Comparative Analysis of the Performance of Oscillating and Propeller Stirrers

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Abstract. The paper considers available modern designs of stirring devices, and their application in various industrial processes has been considered. The operating principle has been considered for a new design of an oscillating stirrer to obtain high-viscosity structural and non-Newtonian solutions, suspensions, and emulsions. An experimental unit has been developed to estimate the energy efficiency of the new oscillating stirrer design. Based on the previously developed technique, experimental studies have been performed to estimate the efficiency of using high-speed propeller stirrer and oscillating ones by evaluating the stability of emulsions (industrial oil-water) obtained with various stirring devices. The analysis of the effect of the high-speed and oscillating stirrers' structural and kinematic characteristics on the intensity and efficiency of mixing liquid heterogeneous systems has been performed. The experimental study results have shown that using an oscillating stirrer is more than 20 times more efficient compared to a high-speed propeller one, while it is increasing the power costs by only 25–30%. Using new energy-efficient stirrers in the designed and existing industries would decrease the mixing duration by several times, while obtaining emulsions with desired properties at an overall reduction in power consumption per unit of output.

Keywords: Mixing · Resonance · High-speed stirrer · Oscillating stirrer · Intensity of mixing · Efficiency of mixing

1 Introduction

Mixing media is widely used in various industries to obtain homogeneous solutions, emulsions, and suspensions.

Mixing is an effective way to intensify hydrodynamic as well as heat and mass transfer processes [1–3]. Solving the issue of reducing power consumption in the production of stable, high-viscosity structural and non-Newtonian solutions, suspensions, and emulsions is an urgent task when designing new and retrofitting existing processes in engineering, metallurgy, energy, chemical, petrochemical, and other industries, as well as environmental processes of liquid waste processing, which include mixing.

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The mixing techniques and device designs depend on the source media properties and the requirements for the finished product [4].

Preparing solutions, emulsions, and suspensions in engineering, chemical, petrochemical, and other industries is most often performed using mechanical stirrers rotating in a vessel [4, 5].

Mixing is characterized by efficiency and intensity [5–7]. In this case, efficiency means the uniform distribution of concentrations throughout the volume of liquid. Intensity means the power consumed per unit of the mixed liquid volume. An increase in intensity, as a rule, leads to an increase in energy costs but not always in the mixing efficiency. When choosing the stirrer design, the main task is not only retaining the mixing efficiency but also developing energy-efficient stirrer designs that may reduce power consumption during the stirrer operation.

An advanced direction in mixing liquid media is the development and use of a new generation of equipment, which increases turbulence and circulation of flows while reducing power consumption and mixing time [7].

Considerable attention is paid to mixing modes, as this is one of the defining moments to increase the process efficiency [4, 8].

Currently, a wide range of combined and resonance stirrer designs have been proposed, which allow obtaining stable emulsions using energy-efficient stirrer designs [9–13]. These stirrer designs operate based on the resonance phenomenon, which increases the efficiency of mixing media at the micro- and macro-levels but negatively affects the integrity of equipment designs due to the resonance effect that has been detected during experimental studies [14–16].

Thus, developing the designs of stirring devices operating in a mode close to resonance but not achieving a resonance effect, while increasing the mixing efficiency at the micro- and macro-levels is an urgent task, which, if solved, allows finding the energy-efficient stirring equipment operating modes close to optimal to obtain stable emulsions.

The work objective is to estimate the effect of the high-speed and oscillating stirrers' structural and kinematic characteristics on the intensity and efficiency of mixing based on experimental studies.

2 The Stirring Device Design and Operating Mode

An analysis of new designs of stirrers operating based on the resonance effect principles and previous experimental studies has shown [14, 16] that to increase the mixing intensity, it makes sense to operate a combined stirrer in the effective mode as shown in Fig. 1.

Presumably, such an operating mode of oscillating stirrer would allow a significant increase in the mixing efficiency without entering the resonance oscillation mode, while retaining or slightly increasing the power consumption.

Let us consider the operating principle of a combined stirrer built based on the prototype in a similar mode [13]. The main difference between the experimental unit and the prototype is the absence of radial distributing plates, which allows avoiding a

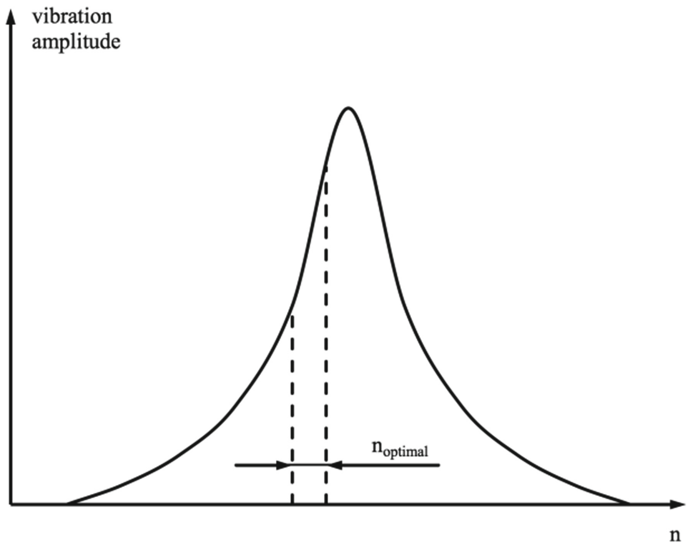

Fig. 1. The effective stirrer operating mode.

resonance phenomenon, while maintaining intensive turbulence of the mixed media due to the simultaneous rotation and oscillation of the stirrer design elements.

The stirrer design [13] is shown in Fig. 2.

The description of the prototype stirrer operating principle indicates that using this stirrer design in devices with baffle plates is effective. In this case, when the coil spring ends pass near the baffle plates, the rotating resistance increases due to the hydraulic wedge effect. Stirrers consisting of coil springs bend in the stirrer rotation plane, after which return to their original position. The circular oscillations of the spring coils contribute even more to the generation of micro-vortices in the liquid mixed intensifying the mixing itself, reducing the required time, and, therefore, increasing productivity [13].

To reduce the resonance effect likelihood, it has been decided to refuse from baffle plates in the experimental unit. Such a change in the stirrer design simultaneously facilitates the further unit operation when working with high-viscosity media, as it allows avoiding a need to additionally clean the plates contaminated.

3 Experimental Unit

Based on the design proposed, a prototype oscillating stirrer has been built. Experimental studies have been performed based on the ES-8300D stirring device having several replaceable shafts, on which a high-speed propeller stirrer and the developed oscillating one have been installed.

The stirring device ES-8300D consists of an engine block with a three-jaw chuck and a control unit (Fig. 3). The lower part of the engine block comprises a sliding bearing with a shaft, on which a three-jaw chuck 5 is fixed. The motor shaft torque is transmitted to the stirrer through a system of two metal bushings and a rubber clutch. Three-jaw chuck 5 allows fixing stirrers with a shaft diameter of 1–8 mm.

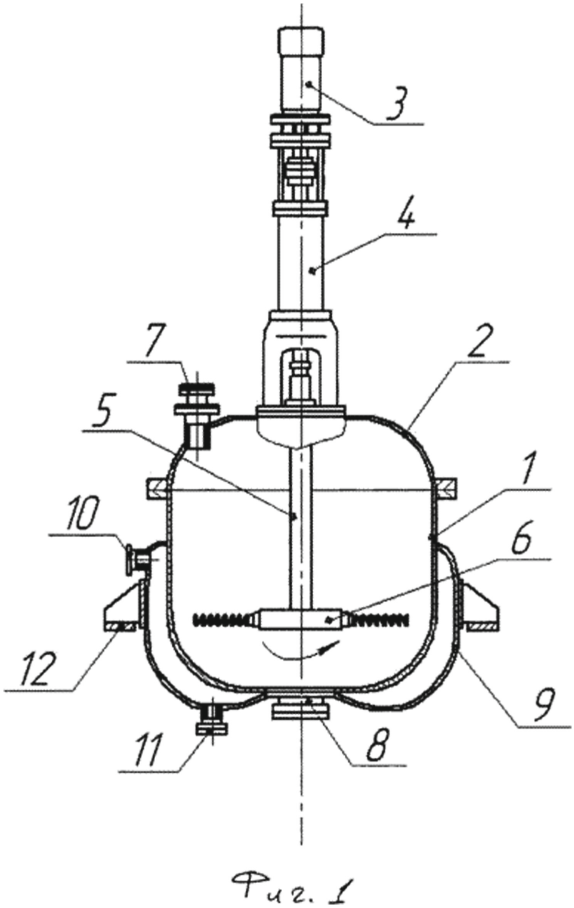

Fig. 2. The oscillating stirrer design [13]: 1—case; 2—removable cover; 3—motor; 4—gear; 5—shaft; 6—stirrer; 7, 8, 10, 11—tubes; 9—jacket; 12—supports.

4 The Study Objects and Their Characteristics

As test fluids, almost immiscible water and industrial oil I-40A in a ratio of 1:1 have been used. The finished mixing product is an emulsion.

The characteristics of the test fluids are given in Tables 1 and 2.

It is worth noting that using an industrial oil in this experiment was a conscious choice, since earlier experimental studies were performed with vegetable oil and water as test fluids and the stability of the emulsions obtained was up to 200 h, which complicated the research, therefore, choosing industrial oil and water reduced the experiment time.

During the experiments, the stability of the emulsions obtained has been studied at the operation of the high-speed propeller and oscillating stirrers.

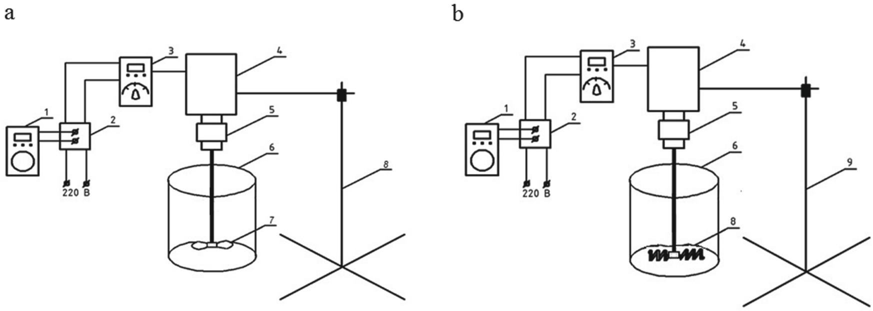

Fig. 3. Experimental unit: a—high-speed propeller stirrer; b—oscillating stirrer. 1—multimeter; 2—ammeter connecting electric circuit breakers; 3—motor control unit with a digital indicator of the stirrer rotation speed; 4—motor; 5—three-jaw chuck; 6—cylindrical vessel with a medium mixed; 7—propeller stirrer; 8—coil spring; 9—holder.

Table 1. Industrial oil I-40A characteristics [17]

Indicators	Value
Kinematic viscosity, mm^2/s, at 20°C	61
Pour point, °C	−15
Density, kg/m^3, at 20°C	900

Table 2. Water characteristics [18].

Indicators	Value
Kinematic viscosity, mm^2/s, at 20°C	1.006
Freezing point, °C	0
Density, kg/m^3, at 20°C	998

5 Analysis of the Experimental Study Results

The most important stirrer characteristics that can be the basis for their comparative evaluation are the mixing efficiency and intensity [6, 19, 20].

Obtaining a stable emulsion depends on the mixing intensity and time. The Reynolds criterion can be used as a parameter characterizing the mixing intensity.

$$\mathrm{Re} = \frac{\rho \cdot n \cdot d_m^2}{\mu}, \tag{1}$$

where ρ is the emulsion density, kg/m^3; n is the stirrer rotation speed, s^{-1}; μ is the dynamic viscosity coefficient, Pa•s; d_m is the stirrer diameter, m.

The stirrer power criterion K_N:

$$K_N = \frac{N}{\rho \cdot n^3 \cdot d_m^5}, \quad (2)$$

where N is the stirrer power consumption, W.

An integral characteristic of the mixing intensity in the device is the intensity coefficient determined by the formula (3):

$$I = \frac{N}{V}, \quad (3)$$

where V is the mixed liquid volume, m^3

To estimate the mixing efficiency, a mixing efficiency coefficient has been introduced, which is determined by the formula (4):

$$E = \frac{\tau_{obt}}{\tau_{ref}}, \quad (4)$$

where τ_{obt}—is the studied emulsion breakdown time, s; τ_{ref}—is the reference emulsion breakdown time, s.

For the experiment, the 10 min reference emulsion breakdown time has been adopted.

The experimental results have been averaged over three parameters. In the course of the experimental studies, the emulsion breakdown time has been recorded (Table 3).

Table 3. Experimental Data for the Mixing Volume V = 2000 ml.

Rotation speed, rpm	Current I, $A \cdot 10^{-3}$		Emulsion breakdown time τ, min					
	Propeller stirrer	Oscillating stirrer	Propeller stirrer			Oscillating stirrer		
600	55	215	0,66	0,7	0,77	7,16	7,4	7,63
800	60	305	0,79	0,75	0,69	18,05	18,3	18,67
1000	90	375	2,18	2,25	2,31	23,59	24	24,29

Based on the experimental study results, the dependencies of the relative efficiency and mixing intensity coefficient values on the stirrer rotation speed have been plotted (Fig. 4).

An analysis of the graphical dependencies shows that the oscillating stirrer efficiency coefficient increases from 7.5 to 25 times as compared to the propeller one.

When using an oscillating stirrer, the mixing intensity increases by 25% maximum compared to the propeller one.

Obviously, the technological effect, which in this case is the emulsion stability increases many times when using an oscillating stirrer that allows reducing the equipment operating time to achieve the specified quality indicators of the product obtained.

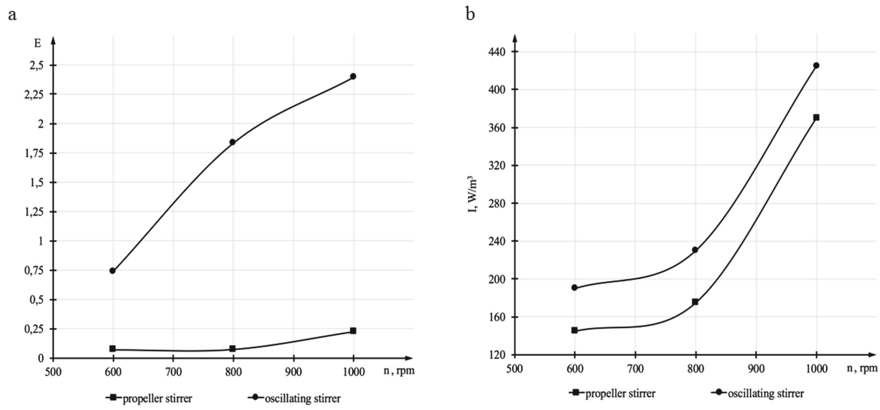

Fig. 4. Dependence of the efficiency **a** and intensity **b** coefficients on the stirrer rotation speed.

Thus, we can talk about a significant reduction in the mixing power consumption due to the use of an oscillating stirrer, which provides the required technological effect for a shorter period.

Oscillating stirrers can be used in the machine-building, chemical, and petrochemical processes. The oscillating stirrer is easy to install both on newly designed devices and operating ones, when retrofitted.

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