

EXPERIMENTAL DETERMINATION AND INVESTIGATION OF THE POWER NUMBER K_N OF A NEW SERIES OF ENERGY-EFFICIENT MECHANICAL AGITATORS FOR BIOTECHNOLOGICAL APPLICATIONS

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Abstract: This article presents the experimental determination and investigation of the power number K_N of a new series of energy-efficient mechanical agitators intended for applications in biotechnological processes. The experimental studies were carried out under laboratory conditions using model fluids representative of biotechnological media, over a wide range of Reynolds numbers covering turbulent flow regime. Based on the measured power consumption, correlations of the power number K_N with the hydrodynamic parameters of the process were established. The results were compared with data for conventional impeller types and they demonstrate lower values of K_N under comparable operating conditions, confirming the energy-saving character of the developed agitator series. The obtained correlations are applicable to the optimisation, design, and scale-up of mechanically agitated vessels in biotechnological practice.

Keywords: power number K_N , energy-efficient mechanical agitators, biotechnological processes, experimental investigation, power characteristics.

ОПИТНО ОПРЕДЕЛЯНЕ И ИЗСЛЕДВАНЕ НА КОЕФИЦИЕНТА НА МОЩНОСТТА K_N НА НОВ ТИП СЕРИЯ ЕНЕРГОСПЕСТЯВАЩИ МЕХАНИЧНИ БЪРКАЧКИ С ПРИЛОЖЕНИЕ В БИОТЕХНОЛОГИИТЕ

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Резюме: В статията е представено опитно определяне и изследване на коефициента на мощността K_N на нов тип серия енергоспестяващи механични бъркачки, предназначени за приложение в биотехнологичните производства. Експерименталните изследвания са проведени в лабораторни условия с използване на моделни флуиди, характерни за биотехнологични процеси, в широк диапазон от числа на Рейнолдс, обхващащ турбулентен режим на течение. На база на измерената консумирана мощност са получени зависимости на коефициента K_N от хидродинамичните параметри на процеса. Резултатите са сравнени с данни за класически типове бъркачки и показват по-ниски стойности на K_N при аналогични условия, което потвърждава енергоспестяващия характер на разработената серия. Получените зависимости са приложими при оптимизацията, проектирането и мащабирането на разбъркващи апарати в биотехнологичната практика.

Ключови думи: коефициент на мощността K_N , енергоспестяващи механични бъркачки, биотехнологични производства, експериментално изследване, мощностни характеристики.

Introduction

Mechanical agitation is one of the key unit operations in biotechnological production, finding widespread application in bioreactors for the cultivation of microorganisms, cell cultures, and enzymatic systems (Nienow, 1996; Doran, 2013). The efficiency of mass and heat transfer processes, gas-phase dispersion, and homogenisation of the reaction medium largely depends on the design and energetic characteristics of the mechanical impellers employed (Paul et al., 2004). At the same time, increasing demands for energy efficiency and sustainable development necessitate the development and implementation of new types of mixing devices with reduced specific energy consumption (Paul et al., 2004).

One of the principal dimensionless criteria used for the quantitative evaluation of the energetic performance of mechanical agitators is the power number, K_N (Nagata, 1975). This parameter characterises the relationship between power consumption, impeller geometry, and the hydrodynamic flow regime, as defined by the Reynolds number. The analysis of the dependence $K_N = f(Re)$ enables the comparison among different impeller types and provides an assessment of their efficiency under various operating conditions (Rushton et al., 1950).

Despite the widespread use of classical impeller designs - such as paddle, turbine, and propeller types - their power characteristics often fail to meet contemporary requirements for energy optimisation, particularly when operating in viscous biotechnological media and during process scale-up (Metzner et

al. 1957). This necessitates the development of new series of energy-efficient mechanical agitators in which targeted design solutions enable a more effective distribution of energy throughout the vessel volume (Nienow, 1996; Paul et al., 2004).

The present article is aimed at the experimental determination and investigation of the power number K_N for a newly developed series of energy-saving mechanical agitators intended for application in biotechnological processes. Through systematic experimental investigations over a wide range of hydrodynamic regimes, reliable power correlations are obtained and the energetic potential of the developed designs is evaluated. The results provide a basis for the optimisation of mixing processes, as well as for their accurate design and scale-up in biotechnological industrial practice (Nagata, 1975; Doran, 2013).

Investigated Mixing Devices and Working Media

The energy characteristic $K_N = f(Re_b)$ constitutes the fundamental basis for the evaluation of any newly designed mechanical agitator. For the experimental determination of the power number K_N , studies were carried out during agitation of two types of liquid systems typical of biotechnological processes:

- single-phase system – water;
- two-phase system – water–vegetable oil emulsion.

The investigations were performed using newly developed series of modified energy-saving mechanical agitators, as follows:

- Modified Narcissus – MN - 6.1
- Impeller – IM - 6.1
- Modified Propeller – MP - 3.1
- “Clover” Propeller – PD – 4.1

The investigated designs represent a new series of energy-efficient mechanical agitators developed to enhance the hydrodynamic efficiency of the process and to reduce specific energy consumption during dispersion, emulsification, and homogenisation of liquid systems characteristic of biotechnological production (Kraychev et al., 2003). The newly designed impeller series is presented in Figures 1–4.



Fig.1. Modified Narcissus – MN - 6.1



Fig.2. Impeller – IM - 6.1



Fig.3. Modified Propeller – MP - 3.1

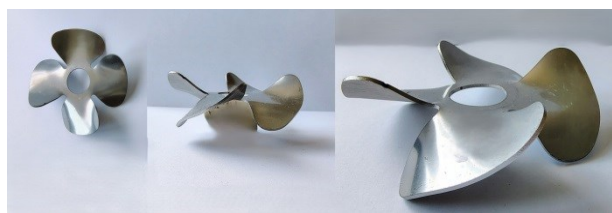


Fig.4. “Clover” Propeller – PD - 4.1

The constructive modification of the working elements is aimed at optimising the flow structure within the vessel, limiting turbulent energy loss, and improving momentum transfer throughout the working volume.

All mixing devices were manufactured of stainless steel type AISI 304, ensuring:

- high corrosion resistance;
- chemical inertness with respect to the investigated media;
- compliance with the hygiene requirements for biotechnological applications;

- good mechanical strength at relatively small material thickness.

The main geometric parameters of the impellers are:

- impeller diameter: $d = 0.09 \text{ m}$;
- blade thickness: $\delta = 0.5 \text{ mm}$.

The selected diameter is consistent with the working volume of the vessel ($V_R = 14.3 \text{ dm}^3$) and provides an appropriate impeller to vessel diameter ratio, necessary for the accurate determination of the power number K_N and for a comparable assessment of the energy efficiency among the individual designs.

Physico-Chemical Properties of the Working Media

The experimental investigations were conducted at a temperature of $T = 20^\circ\text{C}$. The dynamic viscosity of water was $\mu = 0.001 \text{ Pa}\cdot\text{s}$. The liquid media used and their densities were $\rho_{\text{water}} = 998 \text{ kg/m}^3$

Two dispersed-phase concentrations (vegetable oil) were investigated:

- 20% vegetable oil + 80% water - $\rho_{20\%} = 984 \text{ kg/m}^3$
- 40% vegetable oil + 60% water - $\rho_{40\%} = 968 \text{ kg/m}^3$

The dynamic viscosity μ for the dispersed phase concentration at 20% was $0.002 \text{ Pa}\cdot\text{s}$, while at 40% it was $0.005 \text{ Pa}\cdot\text{s}$. The working liquid volume in the experimental vessel was $V = 12 \text{ L}$ (0.012 m^3).

Geometric Ratio d/D and Its Influence on the Power Number

One of the principal dimensionless geometric parameters governing mixing hydrodynamics is the ratio between the impeller diameter d and the internal vessel diameter D : d/D

This ratio significantly influences:

- the formation of circulation flow patterns within the working volume;
- the intensity of turbulence;
- the magnitude of power consumption;
- the value of the power number K_N .

In the present study, the impeller diameter was $d = 0.09 \text{ m}$. The ratio d/D was selected to ensure:

- effective bulk mixing without the formation of a stable central vortex;
- minimisation of dead zones within the reaction volume;
- correct comparison among different impeller types under identical geometric conditions.

Maintaining a constant d/D ratio for all investigated designs guarantees that the observed variations in the power number K_N are attributable solely to the constructive characteristics of the impeller and not to geometric differences in the system (Stephan et al., 2019).

Determination of the Power Number

The power number K_N is the principal dimensionless criterion characterising the energy efficiency of the mixing device and is determined by:

$$K_N = \frac{P}{\rho \cdot n^3 \cdot D^5} \quad (1)$$

where:

P is the power (W)

ρ - fluid density (kg/m³)

n - rotational speed (min⁻¹)

D - impeller diameter (m)

To analyse the hydrodynamic operating regime, the Reynolds number was used:

$$Re = \frac{n \cdot \rho \cdot D^2}{\mu} \quad (2)$$

where:

n is rotational speed (min⁻¹)

ρ - fluid density (kg/m³)

D - impeller diameter (m)

μ - dynamic viscosity (Pa.s)

This criterion enables identification of laminar, transitional, or turbulent flow regimes and examination of the relationship $KN=f(Re)$ (Kraychev et al., 2004). Such an approach is particularly important in biotechnological processes, where an optimal balance is required between:

- energy efficiency;
- mechanically gentle action on biological systems;
- effective mass and heat transfer.

Experimental Setup

The experimental investigations were carried out in a laboratory semi-industrial reactor (10) with a nominal working volume $V_R=14.3$ dm³ and made of transparent PMMA (Plexiglas). Inside the vessel, four vertical baffles (4) were mounted at 90° intervals along the periphery to prevent vortex formation and uncontrolled swirling of the liquid.

A horizontally wound copper coil (3) with a total length $L = 7.94$ m was installed along the internal wall of the reactor. Its function was to serve as a heat-transfer surface through which a heat carrier flows to maintain the set temperature conditions within the reaction volume.



Fig. 5. Laboratory reactor in operating mode

At the bottom of the reactor, a sparger (11) was installed, consisting of a porous element for inert gas introduction. The mixing mechanism was driven by a stainless steel shaft (2), to which the mechanical agitator (9) was attached, coupled to a DC electric motor (1) allowing stable operation at different rotational regimes (Fig. 5) (Kraychev, 2023).

The rotational speed of the main shaft was regulated by an autotransformer and monitored via potentiometers with voltmeter and ammeter readings using calibration curves. The rotational speed was measured by an infrared non-contact tachometer (7) and recorded by a data acquisition unit (8).

Sensitive manometric thermometers (5) were mounted at the inlet and outlet of the system, and a digital flow meter (6) recorded the flow rate in real time. A photo and a diagram of the experimental installation are shown in Fig. 6 and 7.

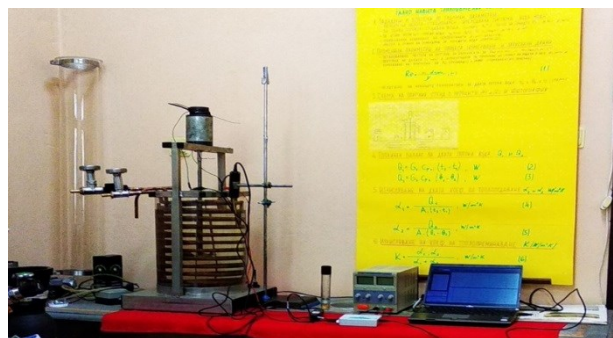


Fig. 6. Photograph of the experimental installation

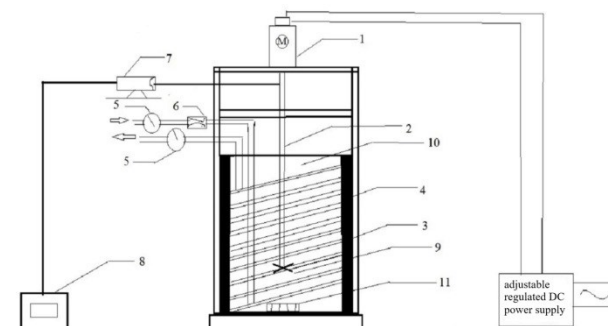


Fig. 7. Diagram of the experimental installation:

1 – DC electric motor; 2 – stainless steel shaft; 3 – copper coil; 4 – baffles (4 pcs.); 5 – manometric thermometers; 6 – digital flow meter; 7 – infrared tachometer; 8 – recording unit; 9 – mechanical agitator; 10 – PMMA (Plexiglas) reactor; 11 – sparger

Experimental Procedure and Presentation of Results

Initially, the “self-consumed” idle power was measured at rotational speeds $n = 200 \div 1000$ min⁻¹, without the impeller being immersed in liquid. This allowed determination of the “net” mixing power for water and water–vegetable oil systems for the four impeller types.

The net power was calculated as:

$$P = P_1 - P_2 \text{ (W)},$$

where P_1 is the gross power and P_2 is the idle power.

It was observed that the power curves of the newly developed devices are less steep, indicating lower electrical energy consumption.

To intensify heat and mass transfer, hot water could be circulated through the copper coil at different inlet and outlet temperatures when necessary. By plotting the relationship $P =$

$f(n)$, the power number K_N was determined according to Equation (1) (Strenk, 1975).

Table 1 compares the gross and net mixing power for water and water-vegetable oil systems for the four impeller series (Kraychev, 2000). The rotational speed varied from 200 to 1000 min^{-1} . The second column presents idle power, while the remaining columns show results for the four impeller series with two liquid systems.

Table 1. Comparison of gross and net mixing power for two types of liquid system and four impeller series.

Rotations (n)	Agitation power-gross							
	Modified Narcissus - MN - 6.1				Impeller IM - 6.1			
	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%
min^{-1}	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
200	0.64	0.87	0.90	1.05	0.56	1.06	0.88	1.02
400	1.11	2.98	3.04	3.20	1.04	3.69	3.63	3.80
600	1.50	8.29	8.06	8.28	1.37	10.43	10.35	10.52
800	2.04	18.23	17.36	17.52	1.90	24.04	23.50	23.71
1000	2.69	35.19	32.76	33.10	2.72	49.66	48.65	48.86
Rotations (n)	Agitation power-net							
	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%
	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
min^{-1}	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
200	0.64	0.23	0.27	0.41	0.56	0.50	0.32	0.46
400	1.11	1.87	1.93	2.09	1.04	2.65	2.59	2.76
600	1.50	6.80	6.57	6.79	1.37	9.06	8.98	9.15
800	2.04	16.18	15.31	15.48	1.90	22.14	21.61	21.81
1000	2.69	32.51	30.08	30.42	2.72	46.95	45.94	46.15
Rotations (n)	Agitation power-gross							
	Modified Propeller - MP - 3.1				"Clover" Propeller - PD - 4.1			
	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%
min^{-1}	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
200	0.59	0.66	0.74	0.85	0.66	0.78	0.85	0.95
400	1.05	2.06	2.11	2.20	1.11	3.07	3.33	3.50
600	1.61	4.66	4.98	5.20	1.67	9.01	9.20	9.35
800	2.10	9.41	9.98	10.15	2.31	19.90	20.90	21.21
1000	2.75	18.26	18.56	18.75	2.79	38.10	40.35	42.40
Rotations (n)	Agitation power-net							
	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%	Power (idle)	Water	Emulsion- 20%/80%	Emulsion- 40%/60%
	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
min^{-1}	(W)	(W)	(W)	(W)	(W)	(W)	(W)	(W)
200	0.59	0.07	0.15	0.26	0.66	0.12	0.19	0.29
400	1.05	1.01	1.06	1.15	1.11	1.96	2.22	2.40
600	1.61	3.05	3.37	3.59	1.67	7.34	7.53	7.68
800	2.10	7.31	7.88	8.05	2.31	17.59	18.59	18.90
1000	2.75	15.52	15.82	16.01	2.79	35.31	37.56	39.61

Figures 8 a–c present the experimental data for $P = f(n)$ for the two investigated systems: mixing of water and emulsions (with 20% and vegetable oil and 80% water, and 40% vegetable oil and 60 % water, respectively) at temperature $T = 20\text{ }^{\circ}\text{C}$. Power was recorded during both increasing and decreasing shaft rotational speeds from 200 to 1000 min^{-1} . The rotation frequency was controlled by an infrared non-contact tachometer (Kraychev, 2023).

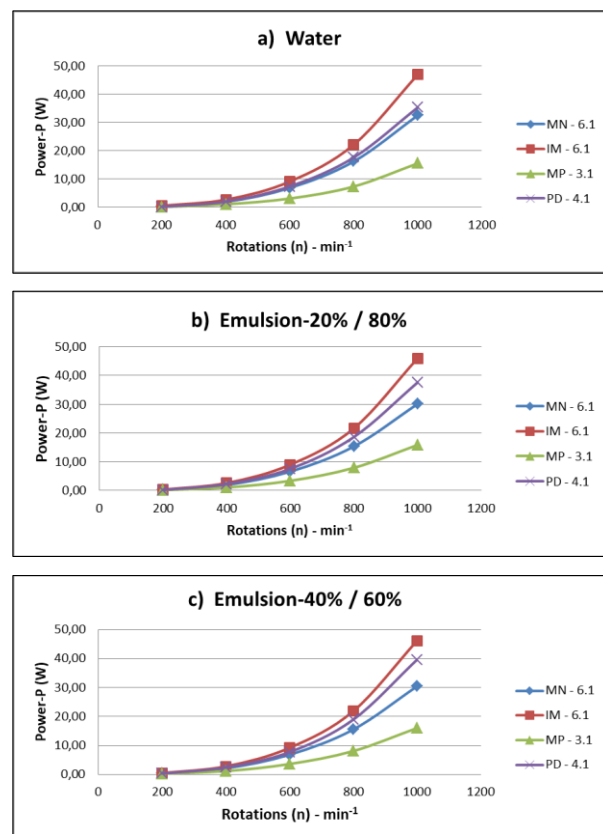


Fig.8. Experimental data for net consumed power (P) for four impeller series during mixing of: a) water; b) 20% vegetable oil emulsion in water; c) 40% vegetable oil emulsion in water

The calculated power numbers K_N (Equation 1) are presented graphically in Fig. 9 a–c as a function of Reynolds number (Equation 2).

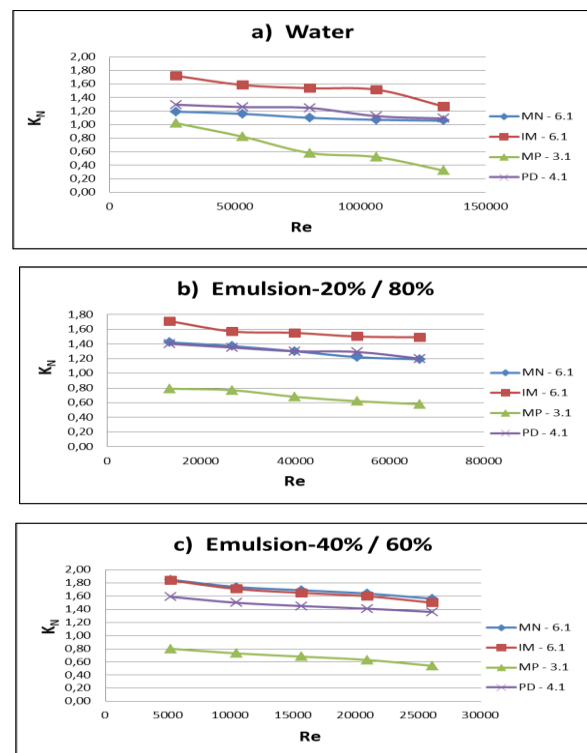


Fig.9. Dependence of $K_N = f(\text{Re})$ for four impeller series under standard reactor configuration during mixing of: a) water; b) 20% vegetable oil emulsion; c) 40% vegetable oil emulsion

Conclusion

Within the scope of this study, new designs of energy-saving impellers were constructed, manufactured, and experimentally characterised. The power number K_N was determined and analysed for four series of modified impellers tested in a laboratory reactor equipped with a horizontally wound copper coil. The obtained K_N values can be used in engineering calculations for determining the theoretical mixing power.

The results demonstrate improved power characteristics under identical operating conditions and comparable Reynolds numbers, which characterise the hydrodynamic mode (laminar, transitional, or turbulent).

From the presented graphical relationships, it is established that at identical rotational speeds and under different operating conditions, the newly developed mixing devices require significantly lower power.

In the working range $Re_0 > 5000 \div 150000$, corresponding to peripheral velocities $3.3 < V_p < 4.5$ m/s, the impellers exhibit $K_N < 1.2$, classifying them as energy-saving mixing devices and confirming their efficiency under turbulent flow conditions.

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