RESEARCH AND EXPERIMENTAL DETERMINATION OF THE OXYGEN MASS TRANSFER COEFFICIENT K_LA OF A NEW TYPE OF STIRRING DEVICE WITH A PLANETARY MECHANISM

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ABSTRACT. The article presents the results regarding a research work and the experimental determining of the coefficient of mass transfer of oxygen KLa, for a new type of stirring device with a planetary mechanism. The stirring device is implemented in a laboratory reactor with a horizontal copper coil and a construction representing a planetary mechanism on which three energy-saving stirring *KS 3.1 PM* devices are mounted. Three different stirring and aeration modes were studied in a bioreactor for deep cultivation of aerobic microorganisms. The results obtained for the K_La value showed the highest values under combined aeration. The application of the studied stirrer is expected to be in the field of wastewater treatment and in aerobic bioreactors for the biotechnology industry.

Keywords: Oxygen mass transfer coefficient, bioreactor, stirring planetary mechanism, combined aeration.

ИЗСЛЕДВАНЕ И ОПИТНО ОПРЕДЕЛЯНЕ НА КОЕФИЦИЕНТА НА МАСОПРЕНАСЯНЕ ПО КИСЛОРОД K_LA, НА НОВ ТИП ПРОПЕЛЕРНА БЪРКАЧКА С ПЛАНЕТАРЕН МЕХАНИЗЪМ

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РЕЗЮМЕ. . В настоящата публикация са представени резултати относно изследване и опитно определяне на коефициента на масопренасяне по кислорород kLa за нов тип разбъркващо устройство с планетарен механизъм. Разбъркването се осъществява в лабораторен реактор с хоризонтално навита медна серпентина и конструкция представляваща планатарен механизъм на които са монтирани три енергоспестяващи бъркачки „КС 3.1 ПМ“. Изследвани са 3 различни режима на разбъркване и аерация в биореактор за дълбочинно култивиране на аеробни микроорганизми. Получените резултати за стойността на KLa показват най високи стойности при комбинирана аерация. Очаква се приложението на изследваната бъркачка да бъде в областта на пречистване на отпадъчни води и в аеробни биореактори за биотехнологичната промишленост.

Ключови думи: Коефициент на масопренасяне по кислород, биореактор, планетарен механизъм за разбъркване, комбинирана аерация.

Introduction

One of the main factors for the successful operation of gas-liquid reactors is mass transfer in the gas-liquid system, which in turn depends on the hydrodynamic picture in the reactors, the mixing of phases, and the physicochemical properties of the medium. Determining the volumetric coefficient KLa in gas-liquid bioreactors is essential in order to establish the efficiency of aeration and to assess the influence of operating parameters on oxygen delivery in the system (Zedníková et al., 2018).

A major challenge is to develop a model that accurately describes the physical nature of mixing in two-phase reactors, takes into account the influence of multiple parameters, and is consistent with a wide range of experimental data. The contact between the two phases (liquid and gas) in the bioreactor primarily depends on its type, the stirring speed, and the gas bubble formation. Additionally, a third phase (solid particles) can be added, forming various suspensions that are stirred and, in some cases, form emulsions, depending on the solubility of the solid phase in different fluids.

The stirring is carried out by an agitator, which is an improved model of an energy-saving blade agitator with radial, axial, and tangential movements during mixing.

The mixing process is carried out by an innovative stirring device, which consists of a planetary mechanism mounted in an aluminium housing with three working elements. The three propeller stirrers also have a specific geometry and simultaneously perform rotational movement around their own axis and along an external gear ring (Fig. 1). In this way, radial, axial, and tangential velocity components are superimposed (Kraychev, 2023). Due to the special shape of the blades, the stirred medium is attacked with the so-called "cutting edge".

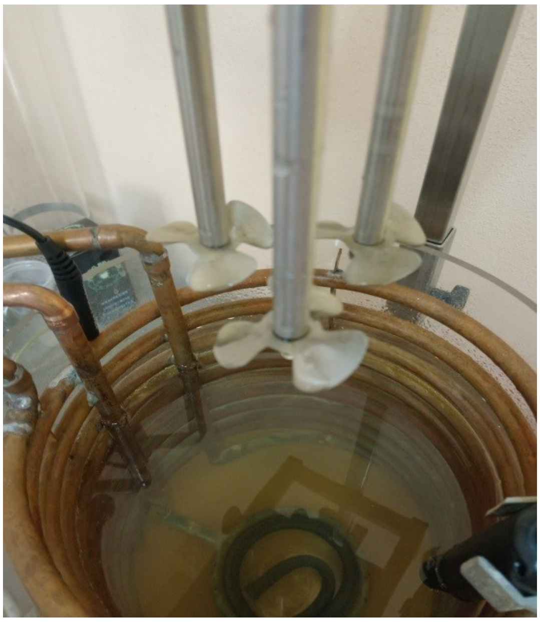

Fig. 1. Picture of the new stirring device with three working bodies.

Experimental studies and test results regarding the hydrodynamic characteristics of the *KS 3.1 PM* device have been compared with classic stirrers, such as the six-blade *Rushton* turbine, the *Interprop*, I*ntermig*, *Eleron-1* and *2*, and *NRE-KM* (Kraychev, 2014).

Typically, the rate of oxygen mass transfer occurs across the entire contact surface and relates to the working volume of the bioreactor. The driving force of this process is the difference between the equilibrium concentration and the current concentration of oxygen in the liquid phase:

$$\frac{dC_L}{dt} = k_L a\left(C_L^* - C_L\right) \quad (1)$$

The proportionality coefficient k_La is called the volumetric mass transfer coefficient of oxygen and plays a significant role in aerobic processes, where C* and C_L are the equilibrium and current oxygen concentrations, respectively. Several authors (Law et al., 2004; Vandu & Krishna, 2004) highlight the so-called "start-up dynamic method" as one of the most effective for determining K_La.

The main objective of the current study is to determine the influence on the value of the oxygen mass transfer coefficient (K_La) under different aeration and mixing conditions using a new type of propeller stirrer with a planetary mechanism.

Materials and methods

To achieve the objectives, the experiments were conducted in a laboratory installation (Fig. 1) including a laboratory semi-industrial reactor (1) with a volume of V_R=14.3 dm^3, made of plexiglass for better visualisation of the processes. The internal diameter of the reactor is 260 mm. It is standardly equipped with four baffle plates (deflectors) and a horizontally coiled copper coil with a length of L_{coil} = 7.94 m. The baffles serve to avoid the "funnel effect" (liquid vortex), and a sparger is installed at the bottom of the reactor to saturate the medium with oxygen using an air pump (3) with a maximum flow rate of 3.5 dm^3/60s.

To determine the volumetric mass transfer coefficient K_La in the reactor, a variant of the dynamic method ("start-up dynamic method") based on the oxygen balance in the liquid phase was used (Vandu & Krishna, 2004). For the purposes of the measurement, different aeration conditions were maintained, under which the concentration of dissolved oxygen reached a steady-state value.

The method was carried out as follows: initially, the dissolved oxygen in the liquid phase was removed by purging with N_2 (2) until the dissolved oxygen content reached 0.1 – 0.05 mg/l O_2. Then, the system was re-aerated, and the concentration of dissolved oxygen CL was immediately measured using an oxygen optical sensor – *Vernier*^{R} *DO-BTA* (7) and the *Logger Pro*^{TM} and *LabQuest* interface. The data ~~are~~ were recorded on a computer equipped with the *Logger Pro*^{TM} software (6).

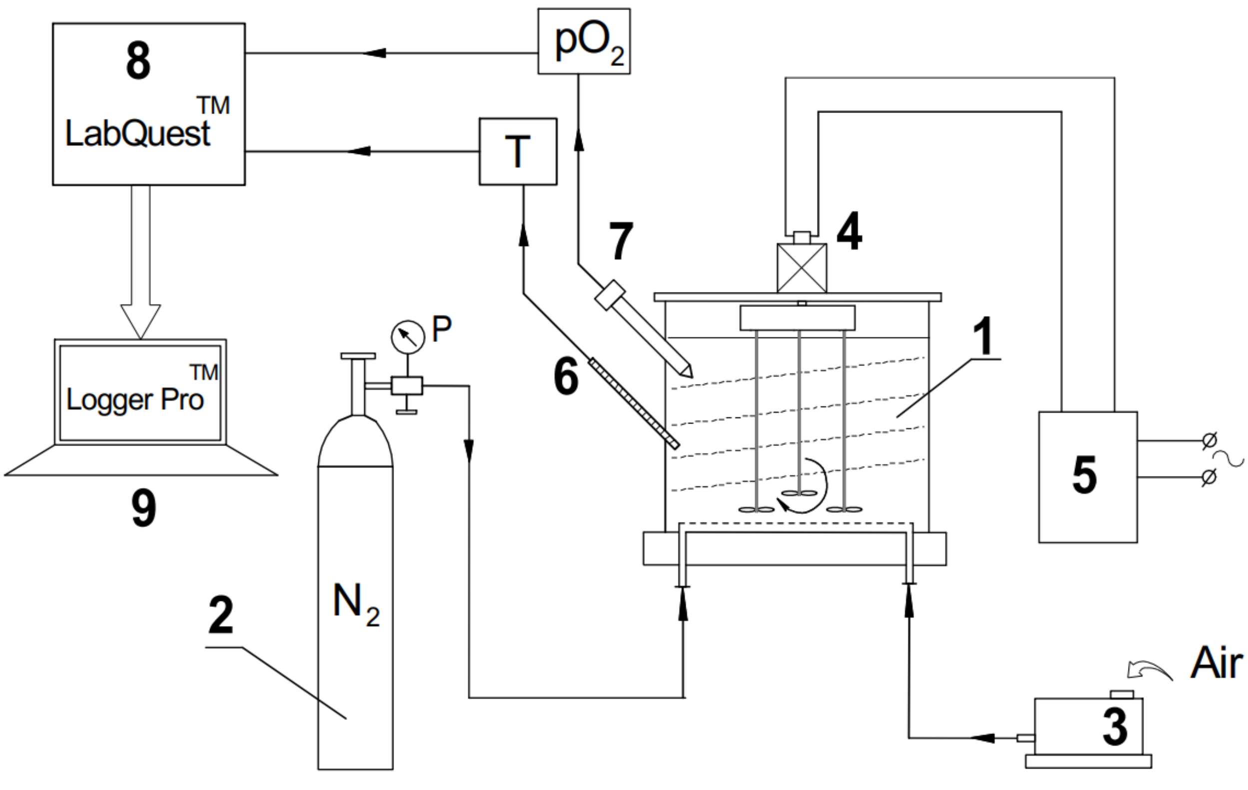

Fig.2. Scheme of the laboratory installation. 1 – bioreactor with the stirrer- type *KS 3.1 PM*; 2 – nitrogen bottle; 3 – air pump; 4 – direct current motor; 5 – adjustable DC power supply, 6- temperature sensor, 7 – *Vernier DO-BTA* oxygen optical sensor; 8 – *LabQuest* interface, 9 – computer with the *Logger Pro* data recording software

The stirring speed was regulated by an autotransformer (5) and ranged from 340 to 360 rpm, while the design of the KS 3.1 PM stirrer included three stirring shafts mounted on a planetary mechanism (8). The blades of the stirring propellers (with a diameter of 40 mm) transferred the liquid to each other, with movement in radial, axial, and tangential directions (Fig. 3 and 4). The diameter of the external gear (crown) was 90 mm, the planetary gears had a diameter of 35 mm, and the diameter of the gear on the input shaft was 20 mm. The actual stirring power was 26.2 W.

Fig. 3. Picture of the experimental setup.

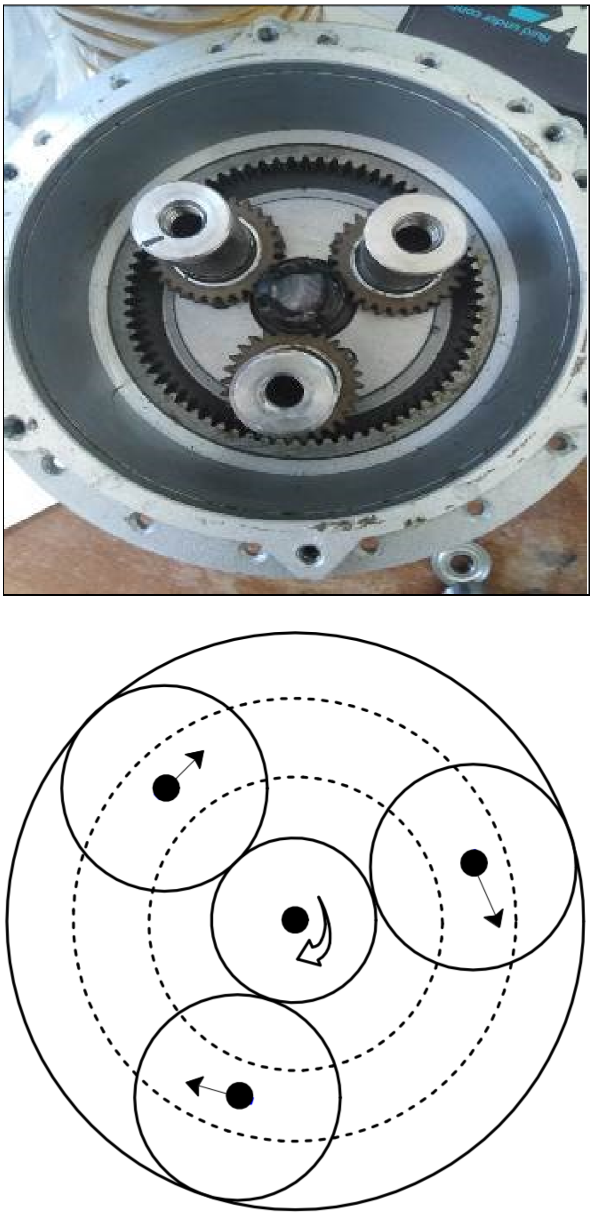

Fig. 4. Planetary mechanism of the KS 3.1 PM stirrer.

The three-blade propeller, conditionally called the "three-leaf clover" (Fig.5), was made of high-quality stainless steel, and the blades were cut and processed with high precision using a state-of-the-art laser (HARIS-1000).

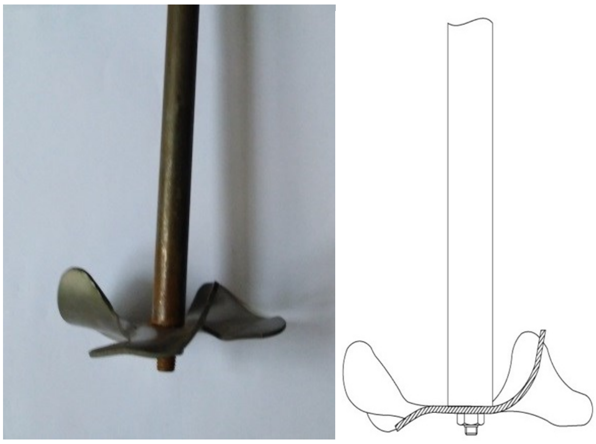

Fig. 5. Propeller of the KS 3.1 PM stirrer.

The mechanics of the stirrer, as well as the hydrodynamics, were presented in a previous publication (Kraychev, 2023). Measurements continued until the equilibrium concentration of oxygen was reached. The process is described by equation (1), and after its integration at t=0, C_L*=const, and C_L=C_L,0, assuming that initially there was no oxygen in the liquid phase C_L,0 = 0, we obtain:

$$\ln\left[\frac{C_L^*}{C_L^* - C_L}\right] = k_L a.t \qquad (2)$$

A graph of as a function of the time t was plotted, and from the slope of the resulting line, the volumetric mass transfer coefficient $k_L a$ was calculated. The optimal stirring speed in stationary mode was chosen in the range of 340-360 rpm from a hydrodynamic perspective. The temperature of the fluid during the experiments was in the range of 16.9 - 21.7 °C. The density of water was 997 kg/m³. Experiments with emulsions of water and vegetable oil in different ratios with varying viscosities were also conducted.

The application of the stirring device is very broad, for example, for aeration in wastewater Aerated Basin, or for suspending and aerating nutrient media in bioreactors for deep cultivation of microorganisms. Another application is in the pharmaceutical industry, specifically in the production of antibiotics, where the stirring time can reach up to 260 hours.

Results and Discussion

The obtained results are presented in Figs. 6, 7, 8, 9, 10 and Table 1. They show the highest values of the mass transfer coefficient for the variant with a maximum air flow rate of 3.5 dm³/60s and stirring.

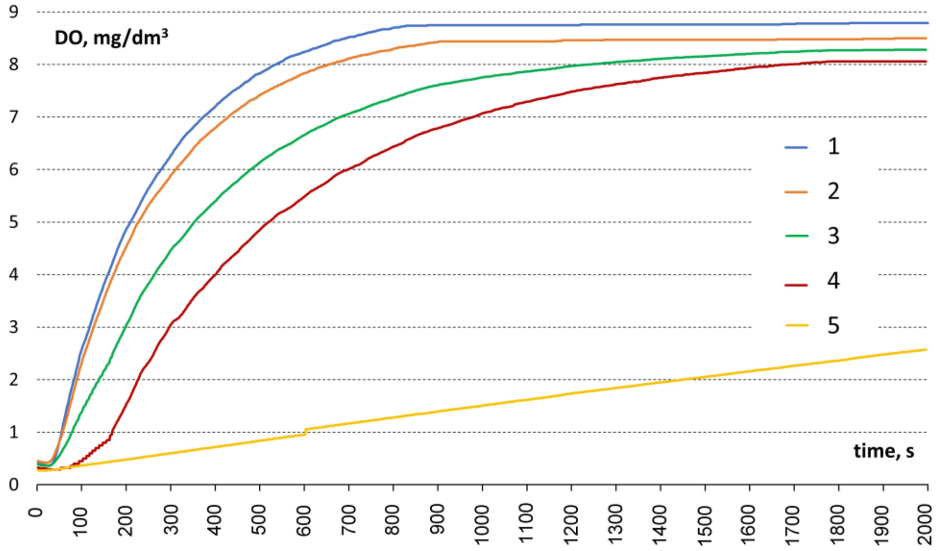

Fig. 6. The change in the dissolved oxygen concentration under different aeration conditions. 1 - values of dissolved oxygen for the variant with stirring and an air flow rate of 3.5 dm³/60s; 2 - values of dissolved oxygen for the variant with stirring and an air flow rate of 1.75 dm³/60s; 3 - values of dissolved oxygen for the variant without stirring and with an air flow rate of 3. 5 dm³/60s; 4 - values of dissolved oxygen for the variant without stirring and an air flow rate of 1.75 dm³/60s; 5 - values of dissolved oxygen for the variant with stirring and without additional air supply.

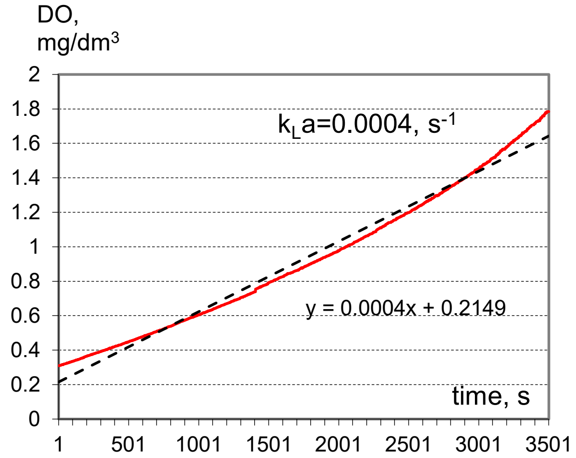

Fig. 7. Time values of dissolved oxygen and K_La for the variant with stirring, without additional air supply.

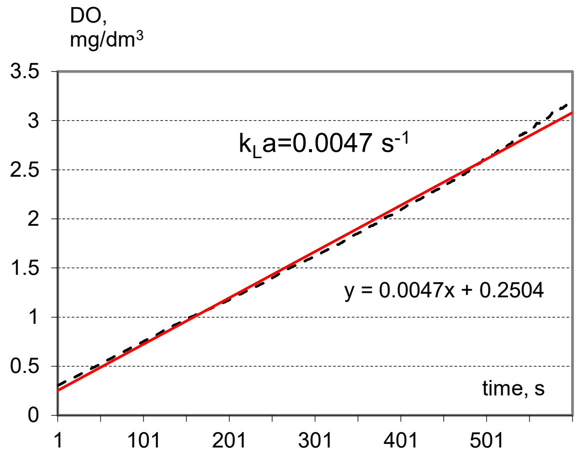

Fig. 9. Time values of dissolved oxygen and K_La for the variant without stirring and a maximum air flow rate of 3.5 dm³/60s.

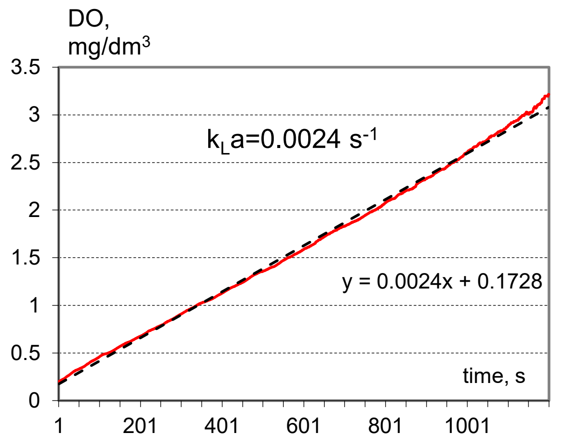

Fig. 8. Time values of dissolved oxygen and K_La for the variant without stirring and with an air flow rate of 1.75 dm³/60s.

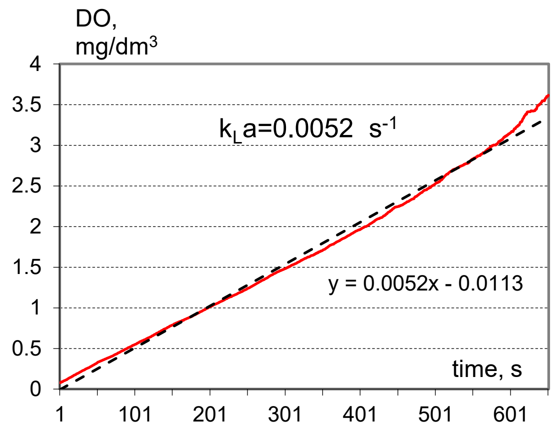

Fig. 10. Time values of dissolved oxygen and K_La for the variant with stirring and a maximum air flow rate of 3.5 dm³/60s.

The results obtained from the four variants of energy input through the gas and liquid phases in the bioreactor show significant differences in terms of the time required to reach the equilibrium concentration of oxygen in the medium (Fig. 6). Specifically, in the variant without air supply (stirring only), it was found that the potential for air injection into the medium by the tested stirrer was not sufficiently high, and within the standard measurement time of 2000 s, the experimentally established equilibrium oxygen saturation concentration of 8.1-8.6 mg/dm³ was not reached. This variant also showed the lowest value of kLa= 0.0004 s^{-1} (Fig. 7).

In the variant without stirring and with an air flow rate of 1.75 dm³/60s (Fig. 8), the equilibrium concentration of oxygen was reached after 901 s, with a kLa value of 0.0024 s^{-1}. In the identical variant with stirring and an air flow rate of 1.75 dm³/60s (Table 1), the k_La value reached 0.0027 s^{-1}.

Table 1. Values of K_La for different stirring and aeration variants.

Aeration mode	Without aeration	Aeration 1,75 dm³/60s	Aeration 3,5 dm³/60s
K_La, s^{-1}			
With stirring	0,0004	0,0027	0,0052
Without stirring	-	0,0024	0,0047

The best results were obtained in the variants with stirring and two different air flow rates. The equilibrium concentration of oxygen at the lower flow rate (1.75 dm³/60s) was reached after 827 s, whereas at the higher flow rate (3.5 dm³/60s) it was reached after 725 s. These two variants also showed the highest K_La values, respectively 0.0047 s^{-1} and 0.0052 s^{-1} (Figs. 9 and 10, and Table 1).

In similar studies conducted with a column-type photobioreactor (Angelov et al., 2019), similar results were obtained for the oxygen mass transfer coefficient in the range of 0.0060-0.0067 s^{-1}, which can be explained by the longer residence time of the gas phase in the column-type bioreactor.

Conclusion

A new stirring device with a planetary mechanism and three working elements (propeller stirrers) with specific, modified blade geometry has been designed, developed, and put into operation. The oxygen mass transfer coefficient, K_La, s^{-1}, was experimentally determined and tested. According to the results from the experimental studies, the *KS 3.1 PM* propeller stirrer belongs to the category of energy-saving stirrers due to its power coefficient and dimensionless Reynolds number.

In general, its application is in the chemical, pharmaceutical, food, and biotechnological industries.

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