Power consumption for non-aerated Na-CMC solutions in multiple bioreactors agitated
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Power consumption for non-aerated Na-CMC solutions in multiple bioreactors agitated

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Abstract

Multiple impeller vessels are generally used in many industries. Among the criteria usable for characterization of mixing processes the mixing power requirement and relation between hydrodynamics of agitators and power requirements are of first importance. The experimental obtained data showed that in double impeller systems the power consumption depends on a distance between impellers. The optimal distance between impellers with the smallest power consumption has been proposed. For three and more impellers it has been shown that mixing power depends on number of impellers.

Keywords: mixing, multiple impellers, power consumption, Na-CMC

1. Introduction

Mixing process is one of the commonly used processes in industries as well in human life. Especially multiple agitators are used in many industries, because of the advantages of the longer residence time, lower decrease of heat exchange area in scale-up treatment, lower power consumption per impeller as compared to single impeller systems. These systems are in the point of interest of biochemical industry, because among the others in such systems the mass transfer coefficient is higher in comparison with single impeller vessels. In the multiple-impeller system a number of independent circulation loops occurs with mass exchange between them. Each loop can be considered as the single tank, and the exchange flow rate between these tanks has a main influence on mixing time.

Mixing in bioreactors is very complicated because in such systems the rheological parameters depend on shear stress. By reason of rheological behavior of systems the accuracy of the proposed models is limited. The power law fluids, especially carboxymethylcellulose sodium salt solutions (Na-CMC), are widely used in the broths simulations in biotechnology. The rheological properties of these liquids can be determined using the power law equation, which is given as:

$$\tau = K\gamma^{m} \tag{1}$$

while

$$\eta_p = K\gamma^{m-1} \tag{2}$$

$$\gamma = kN \tag{3}$$

where K is the consistency factor, m – the flow index, γ – the shear rate, τ – the shear stress, η_p – the apparent viscosity and k is the Metzner and Otto (1957) constant. Mixing of such fluids (Metzner and Otto, 1957; Wassmer and Hungenberg, 2005) is very complicated. It has been already reported that elasticity increases the torque required for mixing (Collias and Prud'homme, 1985). It was found that fluids with pseudoplastic behaviour create small circulation paths around blades and the circulation flow rate decreases (Takahashi *et al*., 1989).

The power consumed by the agitator is usually determined by torque measurements either with the help of a strain gauge (Linek *et al*., 1996; Davies *et al*., 1985) by a torque meter mounted on the impeller shaft (Singh *et al*., 1986; Nocentini *et al*., 1988) or by balancing the rotational movement of the vessel. Arjunwadkar *et al*. (1998) used an ac/dc transducer working on the principle of Hall's effect. Pinelli, Nocentini and Magelli (1994) used a simple technique of measuring the restraining torque necessary to prevent the vessel from rotating with respect to a stationary vessel by means of a load cell.

In many situations the correct knowledge of the power consumption is needed for better design and operation of the agitated vessel with multiple impellers. The vessel with multiple impellers has many unknown factors, i.e. the best set-up positions of impellers, the best combinations of impellers, etc.

The aim of this work was to investigate the power characteristics of turbine impeller systems in carboxymethylcellulose sodium salt (Na-CMC) solutions for multiple impeller (two to five) vessels. Moreover, for double systems the relation of distance between impellers and power consumption was taken into account.

2. Experimental part

The experimental set-up (Fig. 1) consisted of motor, inverter, speed sensor, PC computers, interface, torquemeter. The vessel with diameter T = 0.19 m was equipped with flat bottom. The four baffles of 0.1T width were used and the clearance from the vessel wall was 0.02T. The height of liquid level was taken 2.3T. The three types of impellers were used: Rushton turbine (RT), six flat blade turbine (FBT) and six pitched down blade turbine (PBT). Impellers were mounted on common shaft (D_S = 0.012 m) in two, three, four and five combinations of one type impeller. The ratio of impeller diameter (D = 0.065 m) to vessel diameter was D/T = 0.342. The dimensions of impellers (Fig. 2) used are given in Table 1.

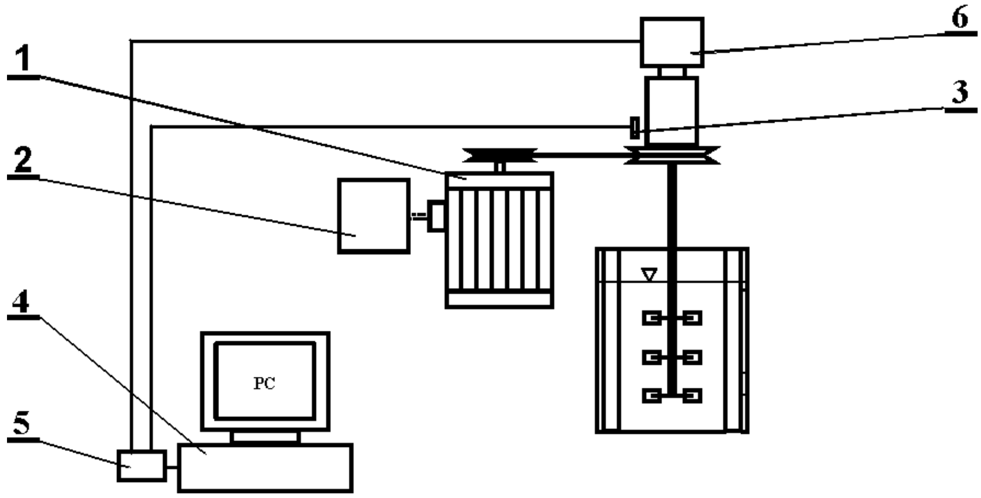

Fig. 1. Measurement set-up: 1 - motor, 2 – inverter, 3 – turning sensor, 4 - IBM PC computer, 5 – transmitter, 6 – torquemeter

a) b) c)

Fig. 2. Impellers used: a) RT, b) FBT, c) PBT

Table 1. Geometric parameters of impellers

Type	Diameter *D* m	Height of blade m	Length of blades m	Angle or pitch of blade
RT	0.065	0.013	0.016	90°
FBT	0.065	0.008	0.025	90°
PBT	0.065	0.008	0.025	45°

As non-Newtonian fluids the aqueous solutions of carboxymethylcellulose sodium salt (Na-CMC, delivered by Sigma-Aldrich Company) were used. The characteristics of non-Newtonian fluids agitated have been shown in Table 2. An electric power *P* required to drive an electromotor coupled with the shaft of the agitated vessel has been calculated on the basis of the knowledge of power characteristics which should be determined for a given type of impeller.

Table 2. Characteristics of the non-Newtonian fluids used

Medium	Molecular weight	Aqueous solution concentration C_p	Temperature T	Flow behaviour index m	Consistency coefficient K	Density ρ
		%	[K]	-	[Pa·s^m]	[kg/m^3]
Na-CMC	250,000	0.5	293	0.71	0.15	996.2
		0.8		0.68	0.44	999
		1.1		0.63	0.73	1004.8
		1.4		0.62	1.16	1007.4
		1.7		0.62	1.64	1012

The experimental results of the power consumption are usually presented in the form of a dimensionless equation

$$Ne_m = ARe_m^B Fr_m^C \tag{4}$$

where dimensionless numbers are defined as follows:

$$Ne_m = \frac{P}{N^3 D^5 \rho} \tag{5}$$

$$Re_m = (4\pi)^{1-m} \frac{ND^{2-m}\rho}{K} \tag{6}$$

$$Fr_m = \frac{N^2 D}{g} \tag{7}$$

and power consumption P is determined from the equation

$$P = 2\pi NM \tag{8}$$

In turbulent flow regime in the agitated vessel equipped with baffles, exponents B and C are equal to zero, then Eq. (4) simplifies to

$$Ne_m = const \tag{9}$$

In the transitional flow regime the power number is dependent on Reynolds and Froude numbers.

3. Results and discussion

The investigation has been performed in the transitional flow regime ($100 < Re_m < 10000$). Figs. 3 and 4 show the plot of power number Ne_m vs. Reynolds number for double RT and PBT systems. In the transitional flow regime $100 < Re_m < 3000$ it is interesting that the power number values remain practically unchanged. This relation is valid for radial and axial double impeller systems. The results of Nienow *et al.* (1995) support these observations. It has been shown that power number values for RT-RT, FBT-FBT and PBT-PBT are lower in transitional flow regime compared with these in turbulent flow. Ibrahim and Nienow (1995) attribute this to the reduction in the rate of shedding of trailing vortices in the transitional flow regime, which reduces the pressure difference between the front and backside of the blades, and to the lower power dissipation.

Hudcova *et al*. (1989) showed that in dual impeller system the power number increases and reaches the individual additive power as the impeller spacing increases.

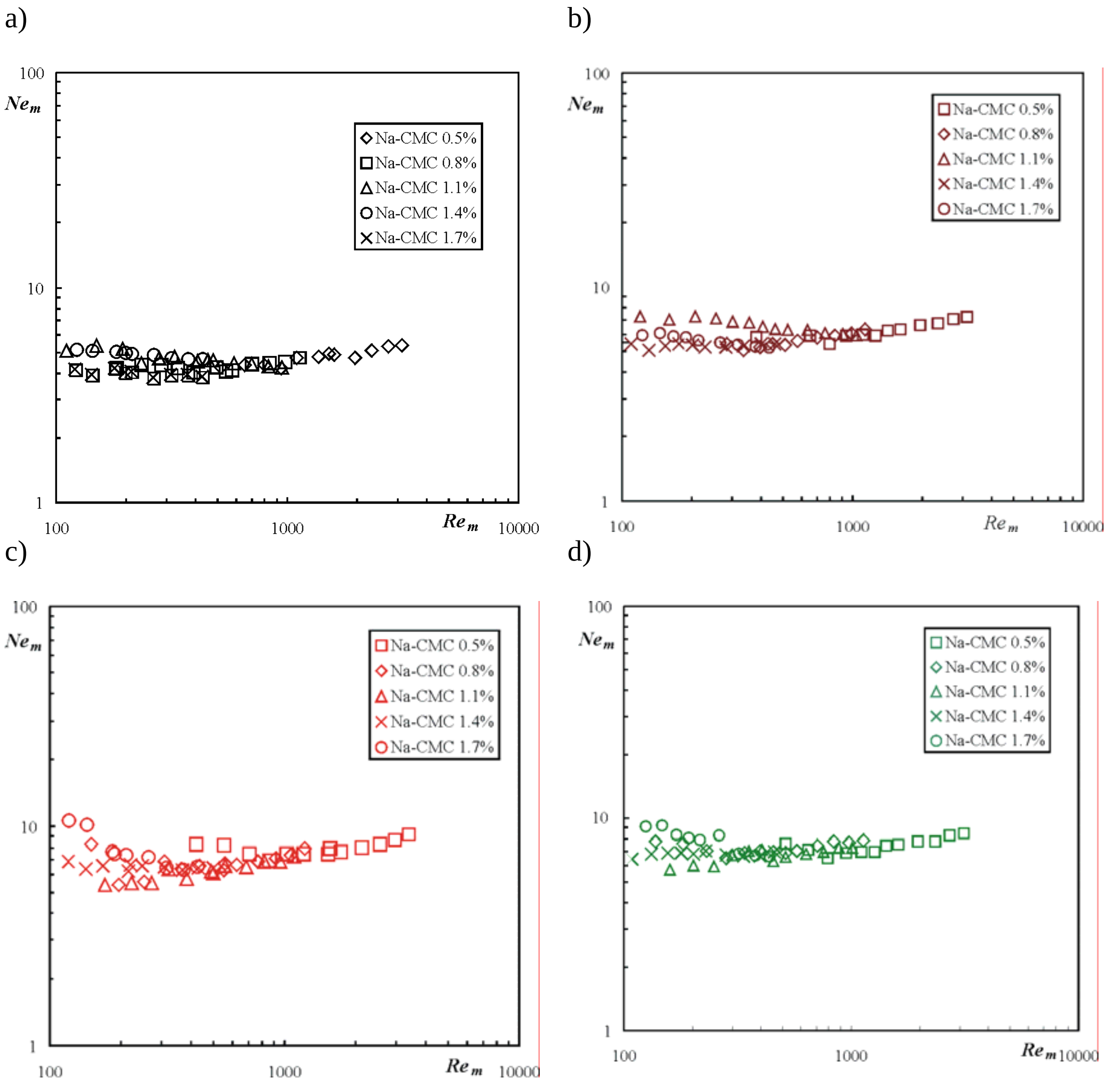

Fig. 3. The power characteristics of double RT system in function of distance between impellers:
a) $\Delta h/D$ = 1, b) $\Delta h/D$ = 2, c) $\Delta h/D$ = 3, d) $\Delta h/D$ = 4

If the impeller spacing is in the range of $0.5 < \Delta h/D < 1.5$, one circulation loop per impeller has been found with the discharge from the lower impeller leaving at 45º upwards from the horizontal and that from the upper leaving at 45º downwards, with solid body rotation of the liquid between them. These observations are partially confirmed. The power number values increase with a distance between impellers, while the change of these values is about 50% for radial impellers and about 100% for axial impellers.

According to the literature data, the mixing power reduction occurs in range of $Re_m \in (100, 200)$ (Metzner and Otto, 1957; Calderbank and Moo-Young, 1961; Broniarz-Press *et al*., 1997; Paul *et al*., 2003). For double Rushton turbine systems the relation between power number and Reynolds number can be described by $Ne_m \propto Re_m^{-0.1}$ while for FBT's and PBT's this relation is $Ne_m \propto Re_m^{-0.25}$.

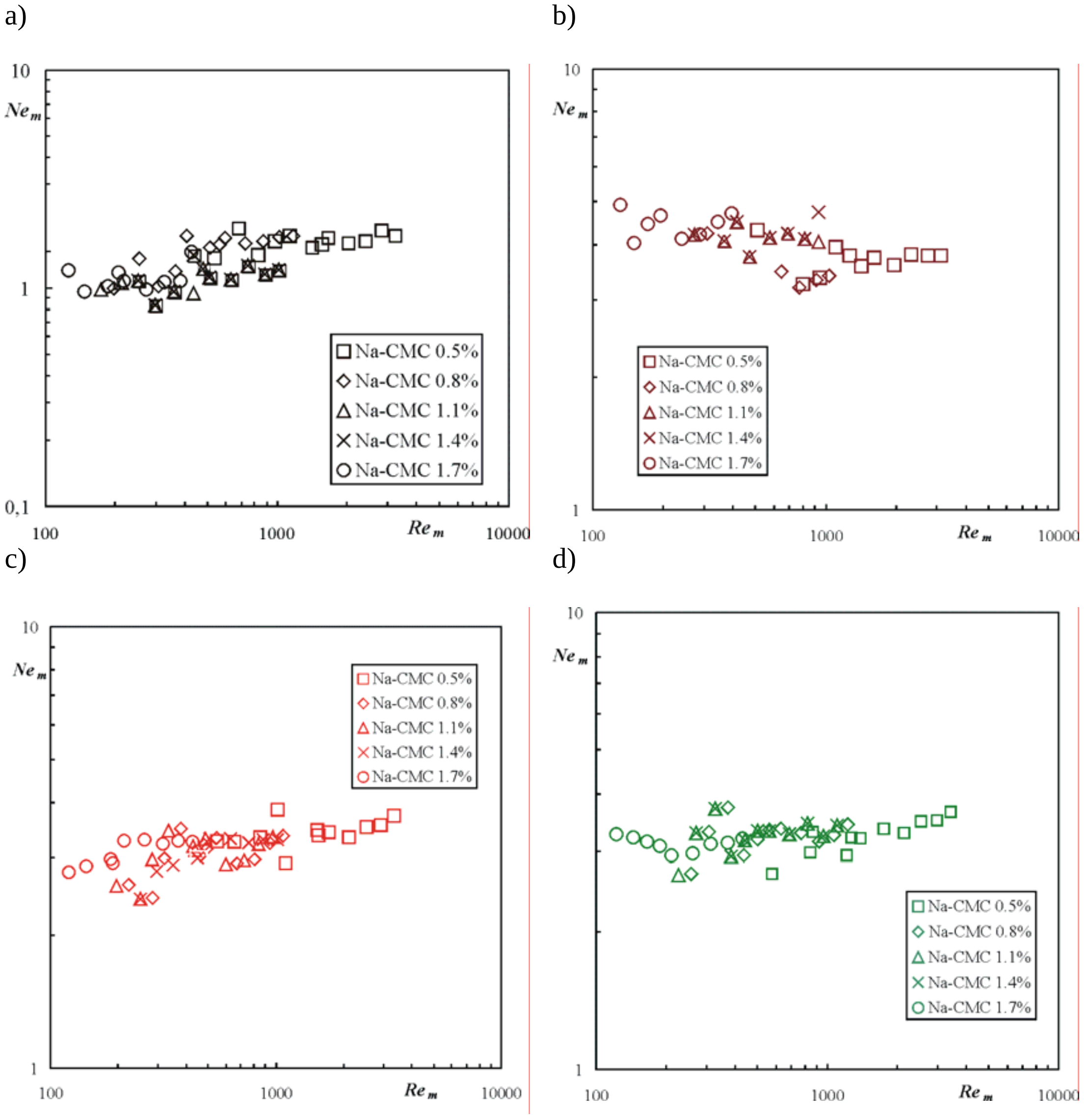

Fig. 4. The power characteristics of double PBT system in function of distance between impellers:
a) $\Delta h/D = 1$, b) $\Delta h/D = 2$, c) $\Delta h/D = 3$, d) $\Delta h/D = 4$

For vessels equipped with three, four and five impellers it has been found that the mixing power reduction is smaller in comparison with double impeller systems (Fig. 5). Armenante and Mazzarotta (1999) have also shown that the power consumption in the multiple-impeller systems is inversely proportional to the impeller spacing. They have shown that the power number for the impeller increases with the decrease in the clearance of the bottom impeller and increase in the impeller spacing. The effect of impeller clearance can be explained by the throttling effect which indicates that there is a change in the direction of the flow when the downward jet discharged by the impeller impinges on the tank bottom. If the clearance is smaller, the change in the flow direction is more abrupt, generating more turbulence resulting in increased power consumption of the lower impeller.

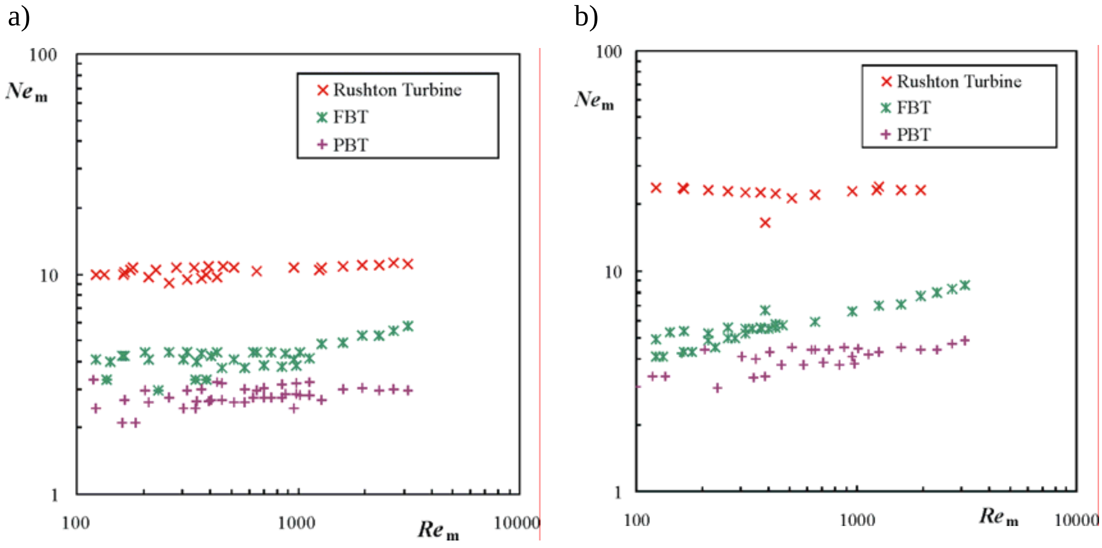

Fig. 5. The exemplary relation $Ne_m = f(Re_m)$ for: a) three impeller systems, b) five impeller systems

The enlargement of number of impellers causes the reduction of distance between them. The hydrodynamic conditions in such systems have the major effect on mixing power. It has been shown that mixing power for three and more impellers is not proportional to the number of impellers. The hydrodynamic interactions between particular impellers causes the reduction in total power requirements.

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