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INVESTIGATION OF POWER CONSUMPTION IN A MIXING DEVICE WITH SWINGING MOVEMENT OF THE ACTUATING ELEMENT

A. A. Prikhod'ko and A. I. Smelyagin

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A mixing device with swinging (rotationally reciprocating) movement of the actuating element, the advantage of which, compared to the classical units, is that it produces a higher mixing rate, is investigated. In designing the new devices, it is necessary to know the moment of resistance of the liquid medium and the power consumed in the mixing process. It is shown that, in the general case, the actuating element is affected by both the linear and quadratic resistance of the fluid and formulas are found for determining the moment of resistance and the power. As a result of the study it is found that the Reynolds number grows and the power consumption increases as the oscillation angle and rotational speed of the actuating elements increase.
Keywords: *mixing device, swinging movement, rotationally reciprocating movement, Reynolds number, moment of resistance of fluid, power, oscillation angle, rotational speed.*

Mixing devices are widely used in the chemical and petrochemical industries to produce solutions, emulsions, and suspensions [1, 2]. Devices with one-way rotary motion of one or more actuating elements are the most common and have been the most extensively studied; such devices are reliable and simple to use and maintain. Since a high degree of efficiency of heat and mass exchange can be achieved with an optimal choice of the geometry of the actuating element, there has been a large number of studies [3, 4] devoted to the creation and study of nontraditional actuating elements for such devices.

The drawback of the classical devices is that in the steady state regime, the speed of the mixing fluid and that of the actuating element are equalized and this leads to a decrease in the mixing rate. In order to eliminate this drawback, a device with periodic internal variation of the angular rate of the agitator was proposed in [5]. A higher velocity gradient of the mixed fluid can be achieved if not only the magnitude, but also the direction of the angular speed of the actuating element are varied.

Experimental investigations [6, 7] of mixing devices with reciprocal and swinging (rotationally reciprocating) regimes of motion of the actuating elements have been carried out and a higher level of efficiency of these devices by comparison with traditional rotary agitators has been demonstrated. It follows from the results of these investigations that the highest mixing rate is not always achieved in the case of the maximum oscillation angle or maximum rotational speeds. The power consumption is, therefore, one of the important parameters in estimating the efficiency of mixing devices with different actuating elements.

In the present mixing device (Fig. 1), the actuating element completes swinging movement. A novel planetary mechanism with elliptical gears [8] is used as the drive of the device.

The mixing device (cf. Fig. 1) comprises a reaction vessel *1*, engine *2*, actuating element *3*, and planetary actuator *4*, which transforms the rotation of the engine shaft into the swinging movement of the actuating element. The actuator (double-row planetary reducing gear with two external linkages in which one pair of cylindrical gears is replaced by elliptical gears) comprises an input shaft *5*, guide pole *6*, output shaft *7*, sun gear *8*, elliptical gear wheels *9* and *10* on the output shaft arranged at an

Kuban State Technological University, Krasnodar, Russia; e-mail: sannic92@gmail.com. Translated from Khimicheskoe i Neftegazovoe Mashinostroenie, No. 3, pp. 9–12, March, 2018.

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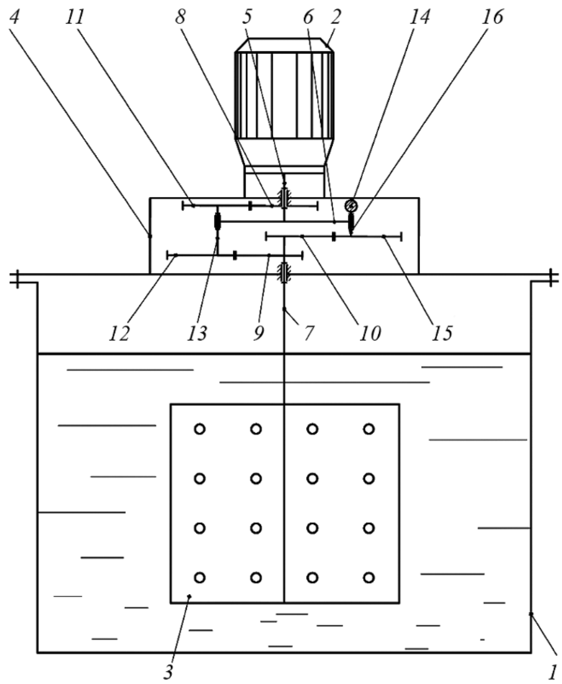

Fig. 1. Schematic diagram of swinging mixing device.

angle of 180°, a first planetary gear (consisting of a cylindrical gear wheel *11*, elliptical wheel *12*, and shaft *13*), and a second planetary gear (consisting of a counterweight *14*, elliptical wheel *15*, and shaft *16*). With a correct choice of the masses of the gears and counterweight [9], the mechanism will be balanced, consequently, undesirable vibrations will not arise.

The swinging movement of the output shaft is achieved due to the variable gear ratio of the pair of elliptical gear wheels. As a result of a kinematic analysis [10] it was established that the velocity analog φ'_{out} and rotation angle of the output shaft φ_{out} of the mechanism are determined in the following way:

$$\varphi'_{out} = \frac{d\varphi_{out}}{d\varphi_{in}} = 1 - \frac{p}{2a[1 - e\cos(\varphi_{in} + \pi)] - p}; \tag{1}$$

$$\varphi_{out} = \int \varphi'_{out}\, d\varphi_{in}, \tag{2}$$

where a, e, and p are the major axis, eccentricity, and focal parameter of the elliptical wheels, respectively; and φ_{in} is the rotation angle of the input shaft of the planetary mechanism.

The angle of swinging movement of the output shaft as well as the asymmetry of the forward and reverse motion both depend on the choice of the eccentricity of the pair of elliptical gear wheels (Fig. 2).

In swinging movement of the actuating element, the moment of resistance and angular speed depend on time, hence the average power is determined by the expression

$$P = \frac{A}{T} = \int_0^T M_{act}(t)\omega_{a.e}(t)\,dt \Big/ T, \tag{3}$$

where A is the work of the moment of resistance in a single period T; M_{act}, moment of resistance in the actuating element; and $\omega_{a.e} = \omega_{out}$, angular speed of actuating element.

The moment of resistance M_{act} depends on which motion regime of the fluid is realized in the reaction vessel, whether laminar or turbulent. The following formula for determining the Reynolds number in swinging movement of the actuating element is proposed in [11]:

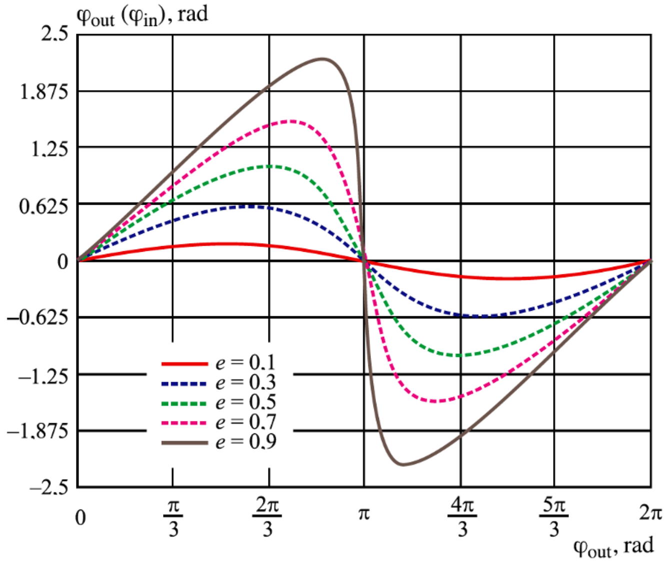

Fig. 2. Curves of the functions φ_{out} (φ_{in}) for different eccentricities of the elliptical wheels.

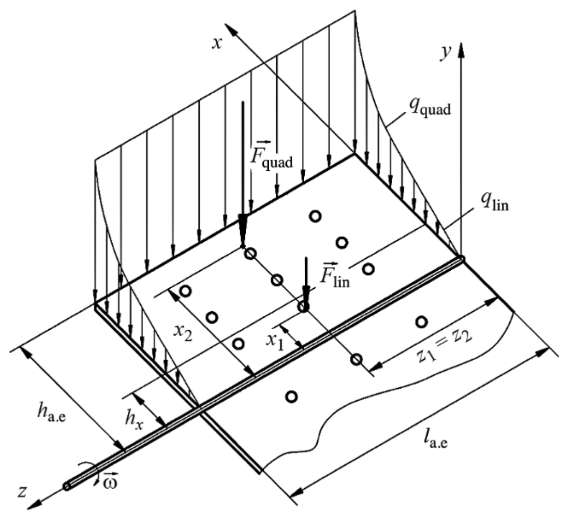

Fig. 3. Analytical mode for determining the moment of resistance.

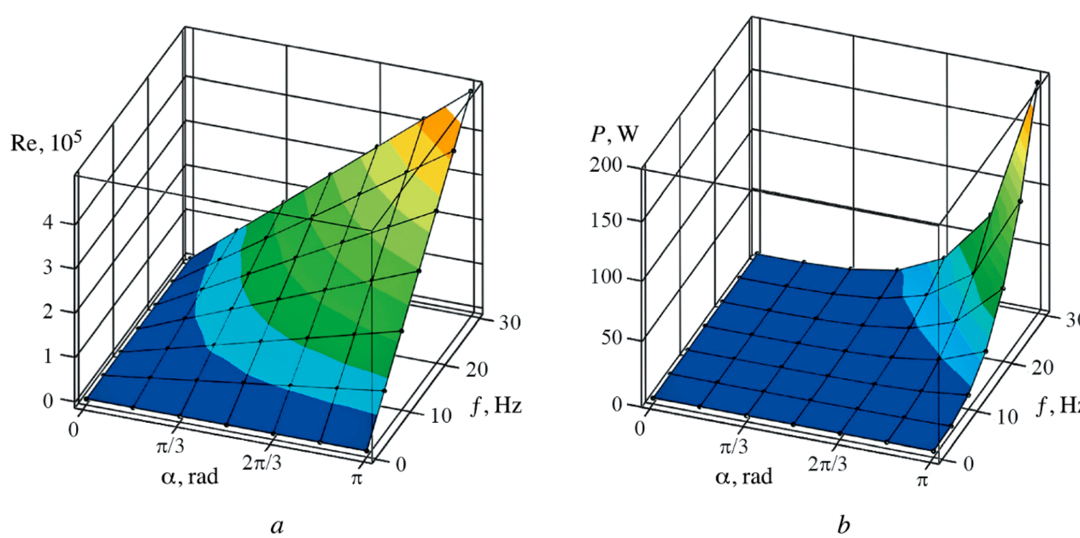

Fig. 4. Graphs of two relationships Re(α, f) and P(α, f).

$$\mathrm{Re} = \sqrt{\frac{4S}{\pi}}\frac{\alpha f h}{\nu}, \tag{4}$$

where $S = l_{\mathrm{a.e}}h_{\mathrm{a.e}}n$ is the area of the actuating element; n, number of blades in actuating element; α, angle of swinging oscillations of actuating element; f, oscillation frequency of actuating element; h, distance from studied element of actuating element to axis of rotation; and ν, kinematic viscosity of fluid.

At low Reynolds number (Re ≤ 100), the resistance of the fluid is directly proportional to the velocity, while at high Reynolds numbers (Re > 100), it is directly proportional to the square of the velocity [12]. Since the Reynolds number is different for different sections of the actuating element, the actuating element may be simultaneously affected by two types of resistance – linear and quadratic (Fig. 3).

In this case, there exists a boundary h_x at which the law of resistance of the medium changes. The intensity of the distributed load acting on a blade of the actuating element is then given as

$$q_{\mathrm{lin}} = B_{\mathrm{lin}}v, \quad \mathrm{Re} \le 100; \tag{5}$$

$$q_{\mathrm{quad}} = B_{\mathrm{quad}}v^2, \quad \mathrm{Re} > 100; \tag{6}$$

where B_{lin} and B_{quad} are the coefficients of linear and quadratic resistance; and v, linear velocity of a point of the actuating element for which it is necessary to determine the intensity of the effective load.

We replace the distributed loads q_{lin} and q_{quad} by equivalent concentrated forces. The equivalent force for loads that are distributed across the area is determined by the formula [13]

$$F = \int q(S)dS. \tag{7}$$

Substituting formulas (5) and (6) into (7) yields

$$F_{\mathrm{lin}} = \int_0^{h_x} B_{\mathrm{lin}}v\,d(l_{\mathrm{a.e}}x), \quad 0 \le x \le h_x; \tag{8}$$

$$F_{\mathrm{quad}} = \int_{h_x}^{h_{\mathrm{a.e}}} B_{\mathrm{quad}}v^2 d(l_{\mathrm{a.e}}x), \quad h_x \le x \le h_{\mathrm{a.e}}, \tag{9}$$

where h_x is the boundary at which the law of resistance of the fluid changes. We determine this boundary from Eq. (4) with Re = 100:

$$h_x = \frac{100\nu}{\alpha f}\sqrt{\frac{\pi}{4S}}. \tag{10}$$

In view of the fact that $v = \omega x$, formulas (8) and (9) assume the following form as a result of integration:

$$F_{\mathrm{lin}} = B_{\mathrm{lin}}\omega l_{\mathrm{a.e}}\frac{h_x^2}{2}; \tag{11}$$

$$F_{\mathrm{quad}} = B_{\mathrm{quad}}\omega^2 l_{\mathrm{a.e}}\frac{h_{\mathrm{a.e}}^3 - h_x^3}{3}. \tag{12}$$

The forces F_{lin} and F_{quad} are applied to the centers of gravity of the representations of the distributed loads $q_{\mathrm{lin}}(S)$ and $q_{\mathrm{quad}}(S)$ (cf. Fig. 3). We determine the coordinates x_1, x_2 and z_1, z_2 of the centers of gravity (cf. Fig. 3) from the formulas [13]:

$$x_1 = (2/3)h_x; \tag{13}$$

$$x_2 = \frac{3}{4}\frac{h_{\mathrm{a.e}}^4 - h_x^4}{h_{\mathrm{a.e}}^3 - h_x^3}; \tag{14}$$

$$z_1 = z_2 = l_{\mathrm{a.e}}/2. \tag{15}$$

Since the actuating element may contain not just one, but in fact n blades, we may determine the moment of resistance of the medium as follows:

$$M_{\text{act}} = n(F_{\text{lin}} x_1 + F_{\text{quad}} x_2). \tag{16}$$

Substituting formulas (11)–(14) into formula (16), we obtain

$$M_{\text{act}} = \frac{n}{3} B_{\text{lin}} \omega l_{\text{a.e}} h_x^3 + \frac{n}{4} B_{\text{quad}} \omega^2 l_{\text{a.e}} (h_{\text{a.e}}^4 - h_x^4). \tag{17}$$

Through the use of the latter expression, we are able to find the moment of resistance of the agitated medium in the case of swinging movement of the actuating element when laminar and turbulent regimes of motion of the fluid are observed simultaneously. If the boundary h_x falls outside the limits of the actuating element (laminar regime) or is too close to the axis or rotation (turbulent regime), one of the terms in formula (17) vanishes.

We next introduce the following notation:

$$\lambda_1 = \frac{n}{3} B_{\text{lin}} l_{\text{a.e}} h_x^3; \tag{18}$$

$$\lambda_2 = \frac{n}{4} B_{\text{quad}} l_{\text{a.e}} (h_{\text{a.e}}^4 - h_x^4). \tag{19}$$

In light of (17)–(19), formula (3) assumes the following form:

$$P = \int_0^T (\lambda_1 \omega_{\text{a.e}}^2(t) + \lambda_2 \omega_{\text{a.e}}^3(t))\, dt \Big/ T. \tag{20}$$

It follows from formulas (4), (17), and (20) that the Reynolds criterion, moment of resistance, and useful power where the geometric parameters of the actuating element and the reaction vessel are invariant as well as the kinematic viscosity of the medium all depend on the oscillation frequency and oscillation angle of the actuating element.

As an example, let us study a mixing device with the following parameters: length of actuating element $l_{\text{a.e}} = 0.12$ m; width of blade $h_{\text{a.e.}} = 0.045$ m; $n = 2$; agitated fluid – water; and $\nu = 1.004 \cdot 10^{-6}$ m^2/sec.

The oscillation frequency of the actuating element is determined by the rotational speed of the engine *2* which sets the input shaft *5* of the planetary actuator in motion (cf. Fig. 1). The oscillation angle is determined by the dimensions of the elliptical wheels of the planetary mechanism and grows with increasing eccentricity of the wheels.

Using the formulas that have been presented here and substituting the results which have been obtained into expressions (4) and (20), we obtain the values of the Reynolds number and the power for different oscillation angles α and different oscillation frequencies f of the actuating element. The values thus found are represented in the form of the two relationships $\text{Re}(\alpha, f)$ and $P(\alpha, f)$, the graphs of which are presented in Fig. 4.

A simultaneous increase in the oscillation angle and oscillation frequency leads to a growth in the Reynolds number and the power consumption. A turbulent mixing regime is predominantly observed in swinging motion of the actuating element. Consequently, such mixing devices may be effectively used for processes in which a high rate of heat and mass exchange and great drop in the velocity of the mixed medium are required.

Thus, expressions have been found for calculating the moment of resistance and useful power of a mixing device with swinging motion of the actuating element. A higher mixing rate as well as the development of new converters of rotary motion into swinging motion will make possible broader development and application of swinging devices in different branches of industry.

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