against the contact surface of an elementary volume of the material being molded (Fig. 1), r is the radius of the die, Δz is the height of the lateral surface of the elementary volume of material, t represents the tangential stresses acting on the contact surface, and u is the displacement of the upper boundary of the elementary volume under the active external force.

The relationship between the tangential stresses and the stresses normal to the contact surface is adopted as

$$\tau = f\sigma_r,$$

where f is the coefficient of external friction of the material, and σ_r is the stress normal to the contact surface (radial stress) [2].

Assuming constancy of the velocity profile in the cross section of the molding tool (hypothesis of plane sections [2]), the relation between the stresses normal to the surface of contact, and the stresses due to the active external force can be expressed as

$$\sigma_r = \xi\sigma_z,$$

where ξ is the coefficient of lateral pressure, and σ_z is the normal stress due to the active external force.

Applying the assumptions adopted, the force against the contact surface will be

$$\Delta T = 2\pi f\xi\sigma_z r\Delta z.$$

Considering compressive strains ε_z to be positive, we obtain

$$\varepsilon_z = -\ln\left(\frac{z}{z_0}\right) = -\ln\left(\frac{z_0 - u}{z_0}\right) = -\ln\left(1 - \frac{u}{z_0}\right),$$

where z_0 and z are the coordinates of the elementary volume of material prior to and after its deformation.

Considering that the thicknesses of the layers of the combined articles are substantially smaller than its diameter, it is possible for simplification of the solution to assume that the strains are small, i.e.,

$$u \approx \varepsilon_z z.$$

The elementary work of the friction forces against the contact surface, which falls on a unit area of the section of the die, will be

$$\frac{\Delta A_T}{\pi r^2} = \frac{2 f \xi}{r} \sigma_z \varepsilon_z z \Delta z. \quad (3)$$

The equation of the bulk compression at low strain rates will take on the form [2]:

$$\varepsilon_v = m\left(\frac{\sigma_{\text{avg}}}{\sigma_0}\right)^n,$$

where ε_v is the volumetric strain, σ_{avg} is the average normal stress, $\sigma_0 = 0.1$ MPa, and m and n are dimensionless coefficients.

Since $\varepsilon_v \approx \varepsilon_z$ and $\sigma_{\text{avg}} = (1 + 2\xi)\sigma_z/3$,

$$\varepsilon_z = m\left(\frac{1+2\xi}{3}\right)^n \left(\frac{\sigma_z}{\sigma_0}\right)^n. \quad (4)$$

The normal stresses are functions of the coordinate z. The distribution functions of the stresses in solid cylindrical presses, which are derived using the hypothesis of plane sections [2, 3], assume the form:

$$\sigma_z = p\exp\left[-\frac{2 f \xi}{r}(H_0 - z)\right], \quad (5)$$

where p is the assigned pressure on the upper die, and H_0 is the initial height of the material in the die.

Substituting (4) and (5) in (3), and integrating the expression obtained, it is possible to determine the total work of the contact-friction forces:

$$\frac{A_{\text{f}}}{\pi r^2} = \frac{2 f \xi m}{r}\left(\frac{1+2\xi}{3\sigma_0}\right)^n p^{n+1} \exp\left[-(n+1)\frac{2 f \xi}{r} H_0\right] \int_{H_0}^{0} z \exp\left[(n+1)\frac{2 f \xi}{r} z\right] dz;$$

$$A_{\text{f}} = \frac{\pi r^3 m}{2 f \xi (n+1)^2}\left(\frac{1+2\xi}{3\sigma_0}\right)^n p^{n+1}\left\{1 - (n+1)\frac{2 f \xi}{r} H_0 - \exp\left[-(n+1)\frac{2 f \xi}{r} H_0\right]\right\}. \quad (6)$$

In the case where the initial height of the layer is sufficiently large, it can be divided into a series of thin layers for calculation of the work of the contact-friction forces, and the total work computed as the sum of the elementary works:

$$A_{\text{f}} = \frac{\pi r^3 m}{2 f \xi (n+1)^2}\left(\frac{1+2\xi}{3\sigma_0}\right)^n \left\{1 - (n+1)\frac{2 f \xi}{r} h - \exp\left[-(n+1)\frac{2 f \xi}{r} h\right]\right\} \sum_{i=1}^{q} \sigma_{zi}^{n+1}, \quad (7)$$

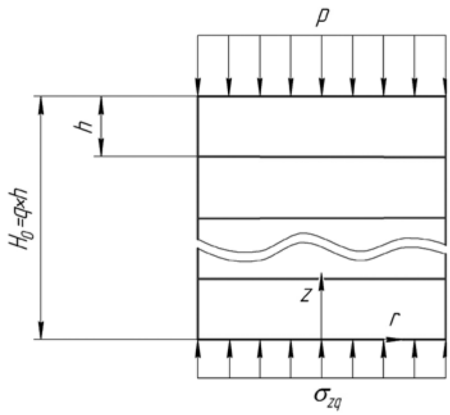

Fig. 2. Diagram used to analyze work performed by contact-friction forces in single-layer article.

where h is the thickness of a thin layer, σ_{zi} are the stresses due to the active external force on the boundary of layers i and $i + 1$, and q is the number of thin layers (Fig. 2).

The elementary work of deformation of the material in the die is

$$A_\mathrm{d} = F\Delta u,$$

where $F = \pi r^2\sigma_z$ is the compressive force on the upper boundary of an elementary layer of the material, and $\Delta u = \Delta\varepsilon\Delta z$ is the displacement of the upper boundary of the elementary layer of material as a result of its deformation.

The total work of deformation of the material over the height of the molding will be [4]:

$$A_\mathrm{d} = \pi r^2 \iint\limits_u \sigma_z(\varepsilon_z, z)\, d\varepsilon_z dz. \tag{8}$$

It follows from (4) that

$$d\varepsilon_z = \varepsilon_z'(\sigma_z)\, d\sigma_z = mn\left(\frac{1+2\xi}{3\sigma_0}\right)^n \sigma_z^{n-1} d\sigma_z.$$

The expression for the total work of deformation of the material is then reduced to the form:

$$A_\mathrm{d} = \pi r^2 mn\left(\frac{1+2\xi}{\sigma_0}\right)^n \iint\limits_u \sigma_z^n d\sigma_z dz. \tag{9}$$

Solution of integral (9) reduces to solution of the iterated integral:

$$A_\mathrm{d} = \pi r^2 mn\left(\frac{1+2\xi}{\sigma_0}\right)^n \int_0^{H_0} dz \int_\sigma^p \sigma_z^n d\sigma_z.$$

The work of deformation of the material up to the assigned molding pressure p will then be

$$A_\mathrm{d} = \pi r^3 \frac{mn}{2f\xi(n+1)^2}\left(\frac{1+2\xi}{\sigma_0}\right)^n p^{n+1}\left\{1 - \exp\left[-(n+1)\frac{2f\xi}{r}H_0\right]\right\}. \tag{10}$$

Substituting (6) and (10) in (2), it is possible to determine the work performed by the active external molding forces:

$$A = \frac{\pi r^3 m}{2f\xi(n+1)}\left(\frac{1+2\xi}{3\sigma_0}\right)^n p^{n+1}\left\langle 1-\frac{2f\xi}{r}H_0-\exp\left[-(n+1)\frac{2f\xi}{r}H_0\right]\right\rangle. \tag{11}$$

According to the theorem of averages, the work performed by external forces during the molding of a one-sided layer of material is equal to the product of a certain average value of the pressure by the cross-sectional area of the die, and also by the difference in the heights prior to and after molding:

$$A_i = \pi r^2 \sigma_{zi}(\zeta)(H_0 - H). \tag{12}$$

During molding, the final height H is unknown with respect to the pressure, while the final molding pressure p is unknown when molding with respect to the height. The relation between the height of the molding and molding pressure can be derived by use of a molding equation. The Kunin–Yurchenko formula has come into the most widespread use for analysis of articles formed from disperse systems [2, 3]:

$$\rho = \rho_{\lim} - \frac{k_0}{\alpha_{\mathrm{cl}}}\exp(-\alpha_{\mathrm{cl}}\sigma_z),$$

where $\rho_{\lim}$ is the conditional limiting density, k_0 is the initial molding factor, and α_{cl} is the compressibility-loss factor.

The average density of the molded article is

$$\rho = \frac{M}{\pi r^2 H}.$$

For the condition $H_0 < r$, we can then assume that

$$\sigma_z(\xi) = \frac{1}{\alpha_{\mathrm{cl}}}\ln\frac{k_0}{\alpha_{\mathrm{cl}}\left(\rho_{\lim}-\dfrac{M}{\pi r^2 H}\right)}. \tag{13}$$

It then follows from simultaneous solution of Eqs. (11)–(13) that

$$\frac{rm}{2f\xi(n+1)}\left[\frac{(1+2\xi)p}{\sigma_0}\right]^n p\left\langle 1-\frac{2f\xi}{r}H_0-\exp\left[-(n+1)\frac{2f\xi}{r}H_0\right]\right\rangle -$$

$$-\frac{(H_0-H)}{\alpha_{\mathrm{cl}}}\ln\frac{k_0}{\alpha_{\mathrm{cl}}\left(\rho_{\lim}-\dfrac{M_i}{\pi r^2 H}\right)} = 0. \tag{14}$$

Solving the equation derived by numerical methods, it is possible to determine the height of the article with respect to an assigned molding pressure, and, conversely, the working molding pressure with respect to the assigned height of the article.

Substituting (11) in (1), we obtain

$$\varphi = \frac{rm}{2f\xi(n+1)(H_0-H)}\left[\frac{(1+2\xi)p}{3\sigma_0}\right]^n\left\langle 1-\frac{2f\xi}{r}H_0-\exp\left[-(n+1)\frac{2f\xi}{r}H_0\right]\right\rangle. \tag{15}$$

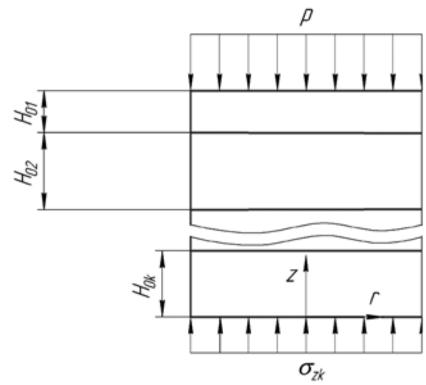

Fig. 3. Working diagram for combined article of k layers.

If the molding pressure p and the final height H of the article are known, the degree of fullness of the force diagram can be determined from (15), and the problem of optimal selection of the design of the drive for the hydraulic equipment solved [5].

In the case where the thickness of the layer of the article $H_0 > r$, the pressing must be divided into a finite number of thin layers with an initial thickness $h_0 \ll r$.

The average density ρ_i of the layer after molding, and the average stress in the corresponding layer will then be

$$\rho_i = \frac{M_i}{\pi r^2 h_i};$$

$$\sigma_{zi}(\xi) = \frac{1}{\alpha_{\text{cl}}} \ln \frac{k_0}{\alpha_{\text{cl}}\left(\rho_{\lim} - \dfrac{M_i}{\pi r^2 h_i}\right)},$$

where M_i is the mass of the ith layer, and h_i is the thickness of the ith layer.

In that case, Eq. (14) will take on the form:

$$\frac{rm}{2f\xi(n+1)}\left[\frac{(1+2\xi)\sigma_{zi}}{\sigma_0}\right]^n \sigma_{zi}\left\langle 1 - \frac{2f\xi}{r}h_0 - \exp\left[-(n+1)\frac{2f\xi}{r}h_0\right]\right\rangle -$$

$$-\frac{(h_0 - h_i)}{\alpha_{\text{cl}}} \ln \frac{k_0}{\alpha_{\text{cl}}\left(\rho_{\lim} - \dfrac{M_i}{\pi r^2 h_i}\right)} = 0. \qquad (16)$$

After calculating the value of h_i, the magnitude of the deformation of an elementary layer $u_i = h_0 - h_i$ is calculated.

Similarly calculated is the deformation of the next elementary layer u_{i+1}. Here, the stress on the boundary of layers i and $i + 1$ is calculated from the formula

$$\sigma_{zi+1} = \sigma_{zi} \exp\left[-\frac{2f\xi}{r}h_0\right].$$

The length of the working throw of the press will be equal to the total deformation of the pressing:

$$S_w = \sum_{i=1}^{q} u_i .$$

Given the final value of the molding pressure on the upper die $\sigma_{zi} = p_j$, it is possible to calculate the corresponding value of the working throw S_{pj}, and construct a force diagram for molding of the corresponding article.

Analysis of Combined Article. As in [6], analysis of the work performed for the molding of a combined article is reduced to stepwise calculation of the work performed by the active external forces for each of the layers of material, beginning with the upper layer (Fig. 3).

The total work of the external forces for the first layer will be

$$A_1 = \frac{\pi r^3 m_1}{2 f_1 \xi_1 (n_1 + 1)} \left(\frac{1 + 2\xi_1}{3\sigma_0} \right)^{n_1} p^{n_1 + 1} \left\langle 1 - \frac{2 f_1 \xi_1}{r} H_{01} - \exp\left[-(n_1 + 1) \frac{2 f_1 \xi_1}{r} H_{01} \right] \right\rangle .$$

Accordingly, for the ith layer:

$$A_i = \frac{\pi r^3 m_i}{2 f_i \xi_i (n_i + 1)} \left(\frac{1 + 2\xi_i}{3\sigma_0} \right)^{i_1} \sigma_i^{n_i + 1} \left\langle 1 - \frac{2 f_i \xi_i}{r} H_{0i} - \exp\left[-(n_i + 1) \frac{2 f_i \xi_i}{r} H_{0i} \right] \right\rangle .$$

The total work of the external forces for the combined article formed from k layers will be equal to the sum of the work performed by the external forces for the molding of all layers:

$$A_{\text{comb}} = \sum_{i=1}^{k} A_i = \pi r^3 \sum_{i=1}^{k} \frac{m_i}{2 f_i \xi_i (n_i + 1)} \left(\frac{1 + 2\xi_i}{3\sigma_0} \right)^{n_i} \sigma_i^{n_i + 1} \times$$

$$\times \left\langle 1 - \frac{2 f_i \xi_i}{r} H_{0i} - \exp\left[-(n_i + 1) \frac{2 f_i \xi_i}{r} H_{0i} \right] \right\rangle . \qquad (17)$$

Just as the final height H_i of each of the layers, or the molding pressure can be determined from Eq. (14) for the thin layers, it is possible to determine these values from Eq. (16) for layers with a thickness greater than the radius of the die.

Substituting (17) in (1), it is possible to determine the degree of fullness of the force diagram for a combined article:

$$\varphi = r \sum_{i=1}^{k} \frac{m_i}{2 f_i \xi_i (n_i + 1)(H_{i0} - H_i)} \left[\frac{(1 + 2\xi)\sigma_i}{3\sigma_0} \right]^n \left\langle 1 - \frac{2 f_i \xi_i}{r} H_{i0} - \exp\left[-(n_i + 1) \frac{2 f_i \xi_i}{r} H_{i0} \right] \right\rangle . \qquad (18)$$

Experimental investigations of the dependence of the load applied by the press on the working throw of the upper die were conducted to verify the theoretical positions.

The theoretical curve was first constructed in accordance with the following procedure. Prior to the start of deformation, the article was divided into a series of thin layers with a height $h_0 = r/q$ (see Fig. 2).

The height h_i of each layer after deformation was computed from Eq. (16). After the value of h_i has been calculated, the deformation of the elementary layer $u_i = h_0 - h_i$ is calculated.

The deformation of the next elementary layer u_{i+1} was calculated in a similar manner. Here, the stress on the boundary of layers i and $i + 1$ was determined from the formula

$$\sigma_{zi+1} = \sigma_{zi} \exp\left[-\frac{2 f \xi}{r} h_0 \right] .$$

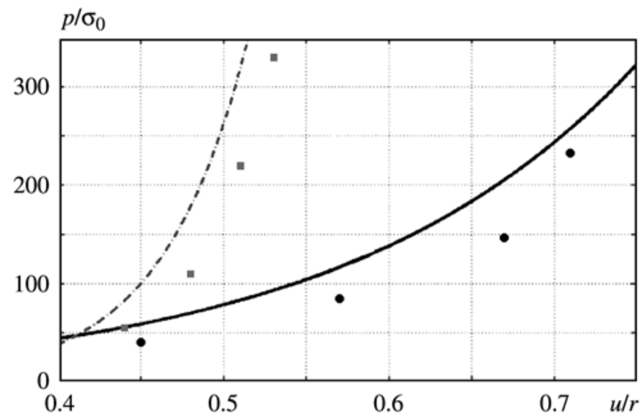

Fig. 4. Force diagrams plotted for molding of several disperse materials: ——) granulated mixture of naturally concentrated chalk (GOST 12065–73), aluminum powder PA-2 (GOST 6058–73), and binder – 15% solution of nitrate film (TU 84-888–81) in acetone (GOST 2768–84); – – –) ammonium oxylate (GOST 5712–78).

The working throw of the press is equal to the total deformation of the molding:

$$S_w = \sum_{i=1}^{q} u_i .$$

Given the final molding pressure on the upper die $\sigma_{z1} = p_j$, it is possible to calculate the corresponding working throw S_{wj} and construct the force diagram for molding of the corresponding article.

Experimental Procedure. The pressure valve on the hydraulic unit was adjusted to the assigned pressure, and the material to be pressed was then poured into the die and loaded until the press had come to a complete stop. The difference in the height of material in the die was measured prior to and after molding. The pressure on the upper die was determined from the formula

$$p = \frac{4P_0}{\pi d^2},$$

where P_0 is the dynamometer reading on the face of the upper die.

A model DOSM-3-5 dynamometer (Technical Specification TU 25.06.590–76) with a measurement range of from 5 to 50 kN was used to measure the force on the face of the upper die.

Figure 4 shows plots of the molding pressure for several disperse materials as a function of the working throw of the upper die in dimensionless coordinates, as well as experimental data.

The computed molding pressures are somewhat higher than those obtained experimentally. This is associated with use of the simplified relationship between stress distribution and the height of the pressing (5). More precise relationships between stress distribution and height, for example, those presented in [2], should be used, and the number of layers q increased to improve the accuracy of the calculations; this may, however, lead to unjustified complication of the calculations.

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