# Reciprocating plate column – fundamental research and application in Serbia from 1970 to 2020

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*Abstract*

In the group of multiphase contactors and reactors, an important place belongs to reciprocating plate columns (RPCs), which consist of a set of perforated plates fixed on a carrier (the so-called reciprocating or vibrating agitator) moving periodically up and down through a column. This construction maximizes the positive effects of mechanical agitation and minimizes or eliminates the adverse effects characteristic of column-type contactors and reactors. In RPCs, the highest dispersed-phase holdup is achieved at a lower dispersed-phase velocity due to the influence of mechanical agitation on the bubble or drop comminution. Therefore, this device can be the most acceptable contactor or reactor for performing complex actions in multiphase systems. The paper reviews the fundamental research and application of RPCs in Serbia in the last fifty years, from 1970 to 2020. Hydrodynamic and mass-transfer characteristics are analyzed, such as the pressure variation at the column bottom, power consumption, dispersed-phase holdup, axial dispersion, liquid mass transfer coefficient, specific interfacial area, and volumetric mass transfer coefficient. The use of RPCs as reactors in bioprocesses and biodiesel production processes is also discussed.

*Keywords:* Reciprocating plate agitator, pressure variation, power consumption, dispersed-phase holdup, axial dispersion, volumetric mass transfer coefficient

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## 1. INTRODUCTION

Various mechanical agitation methods improve mass transfer in multiphase contactors and reactors. Mechanical agitation is often performed using a rotating agitator (stirred vessels) or perforated plates fixed on a reciprocating (vibrating) plate carrier moving up and down through a column (so-called reciprocating plate columns, RPCs). Compared to bubble columns, a significantly higher gas holdup and larger specific interfacial area can be achieved in RPCs [1,2]. Additional advantages of RPCs over bubble columns are reduced backmixing [3], a prolonged bubble residence time in the dispersion, and a greater contact area between the phases [4]. Moreover, RPCs are characterized by ease of maintenance, simple construction, the possibility of applying large fluid flows, and a simple scale-up procedure [4].

The axial reciprocating motion of a set of perforated plates through a column was patented in 1935 [5]. However, this device remained unused until 1959, when Karr developed an extraction RPC with perforated plates of a large free surface area [6]. Since then, the application of RPCs as extractors has increased because a uniform dispersion, with little axial mixing, is achieved with a relatively little external energy input. Since the 1960s, RPCs with different reciprocating elements (Table S-1, Supplementary Material) have been studied as absorption columns. In the 1980s, 'pure' liquids were used, while later, the gassed systems (gas-liquid and gas-liquid-solid particles) were tested. Newtonian liquids, most frequently water, were mainly used as the liquid phase, while spherical particles and Raschig rings were used as the solid phase.

The first tests of Karr-type RPCs as liquid-liquid extractors in Serbia were conducted on the pressure variation at the column bottom (PVCB) and power consumption [7,8]. Then, studies of gas-liquid [3,9] and gas-liquid-solid phase [10-16] systems were conducted to understand the hydrodynamic and oxygen mass transfer phenomena. After that, RPCs were

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tested as reactors for biodiesel production [17-20]. Table S-2 overviews the previous research on hydrodynamics, mass transfer, and applications of RPCs in Serbia.

This paper reviews the fundamental research and application of RPCs in Serbia in the last fifty years, from 1970 to 2020. Both hydrodynamic and mass-transfer characteristics are analyzed, such as the PVCB, power consumption, dispersed-phase holdup, axial dispersion, liquid mass transfer coefficient, specific interfacial area, and volumetric mass transfer coefficient. The analysis mainly focuses on 'pure' liquid, gas-liquid, and gas-liquid-solid systems, although some liquid-liquid systems are also discussed. In addition, the use of RPCs as reactors in bioprocesses and biodiesel production processes is also discussed.

## 2. HYDRODYNAMICS OF RPCS

The studies of the RPC hydrodynamics include regime and flow models, PVCB, power consumption, dispersed phase holdup, bubble size, and axial dispersion. Knowledge of PVCB is an additional requirement for large-scale device construction of equipment. Power consumption is essential for appraising the mechanical driving mechanism and the operating cost. Dispersed phase holdup is crucial for the dispersed phase retention time and specific gas-liquid interfacial area. Bubble size determines the interfacial area and the mass transfer rate, while axial dispersion is essential for the efficacy of RPCs.

### 2. 1. Flow regime and models

When a set of reciprocating plates moves through the column filled with a liquid, a characteristic flow develops between two perforated plates [21]. As the plates move upwards, liquid jets are induced in the plate openings, which are directed downwards; a ring vortex surrounds each jet. By changing the plate movement direction, the fluid flow direction in jets and ring vortices changes but not the fluid circulation inside vortices. During the plate movement, the liquid is exchanged between neighboring interplate spaces in the vertical direction due to the jet movement as well as in the horizontal direction due to the creation, destruction, and recreation of ring vortices, thus inducing an intensive liquid mixing in interplate spaces. The mixing intensity is enhanced by turbulence due to the shear forces at the jet and vortex interface. In multiphase RPCs, the flow is dependent on plate movement, superficial gas and liquid velocities, and solid particle type and content. In gas-liquid systems, when the direction of the jet is changed (twice in one cycle), gas bubbles are forced to move with the liquid, resulting in periodic repetition of coalescence and dispersion [21]. Visual examination of a gas-liquid dispersion shows several characteristic dispersion states depending on the reciprocating intensity and superficial gas velocity [22]: segregated (mixer-settler), homogeneous, cellular, and slug bubble dispersion.

The liquid flow through an RPC is usually described by the quasi-steady-state flow model [23]. It supposes the fully developed liquid flow, steady-state changes of the pressure at the column bottom and power consumption equal to the mean values over a long-time interval. This model is confirmed when the reciprocating amplitude exceeds 1 cm [24]. Therefore, for smaller reciprocating amplitudes, an alternative ‘acoustic’ flow model was developed [25], which assumes most of the external energy dissipation near the plates.

### 2. 2. The PVCB and power consumption

Several forces influence the PVCB [26]: inertia (because of the reciprocating plate movement and a part of the liquid near the plates), friction (which occurs in all mechanical contacts of plates with the column wall and liquid contacts with moving and stationary parts of the column), gravity, and buoyancy. The energy of mechanical agitation is determined based on the quasi-steady-state flow model [23]. The PVCB and power consumption depend on the amplitude and frequency of reciprocating movement, the system's physical properties, the solid particle type and concentration, the column's geometry, and the hydrodynamic flow conditions [27], as can be seen in Table 1.

The instantaneous PVCB depends on inertial and frictional components of the pressure variation [28]:

$$(p_2 - p_1) - \rho_l g(z_2 - z_1) = \rho_l n_p s_e \frac{1-\varepsilon}{\varepsilon}\left(\frac{du_s}{dt}\right) + n_p \rho_l \frac{1-\varepsilon^2}{2C_0^2\varepsilon^2} u_s \left|u_s\right| \tag{1}$$

while the instantaneous power consumption is equal to the product of the cross-sectional column area, instantaneous plate movement speed, and PVCB:

$$P = A_\mathrm{c}\left|\Delta p u_\mathrm{s}\right| = n_\mathrm{p}\rho_\mathrm{l}A_\mathrm{c}\frac{1\text{-}\varepsilon^2}{2C_0^2\varepsilon^2}{u_\mathrm{s}}^2\left|u_\mathrm{s}\right| \tag{2}$$

Adopting the assumptions of the quasi-steady-state flow model, the instantaneous PVCB and power consumption in RPCs filled with a ‘pure’ liquid are [28]:

$$\Delta p = n_\mathrm{p}\rho_\mathrm{l}\frac{1-\varepsilon^2}{2{C_0}^2\varepsilon^2}u_\mathrm{s}\left|u_\mathrm{s}\right| \tag{3}$$

$$P = n_\mathrm{p}\rho_\mathrm{l}A_\mathrm{c}\frac{1-\varepsilon^2}{2{C_0}^2\varepsilon^2}{u_\mathrm{s}}^2\left|u_\mathrm{s}\right| \tag{4}$$

The average and total PVCB ($\Delta p$ and $\Delta p^*$) and power consumption ($\bar{P}$ and $P^*$) are as follows [28]:

$$\Delta\bar{p} = n_\mathrm{p}\rho_\mathrm{l}\frac{1-\varepsilon^{2}}{2C_0^2\varepsilon^2}(2\pi Af)^2\left(\frac{1}{2}+\frac{4s}{3\pi}+\frac{s^2}{8}\right) \tag{5}$$

$$\Delta p^* = n_\mathrm{p}\rho_\mathrm{l}\frac{1-\varepsilon^2}{C_0^2\varepsilon^2}(2\pi Af)^2 \tag{6}$$

$$\bar{P} = \frac{16\pi^2}{3}n_\mathrm{p}\rho_\mathrm{l}A_\mathrm{c}\frac{1-\varepsilon^2}{C_0^2\varepsilon^2}(Af)^3\left(\frac{3}{5}s^2+1\right) \tag{7}$$

$$P = A_\mathrm{c}\Delta p^* u_\mathrm{s,m} = 8\pi^3 n_\mathrm{p}\rho_\mathrm{l}A_\mathrm{c}\frac{1-\varepsilon^2}{C_0^2\varepsilon^2}(Af)^3\left[\left(\sin 2\pi ft(1+s\cos 2\pi ft\right)\right]_\mathrm{max} \tag{8}$$

Rational physical models for gas-liquid and gas-liquid-solid systems in RPCs do not exist. For these systems, the empirical correlations assume proportionality of the PVCB and power consumption on $(Af)^n(1-\varepsilon_\mathrm{g})$ (Table 1), which are based on theoretical equations corrected for the liquid holdup ($1-\varepsilon_\mathrm{g}$), where $\varepsilon_\mathrm{g}$ is the gas holdup; the exponent $n$ is dependent on the flow regime [22,28].

Rheological properties of the liquid significantly affect the PVCB and power consumption that increase with the increase in the liquid viscosity due to more intense friction between the liquid and the reciprocating plates [11,28-30]. In the case of Newtonian liquids in the turbulent flow (Re >50), the PVCB and power consumption are about proportional to $(Af)^2$and $(Af)^3$, respectively [11,30]. This indicates the applicability of the quasi-steady-state flow model and suggests that frictional losses determine the PVCB. For non-Newtonian liquids, there is a deviation from the model, which is more significant if the solution is more pseudoplastic. In the laminar flow regime, for Re <10, the PVCB and power consumption are approximately proportional to $Af$ and $(Af)^2$, respectively [11].

The PVCB and power consumption for gas-liquid systems are smaller compared to those in ‘pure’ liquids, regardless of the column diameter and the type of liquid [9,11,22,28-35]. It is ascribed to a lower dispersion density and a weaker interaction between reciprocating plates and gas-liquid systems. A decrease in the superficial gas velocity increases the pressure change in the two-phase system despite the rheological properties of the liquid [11,30]. With increasing the reciprocating intensity, the PVCB increases linearly or reaches a maximum and then decreases in the unstable operation regime [11,22,28]. The critical reciprocating intensity at which the PVCB shows a maximum is dependent on the superficial gas velocity, the reciprocating amplitude, the number of perforated plates [22], and the liquid rheological properties [11]. Up to a critical reciprocating intensity, the average PVCB is proportional to $(Af)^n$, where the value of the exponent is 1.67 to 2.10 [11,30] and 1.2–1.3 [11,29] for Newtonian and viscous non-Newtonian fluids, respectively. A decrease in the exponent indicates a change from turbulent to laminar flow.

Regardless of the solid particle type placed in the interplate spaces (spheres or Raschig rings), the PVCB and power consumption for liquid-solid systems are greater if the solid phase fraction is larger under the same operating conditions and independently of the rheological properties of the liquid [10,11,29,32,33,37]. It results from greater frictional interaction between solid particles, liquid, and plates.

*Table 1. Empirical correlations for the PVCB and power consumption in RPCs developed in Serbia*

| System | | Correlation | | Ref. |
|---|---|---|---|---|
| | | PVCB | Power consumption | |
| 'Pure' liquid | Water | - | $\overline{P}=2.688\cdot10^{-4}n_p\rho_l(2\pi Af)^3$ | [7] |
| | Water | - | $\overline{P}=1.742\cdot10^{-3}n_p\rho_l(2\pi Af)^3$ | [8] |
| | Distilled water, sucrose solution, and a model dextran fermentation broth | $\Delta p^*\propto n_p\rho_l(Af)^2$ | $P^*=2.567\cdot10^{-3}n_p\rho_l(2\pi Af)^3$ | [22] |
| | Water | $\Delta p^*=0.113n_p\rho_l(Af)^2$ | $P^*=0.34n_p\rho_l(Af)^3$ | [28] |
| | | $\Delta\overline{p}=0.0317n_p\rho_l(Af)^2$ | $\overline{P}=0.0642n_p\rho_l(Af)^3$ | |
| | Water | $\Delta p^*=0.082n_p\rho_l(Af)^2$ | $P^*=5.49n_p\rho_l(Af)^3$ | [11] |
| | | $\Delta\overline{p}=0.023n_p\rho_l(Af)^2$ | $\overline{P}=1.157n_p\rho_l(Af)^3$ | |
| | Water | $\Delta p^*=657.2(Af)^{1.57}$<br>$\Delta\overline{p}=457.8(Af)^{1.96}$ | | [20] |
| | CMC (1 %) solution | $\Delta p^*=314.5(Af)^{1.21}$<br>$\Delta\overline{p}=115(Af)^{1.2}$ | | |
| | Water | $\Delta p^*=899(Af)^{1.617}$ | | [30] |
| | | $\Delta\overline{p}=615.6(Af)^2$ | | |
| | Sunflower oil (batch) | $\Delta p^*=2.081(Af)^{1.35}$ | $P^*=6.840(Af)^{2.36}$ | [17] |
| | | $\Delta\overline{p}=0.542(Af)^{1.32}$ | $\overline{P}=1.345(Af)^{2.33}$ | |
| | Sunflower oil (continuous) | $\Delta p^*=1.652(Af)^{1.31}$ | $P^*=5.432(Af)^{2.32}$ | |
| | | $\Delta\overline{p}=0.591(Af)^{1.39}$ | $\overline{P}=1.434(Af)^{2.39}$ | |
| Gas-liquid | Air-distilled water, sucrose solution, and a model dextran fermentation broth | - | $P^*=1.804\cdot10^{-3}n_p\rho_l(1-\varepsilon_g)(2\pi$ | [22] |
| | Air-water | | $P^*=0.310n_p\rho_l(1-\varepsilon_g)(Af)^3$ | [32] |
| | | | $\overline{P}=0.0664n_p\rho_l(1-\varepsilon_g)(Af)^3$ | |
| | Air-water | $\Delta p^*=0.0647n_p\rho_l(1-\varepsilon_g)(Af)^2$ | $P^*=0.199n_p\rho_l(1-\varepsilon_g)(Af)^3$ | [28] |
| | | $\Delta\overline{p}=0.0176n_p\rho_l(1-\varepsilon_g)(Af)^2$ | $\overline{P}=0.0403n_p\rho_l(1-\varepsilon_g)(Af)^3$ | |
| | Air-water | $\Delta p^*=0.1087n_p\rho_l(1-\varepsilon_g)(Af)^2$ | $P^*=4.481n_p\rho_l(1-\varepsilon_g)(Af)^3$ | [11] |
| | | $\Delta\overline{p}=0.0322n_p\rho_l(1-\varepsilon_g)(Af)^2$ | $\overline{P}=1.034n_p\rho_l(1-\varepsilon_g)(Af)^3$ | |
| | Air-water | $\Delta p^*=711.9(Af)^{1.67}$<br>$\Delta\overline{p}=425.4(Af)^{1.93}$ | | [20] |
| | Air-CMC (1 %) solution | $\Delta p^*=321.5(Af)^{1.14}$<br>$\Delta\overline{p}=115.1(Af)^{1.21}$ | | |
| | Air-water | $\Delta p^*=899(1-\varepsilon_g)(Af)^{1.617}$ | | [30] |
| | | $\Delta\overline{p}=615.6(1-\varepsilon_g)(Af)^2$ | | |
| | Air-CMC (0.5 %) solution | $\Delta p^*=862.3(1-\varepsilon_g)(Af)^{1.57}$ | | |
| | | $\Delta\overline{p}=473.4(1-\varepsilon_g)(Af)^{1.85}$ | | |
| | Air-CMC (1 %) solution | $\Delta p^*=740.6(1-\varepsilon_g)(Af)^{1.46}$ | | |
| | | $\Delta\overline{p}=390.9(1-\varepsilon_g)(Af)^{1.71}$ | | |
| Liquid-solid | Water-solid (spheres, 8.4 mm, 5 spheres per each second or third interplate space) | $\Delta p^*=0.279n_p\rho_l(Af)^2$ | $P^*=0.88n_p\rho_l(Af)^3$ | [32] |
| | | $\Delta\overline{p}=0.0322n_p\rho_l(Af)^2$ | $\overline{P}=0.152n_p\rho_l(Af)^3$ | |
| | Water-solid (spheres, 8 mm, 0.35-3.2 %) | $\Delta p^*=699.7(Af)^{1.56}$<br>$\Delta\overline{p}=458.4(Af)^{1.95}$ | | [20] |
| | CMC (1 %) solution -solid (0.35-3.2 %) | $\Delta p^*=248.4(Af)^{0.93}$<br>$\Delta\overline{p}=92.3(Af)^{1.0}$ | | |

| System | | Correlation | | Ref. |
|---|---|---|---|---|
| | | PVCB | Power consumption | |
| Liquid-solid | Water-solid (spheres: 8.4 mm, 3.8 %) | $\Delta p^* = 610.7(Af)^{1.31}$ | | [30] |
| | | $\Delta \overline{p} = 324.6(Af)^{1.58}$ | | |
| | Water-solid (6.6 %) | $\Delta p^* = 425.5(Af)^{10.97}$ | | |
| | | $\Delta \overline{p} = 265.4(Af)^{1.29}$ | | |
| | CMC (0.5 %) solution-solid (3.8 %) | $\Delta p^* = 683.7(Af)^{1.34}$ | | |
| | | $\Delta \overline{p} = 419.6(Af)^{1.64}$ | | |
| | CMC (0.5 %) solution-solid (6.6 %) | $\Delta p^* = 416.9(Af)^{0.91}$ | | |
| | | $\Delta \overline{p} = 187.2(Af)^{1.09}$ | | |
| | CMC (1 %) solution-solid (3.8 %) | $\Delta p^* = 1276.4(Af)^{1.54}$ | | |
| | | $\Delta \overline{p} = 676.1(Af)^{1.78}$ | | |
| | CMC (1 %) solution-solid (6.6 %) | $\Delta \overline{p} = 255(Af)^{1.18}$ | | |
| | | $\Delta p^* = 479(Af)^{1.2}$ | | |
| Gas-liquid-solid | Water | | $P^* = 0.31 n_p \rho_l (1-\varepsilon_g)(Af)^3$ | [32] |
| | | | $\overline{P} = 0.0664 n_p \rho_l (1-\varepsilon_g)(Af)^3$ | |
| | Air-water-solid (spheres, 8 mm, 0.35-3.2 %) | $\Delta p^* = 413.8(Af)^{1.43}$ | - | [20] |
| | | $\Delta \overline{p} = 327.5(Af)^{1.84}$ | | |
| | Air-CMC (1 %) solution-solid (0.35-3.2 %) | $\Delta p^* = 173(Af)^{0.86}$ | | |
| | | $\Delta \overline{p} = 70.1(Af)^{0.93}$ | | |
| | Air-water-solid (spheres: 8.4 mm, 3.8 %) | $\Delta p^* = 610.7(1-\varepsilon_g)(Af)^{1.31}$ | | [30] |
| | | $\Delta \overline{p} = 324.6(1-\varepsilon_g)(Af)^{1.58}$ | | |
| | Water-solid (6.6 %) | $\Delta p^* = 425.5(1-\varepsilon_g)(Af)^{10.97}$ | | |
| | | $\Delta \overline{p} = 265.4(1-\varepsilon_g)(Af)^{1.29}$ | | |
| | Air-CMC (0.5 %) solution-solid (3.8 %) | $\Delta p^* = 683.7(1-\varepsilon_g)(Af)^{1.34}$ | | |
| | | $\Delta \overline{p} = 419.6(1-\varepsilon_g)(Af)^{1.64}$ | | |
| | Air-CMC (0.5 %) solution-solid (6.6%) | $\Delta p^* = 416.9(1-\varepsilon_g)(Af)^{0.91}$ | | |
| | | $\Delta \overline{p} = 187.2(1-\varepsilon_g)(Af)^{1.09}$ | | |
| | Air-CMC (1 %) solution-solid (3.8 %) | $\Delta p^* = 1276.4(1-\varepsilon_g)(Af)^{1.54}$ | | |
| | | $\Delta \overline{p} = 676.1(1-\varepsilon_g)(Af)^{1.78}$ | | |
| | Air-CMC (1 %) solution-solid (6.6 %) | $\Delta p^* = 947(1-\varepsilon_g)(Af)^{1.20}$ | | |
| | | $\Delta \overline{p} = 255(1-\varepsilon_g)(Af)^{1.18}$ | | |
| Liquid-liquid | Sunflower oil-methanol (1:6 mol: mol) | $\Delta p^* = 1.158(1-\varepsilon_d)(Af)^{1.28}$ | $P^* = 3.829(1-\varepsilon_d)(Af)^{2.29}$ | [17] |
| | | $\Delta \overline{p} = 0.428(1-\varepsilon_d)(Af)^{1.37}$ | $\overline{P} = 1.393(1-\varepsilon_d)(Af)^{2.48}$ | |

### 2. 3. Gas holdup

The gas holdup remains unchanged [39,40] or decreases [22,28,41] with increasing the reciprocating intensity at specific superficial gas and liquid velocities due to the superimposition of gas bubbles and reciprocating plate speed, which leads to bubble coalescence. The ‘critical’ $(Af)_{cr}$ at which the gas holdup reaches its minimum value depends little on the superficial gas velocity [22]. After reaching the minimum value, the gas holdup in the gas-liquid system increases almost linearly with a further enhancement in reciprocating intensity due to the bubble comminution [22]. By adding solid particles (spheres or Raschig rings), the gas holdup in the 2.54 and 9.2 cm i.d. RPCs increases with an increase in reciprocating intensity and superficial gas velocity because bubble comminution intensifies by shear forces [11,36,42-46]. However, in a 16.6 cm i.d. RPC, a higher gas holdup is observed at a High superficial gas velocity and a smaller solid particle fraction resulting from the change in the liquid flow regime through the plate openings because of the reduced free cross-sectional plate area [15].

Usually, empirical equations for the gas holdup in RPCs involve maximum or average power consumption and superficial gas velocity (Table 2):

$$\varepsilon_g = k(P_g)^a u_g^b \tag{9}$$

The power consumption $P_g$ has a lower influence on gas holdup than the gas flow energy because mechanical energy dissipation occurs only near the plates ($a < b$).

*Table 2. Empirical equations for the dispersed phase holdup in RPCs developed in Serbia.*

| Column type[a] | System | Special conditions | Correlation | Ref. |
|---|---|---|---|---|
| RPC1 | Air-water,<br>Air-sucrose solution | Segregated dispersion | $\frac{u_r}{1-\varepsilon_g} = 0.436 u_g^{0.22} \exp(-0.122\bar{P}\varepsilon_g u_g^{0.88})$ | [56] |
| | | Homogeneous dispersion | $\varepsilon_g = 1.38 P^{*0,25} u_g^{0.6}$ | |
| RPC2 | Air-water-spheres | $Af > 0.03$ ms$^{-1}$ | $\varepsilon_g = 2.515 P^{*0.29} u_g^{0.83}$ | [33] |
| RPC2 | Air-water,<br>Air-sucrose solution | Segregated dispersion | $\varepsilon_g = 7.4 P^{*(-0.05)} u_g$ | [28] |
| | | Homogeneous dispersion | $\varepsilon_g = 6.2 P^{*0.2} u_g$ | |
| | | | $\varepsilon_g = 44.55 (Af)^{0.6} u_g$ | |
| RPC2, RPC3 | Air-water | $Af > 0.03$ ms$^{-1}$ | $\varepsilon_g = 1.38 P^{*0.27} u_g^{0.73}$ | [11] |
| RPC3 | Air-CMC solution (0.5 and 1 %)-spheres (8 mm) | Polymerization degree: 200 | $\varepsilon_g = 0.043 \bar{P}^{0.39} u_g^{0.53}$ | [36] |
| | | Polymerization degree: 1000 | $\varepsilon_g = 0.043 \bar{P}^{0.31} u_g^{0.44}$ | |
| RPC3 | Air-water-Raschig rings (8 mm) | $Af > 0,03$ ms$^{-1}$ | $\varepsilon_g = 1.145 \bar{P}^{0.428} u_g^{0.662}$<br>$\varepsilon_g = 0.393 P^{*0.495} u_g^{0.628}$<br>$\varepsilon_g = 1.06 P_t^{0.456} u_g^{0.663}$ | [42] |
| RPC2, RPC3 | Air-water | | $\varepsilon_g = 1.369 u_g^{0.962} D_c^{-0.483} + 172.26 u_g^{0.33} D_c^{0.453} (Af)^{2.21}$ | [57] |
| | Air-water-Raschig rings (8 mm) | | $\varepsilon_g = 1.369 u_g^{0.962} D_c^{-0.483} + 66.942 u_g^{0.294} D_c^{0.268} (Af)^{1.693} \varepsilon_s^{0.238}$ | |
| RPC3 | Air-CMC solution (0.5, 1, and 2 %)-spheres | $Af > 0.04$ ms$^{-1}$, polymerization degree: 50 | $\varepsilon_g = 0.053 \bar{P}^{0.39} u_g^{0.605}$ | [51] |
| | | $Af > 0.04$ ms$^{-1}$, polymerization degree: 200 | $\varepsilon_g = 0.041 P^{0.4} u_g^{0.54}$ | |
| RPC3 | Air-water, air-water-Raschig rings (12 mm) | $\varepsilon = 0.454$ | $\varepsilon_g = 1.991 \bar{P}^{0.404} u_g^{0.787}$ | [16] |
| | Air-CMC solution (1 %) | $\varepsilon = 0.319$ | $\varepsilon_g = 0.335 \bar{P}^{0.291} u_g^{0.527}$ | |
| | Air-CMC solution (1 %), air-CMC solution (1 %) - Raschig rings (12 mm) | $\varepsilon = 0.319$ | $\varepsilon_g = 0.441 \bar{P}^{0.259} u_g^{0.567}$ | |
| RPC2 | Methanol-sunflower oil | $Af < 0,05$ ms$^{-1}$ | $\varepsilon_d = 4.67 \cdot 10^{-5} (Af)^{0.67} u_d^{-1.22}$ | [17] |
| | | $Af > 0,05$ ms$^{-1}$ | $\varepsilon_d = 4.87 \cdot 10^{-6} (Af)^{0.67} u_d^{-1.24}$ | |

[a] RPC1: $D_c$= 0.025 m, $l_c$ = 1.875 m; RPC2: $D_c$= 0.025 m, $l_c$= 2 m, RPC3: $D_c$= 0.092 m, $l_c$= 1.05 m

The effect of the superficial gas velocity on the gas holdup is very pronounced, regardless of the type of system and column geometry. At $u_g < 3$ cm s$^{-1}$, the gas holdup increases proportionally with the increased superficial gas velocity due to increased resistance to the gas flow through the plate openings [2,11,22,28,33,39-43,47-53]. At higher superficial gas velocities, gas slugs appear in the RPC, and the gas holdup reaches its maximal value and does not change when the superficial gas velocity further increases [28,45].

There are conflicting opinions about the effect of superficial liquid velocity on the gas holdup in two-phase systems. Some researchers believe that superficial liquid velocity does not affect the gas holdup [40,41,54,55], while others believe that it increases with the increase in the superficial liquid velocity [2,22,39] if $u_l > 1.2$ cm s$^{-1}$ [3]. In three-phase systems, the superficial liquid velocity does not significantly affect the gas holdup [43,45].

By increasing the plate opening, the gas holdup decreases in the segregated regime, while the effect is insignificant in the homogeneous regime. Increasing the number of plates increases the gas holdup due to a reduced mean bubble diameter and increased resistance to bubble movement [2,22,39,41]. Independently of the liquid rheological properties and the presence of a solid phase, the gas holdup increases with decreasing the fractional free plate surface due to favoring gas dispersion and making gas and liquid flow through the plate openings difficult [16].

Solid particles have multiple effects on gas-liquid dispersion. The solid particles, forced to move due to the reciprocating plate movement, affect the equalization of the field of turbulent forces in the interplate spaces, prevent coalescence and favor the bubble reduction. By their movement, solid particles reduce the intensity of backmixing and stabilize the column operation [43]. Consequently, the gas holdup is larger in three-phase RPCs than in two-phase RPCs under the same working conditions. This difference is greater at higher reciprocating intensities. Raschig rings disperse gas more efficiently than spheres of approximately the same diameter in RPCs of the same geometry [49].

Physical properties of the liquid affect the gas holdup. It was reported to be higher in *n*-butanol, glycerol, and sodium sulfite solutions than in water [11]. The highest gas holdup is achieved in the *n*-butanol solution due to the prevented coalescence of bubbles. In non-Newtonian solutions of CMC, gas holdup is dependent on the solution concentration and the molar mass of CMC [36].

Among two-phase column contactors, a much higher gas holdup is achieved in a Prochazka RPC [2]. The gas holdup is 50-60 % higher than that in pulsed bubble columns and about 25 % higher than that in vibrating disc columns under similar working conditions. Gas holdup in RPCs is higher than those in stirred vessels, bubble columns, and air-lift rectors, especially at lower superficial gas velocities [11]. At the same specific power consumption and superficial gas velocity, gas holdup was reported to be approximately the same in three RPCs with similar geometric characteristics [52].

### 2. 4. Bubble size

The state of dispersion depends on the relationship between gas bubble formation, dispersion, and coalescence processes [55]. Bubble formation depends on instabilities in the gas flow through plate openings. Bubble dispersion results from external power dissipation and is dependent on the ratio of surface tension forces, stabilizing the bubbles, and local shear forces, which break up the bubbles. If the dynamic forces do not take action evenly over the entire bubble surface, the bubble first deforms and then disintegrates. The maximum size of a stable bubble, which can be maintained in an existing turbulent field, according to the Kolmogoroff's model of isotropic turbulence, depends on the liquid surface tension, $\sigma$, and density, $\rho$, as well as on the specific dissipated energy $P/V_l$ [27]:

$$d_{3,2} = k\frac{\sigma^{0.6}}{\rho^{0.2}\left(\frac{P}{V_l}\right)^{0.4}} \tag{10}$$

The measured Sauter-mean bubble diameter $d_{3,2}$ agrees with that estimated by Eq. (10) for water and glycerol solutions. In contrast, the agreement is relatively poor for *n*-butanol and sodium sulfite solutions. This correlation was also proved for a methanol-to-oil emulsion where the Sauter-mean drop diameter was proportional to the specific power consumption (average power consumption *P* divided by the emulsion mass) on the power of -0.4, *i.e.* $d_{3,2} \propto (\overline{P}/m_e)^{-0.4}$ [17].

With increasing the reciprocating intensity, as a consequence of the contribution of external energy input to the comminution, the mean bubble diameter decreases in RPCs [2,3,11,40,55,58]. When the total power consumption is lower than a critical value, the Sauter-mean bubble diameter is not dependent on the agitation intensity. However, it decreases when the power consumption exceeds the critical value [58]. The decrease in bubble size with increasing reciprocating intensity is more pronounced in the presence of coalescence inhibitors [9].

The superficial gas velocity affects the bubble size due to a facilitated coalescence [2,11,40,58], but this effect is significant only at low superficial gas velocity [2]. Bubble size is not affected by the superficial liquid velocity [2,39,41] or it decreases with increasing the superficial liquid velocity [58] because of turbulent forces created in plate openings [40]. Compared to that in water, bubble size is smaller in liquids that favor bubble reduction by viscous forces (*e.g.* aqueous glycerol solution) or prevent bubble coalescence (*e.g.* aqueous *n*-butanol and sodium sulfite solutions).

The plate geometry significantly affects the Sauter-mean bubble diameter in RPCs. In the segregated regime, it is controlled by the plate opening diameter, and in the homogeneous regime, by the bubble dispersion process. The Sauter-mean bubble diameter is reduced by increasing the plate opening and decreasing the fractional free plate surface area [55]. In three-phase systems, it increases with increasing the solid phase fraction [45]. Also, it is reduced with the increase in the reciprocating intensity and the decrease in the superficial gas velocity.

### 2. 5. Axial mixing

In real column-type multiphase contactors, fluids do not flow in an ideal plug flow due to channeling, recirculating, or creation of stagnant zones. Most often, the non-ideality of the flow is expressed by axial or radial mixing coefficients. Axial mixing does not exist in the ideal plug flow, and the axial mixing (dispersion) coefficient $D_l$ equals zero. In contrast, the axial dispersion coefficient is maximal for the flow with ideal mixing. In smaller-diameter columns, radial mixing is usually neglected. However, when designing column-type reactors with the countercurrent flow of the phases, axial dispersion is desirable to maintain the maximal concentration difference (driving force) in the axial direction.

The dispersion (diffusion) model is most frequently used for describing the flow through multiphase RPCs. Depending on the turbulence intensity in the column, this model, as limit values, defines the cases of the ideal plug flow and the flow with ideal mixing. In RPCs, large mass transfer rates and relatively low axial dispersion can be achieved. In the literature, there is a large amount of data on axial dispersion for ‘pure’ liquids, resulting from researching this contactor as an extraction column [27]. However, the findings of different researchers are often contradictory, which is difficult to explain. For example, the axial dispersion coefficient was reported to increase [59,60] or decrease [61,62] with increasing the interplate space. Similarly, it was reported to increase [60] or decrease [63] with the increase in the plate opening size. However, it was found not to depend [59,64] or to depend weakly [65] on the column diameter.

Conversely, the axial dispersion coefficient increases approximately linearly with the reciprocating intensity [50,60-62]; the increase in amplitude seems to increase axial dispersion [50]. In gas-liquid systems, the axial dispersion coefficient increases with the superficial gas velocity, especially at higher superficial gas and liquid velocities, as well as with the increase in the superficial liquid velocity due to favored backmixing resulting from increased resistance to the flow through the plate openings and the liquid jets intensifying mixing in interplate spaces [66]. In addition, turbulent fluid flow in interplate spaces and circulation due to gas bubbles increase axial mixing compared to a ‘pure’ liquid [67]. Finally, in three-phase systems, solid particles influence the axial dispersion coefficient more significantly than the superficial gas velocity, especially at low reciprocating intensities [57]. However, axial dispersion coefficient is decreased with an increase in reciprocating intensity independently of the superficial gas velocity [57].

Empirical correlations for determining the axial dispersion coefficient are given in Table 3.

*Table 3. Empirical correlations for axial dispersion coefficient in RPCs ($D_c$ = 2.54 cm) developed in Serbia*

| System | Operating conditions | Correlation | Ref. |
|---|---|---|---|
| Water ↓ | $A$ = 0–1.4 cm<br>$f$ = 0–10 Hz<br>$u_l$ = 0.1–1.1 ms$^{-1}$ | $\ln D_l = \ln(D_L)_{l=0} + (Af)^{0.56} \exp(-1.44u_c + 0.912)$<br>$(D_l)_{l=0} = 5.15 \cdot u_l^{0.471}$ | [70] |
| Air-water ↓↑ | $A$ = 0.65–1.5 cm<br>$f$ = 0.5–6.18 Hz<br>$u_l$ = 0.38–1.2 ms$^{-1}$<br>$u_g$ = 0.8–3.2 ms$^{-1}$ | $D_l = 90.5u_R^{-0.964}$ ; $D_l = 81.47 \cdot u_l^{0.627} u_R^{-075+0.19u_l}$<br>with $u_R = \frac{u_g}{\varepsilon_g} + \frac{u_l}{1-\varepsilon_g} + 2Af$ | [3] |
| Water ↓ | $A$= 1 and 2.35 cm<br>$f$ = 2–4.5 Hz<br>$u_l$ = 0.24–0.87 ms$^{-1}$<br>$u_g$ = 0–1.48 ms$^{-1}$ | $D_l = 0.49(Af)^{1.11} u_l^{0.31}$ | [66] |
| Air-water ↓↑ | | $D_l = 3.37(Af)^{0.17} u_l^{0.38} u_g^{0.07}$ | |
| Water ↓ - spheres (8.3 mm) | | $D_l = 1.26(Af)^{1.42} u_l^{0.51} \varepsilon_S^{0.23}$ | |
| Air-water ↓↑ - spheres (8.3 mm) | | $D_l = 1.39(Af)^{0.47} u_l^{0.42} u_g^{0.03} \varepsilon_S^{-0.26}$ | |

Application of these correlations is limited to the liquid (continuous) phase and specific columns used in the axial dispersion studies [62]. Discrepancies between correlations result from different geometries of RPCs and operating condition ranges. Axial dispersion in RPCs is less intensive than in bubble columns [68] but more intensive than in packed columns [69].

## 3. MASS TRANSFER IN RPCS

Efficiency of multiphase RPCs is dependent on the interfacial mass transfer rate of the reactant per unit dispersion volume, i.e., on the volumetric mass transfer coefficient in the liquid phase ($k_la$), which is a product of the liquid mass transfer coefficient ($k_l$) and the specific interfacial area ($a$). The liquid mass transfer coefficient and specific interfacial area in RPCs depend on the reciprocating intensity ($Af$), *i.e.* power consumption, superficial gas and liquid velocities, properties of the phases, column geometry, and bubble size. Many researchers investigated the influence of reciprocating intensity and superficial gas and liquid velocities on the volumetric mass transfer coefficient, liquid mass transfer coefficient, and specific interfacial area in RPCs. Table 4 overviews correlations for the mass transfer characteristics of RPCs developed by Serbian researchers.

*Table 4. Correlations for the liquid mass transfer coefficient, specific interfacial area, and volumetric mass transfer coefficient in RPCs developed in Serbia*

| Phase flow | $D_c$ / cm | $n_p$ | $d_o$ / mm | $\varepsilon$ | $\varepsilon_s$ / % | Special condition | $k_l$ / m s$^{-1}$; $a$ / m$^2$ m$^{-3}$ $k_la$ / s$^{-1}$ | Ref. |
|---|---|---|---|---|---|---|---|---|
| Batch | 2.54 | 65, 33 | 8, 7 | 0.51, 0.41 | 0 | $P_g^* > P_{g,cr}^{*\ a}$ | $k_l = 2.94 \cdot 10^{-4} P_g^{*0.25}$<br>$a = 1783 P_g^{*0,3} u_g^{0,6}$ | [9,56] |
| | | | | | | $P_g^* < P_{g,cr}^*$ | $k_l = 2.62 \cdot 10^{-4} P_g^{*-0.05}$ | |
| | | | | | | | $k_l = 0.0564 d_{3,2}$<br>$a = 1583 u_g^{0,6}$ | |
| | | | | | | | $k_la = 0.467 P_g^{*0.25} u_g^{0.6}$ | |
| Batch | 2.54 | 65, 15 | 8 | 0.51, 0.454 | 0 to 6.6 | $u_g$< 1.5 cm s$^{-1}$ | $k_l = 20.24 d_{3,2}^{1.743}$<br>$a = 18883 \overline{P}^{0,31} u_g^{0,97}$<br>$k_la = 0.719 \overline{P}^{0.74} u_g^{0.63}$ | [11,71,72] |
| Batch | 16.6 | 15 | 8 | 0.466 | 3.8 | $u_g$< 1.5 cm s$^{-1}$ | $k_la = 2.33 \left(\frac{\overline{P}}{V_l}\right)^{0.803} u_g^{0.572}$ | [15,84] |
| | | | | | 6.6 | | $k_la = 0.6 \left(\frac{\overline{P}}{V_l}\right)^{0.572} u_g^{0.316}$ | |
| Batch | 9.2 | 33 | 8 | 0.454 | 0.35 to 3.2 | $u_g$< 1.5 cm s$^{-1}$ | $k_la = 0.995 \left(\frac{\overline{P}}{V_l}\right)^{0.776} u_g^{0.854}$ | [16] |
| Counter-current | 2.54 | 63 | 8 | 0.51 | 0 | Methanol-sunflower oil | $a = 3.3 (Af)^{0.74} u_d^{-1.2}$ | [43] |

[a] $P_{g,cr}^* = 4.2(1 - \varepsilon_{g,cr}) u_g^{0.25}$

The correlations developed by others can be found elsewhere [27]. As with other contact devices with mechanical agitation, these mass transfer characteristics in RPCs can be correlated with the power consumption (total, average, or specific), *i.e.* reciprocating intensity, superficial gas and liquid velocities, and geometric characteristics of the column. Aeration more significantly affects the specific interfacial area than agitation. At the same superficial gas velocity, the specific interfacial area and volumetric mass transfer coefficient in gas-liquid systems are greater in RPCs than in stirred vessels, bubble columns, and air-lift reactors due to larger gas holdup and smaller bubble size resulting from a more intensified bubble dispersion [71,72].

If $P_g^* < P_{g,cr}^*$, where $P_{g,cr}^*$ is the critical value of the maximum power consumption, $P_g^*$, in the gassed RPC, then $k_l \propto (P_g^*)^{0.25}$ [58]. However, when $P_g^* > P_{g,cr}^*$, then $k_l > (P_g^*)^{0.05}$ and $k_l \propto d_{3,2}$, where $d_{3,2}$ is the Sauter-mean bubble diameter [58]. Similar dependencies were found for other RPCs [73], vibrating disc columns [74], and stirred vessels [75]. The dependence of the liquid mass transfer coefficient on the Sauter-mean bubble diameter has been confirmed for vibrating disc columns [74], pulsating columns [76], stirred vessels [77], and bubble columns [78]. Change of the specific interfacial area with reciprocating intensity is dependent on the flow regime in column [58]. At $Af < 2$ cm s$^{-1}$ [40], the specific interfacial area either increases due to the decrease in bubble size [79] or remains unchanged because the gas holdup and bubble size do not change [3,40,58]. The specific interfacial area increases at higher reciprocating intensities, while the liquid mass transfer coefficient decreases with increasing reciprocating intensity because of increased gas holdup and decreased bubble size [11,58]. The volumetric mass transfer coefficient increases with increased reciprocating intensity because of greater power consumption and intensified gas bubble size reduction [3,52,67,71,73,79-81]. This increase is insignificant at lower and significant at higher reciprocating intensities, $Af > 5$ cm s$^{-1}$ [3,79].

The liquid mass transfer coefficient decreases with increased superficial gas and liquid velocities [73,79]. Increasing the superficial gas velocity increases the gas holdup, whereas increasing the superficial liquid velocity decreases the bubble size. Both decrease the liquid mass transfer coefficient and the relative velocity between the liquid and gas phases [79]. The effect of the superficial gas velocity on the specific interfacial surface is particularly significant at low reciprocating intensities when increasing reciprocating intensity helps the bubbles to comminute, thus increasing the interfacial area [11,22]. At larger superficial gas velocities, bubbles increase in size and pack densely, which favors their coalescence [3], but the specific interfacial area may increase due to the increased gas holdup [2,40,58,79]. According to some researchers [58], the superficial liquid velocity negligibly affects the specific interfacial area due to a weak influence on bubble size and gas holdup, while others [1,2,40,79] reported the increased specific interfacial area with increasing the superficial liquid velocity because of a decrease in bubble size. As the superficial gas velocity increases, the volumetric mass transfer coefficient increases to a maximum due to the higher energy that the gas is transferring to the liquid. Then, a larger gas holdup is observed in the RPC, and reduction in the bubble size is enhanced when the gas passes through the plate openings. Some researchers reported constants volumetric mass transfer coefficient with increasing the superficial liquid velocity [79] or ignored this influence [9,81], while the other group found an increase in this coefficient with increasing the superficial liquid velocity [69,73].

The RPC geometry influences the liquid mass transfer coefficient, specific interfacial area, and volumetric mass transfer coefficient. Increasing the opening diameter and the fractional free plate surface reduces the gas holdup, specific interfacial area, liquid mass transfer coefficient, and volumetric mass transfer coefficient. These changes were experimentally observed, although the bubble size decreases insignificantly with increasing the opening diameter [7,80]. In addition, the specific interfacial area and volumetric mass transfer coefficient are higher in cocurrent than in countercurrent flow due to a higher gas holdup [79].

The liquid mass transfer coefficient decreases, and the specific interfacial area increases by adding Raschig rings (2.5 vol.%) to each interplate space [76], while spheres do not affect the specific interfacial area [11]. In a 9.2 cm i.d. RPC, the specific interfacial area is greater with a greater solid phase fraction than in the two-phase (gas-liquid) system [11]. Increasing the reciprocating intensity and superficial gas velocity in a three-phase system increases the volumetric mass transfer coefficient because a higher power consumption favors the bubble size reduction [11,15]. The volumetric mass transfer coefficient is higher in a three-phase system than in a two-phase system due to a more efficient mixing and the influence of the solid phase. However, increasing the solid phase fraction does not significantly affect the volumetric mass transfer coefficient.

Dependence of the volumetric mass transfer coefficient on the liquid properties is complex since they influence the liquid mass transfer coefficient and the specific interfacial area. For example, adding a non-electrolyte (alcohol) at a small concentration increases the volumetric mass transfer coefficient [83]. Conversely, for the liquids with close surface tensions and densities, the volumetric mass transfer coefficient decreases with increased viscosity [9].

## 4. APPLICATION OF RPCS IN SERBIA

RPCs were investigated regarding potential applications as reactors for various aerobic bioprocesses and biodiesel production. RPCs are applied worldwide in the chemical and pharmaceutical industries, hydrometallurgy, biotechnology, and wastewater treatment (Table S-3). For example, they are used for aerobic wastewater treatment [85], biosynthesis of pullulan [86,87], dextran [88], antibiotics [89], lemon acid [21], ethanol [13,21], and enzymes [9,88], as well as in biodiesel production [17,19,20]. Due to their favorable hydrodynamic properties and efficient oxygen mass transfer, RPCs are classified as new-generation bioreactors [90].

RPCs have been used in Serbia to study biosyntheses of dextransucrase, dextran [9, 88], and ethanol [13] as well as biodiesel production [17-20,91] at laboratory and pilot levels.

An RPC (2.54 cm i.d.) was used as a bioreactor for alcoholic fermentation of a glucose medium (40 g dm$^{-3}$) using a commercial yeast *Saccharomyces cerevisiae* immobilized on macroporous polymer particles ($\varepsilon_s$ = 0.236) at 30 °C and a liquid flow rate of about 1.2 dm$^3$ day$^{-1}$ [13]. The dispersion model was verified by comparing predicted and measured glucose concentrations at the exit of the bioreactor. With the zero-order reaction rate law, axial dispersion did not affect the glucose conversion degree. However, with the Monod kinetics, axial dispersion positively influenced the glucose conversion degree and ethanol yield. Furthermore, biosynthesis of dextransucrase by a *Leuconostoc mesenteroides* Zdravlje S-P strain was investigated at a laboratory level in an RPC (2.5 cm i.d.), a bubble column and a stirred vessel, at 25 °C [9,88]. The maximum power consumption was calculated from the maximum PVCB (Table 1) [22], while the volumetric oxygen mass transfer was determined by a dynamic method during aerobic microbial growth (Table 4) [56]. Among the tested bioreactors, the RPC had the highest aeration capacity for the same total specific power consumption and at a much lower superficial gas velocity [88]. Still, it was higher than the optimal one needed for the maximum enzyme biosynthesis. Therefore, the aerated, stirred tank bioreactor was selected for microbial dextransucrase production [9,88].

Continuous KOH-catalyzed biodiesel production from various oily feedstocks (sunflower oil, rapeseed oil, and waste pig-roasting lard) and methanol was performed in RPCs of different diameters [17-20,91]. Hydrodynamics of a cocurrent two-phase upflow in an RPC (2.5 cm i.d.) was investigated for the KOH-catalyzed methanolysis of sunflower oil [17]. Plug flow of the continuous phase (sunflower oil) through the column was confirmed for the flow at the 1 mm reciprocating amplitude. Also, the flow regime through the column and plate openings was laminar and laminar to transitional. The PVCB and power consumption depended on the reciprocating intensity, while the Sauter-mean drop diameter was dependent on the specific power consumption. The dispersed phase (methanol) holdup and the specific interfacial area were correlated with the reciprocating intensity and the superficial dispersed phase velocity (Tables 2 and 4, respectively). Therefore, the hydrodynamic study showed that RPCs offer benefits of plug flow, effective two-phase mixing, and fast reaction of two immiscible reactants, such as sunflower oil and methanol, at room temperature along with the simple scale-up method accepted for Karr type RPCs [17]. Next, the effects of tetrahydrofuran (THF) as a cosolvent on hydrodynamics and kinetics were studied [19]. The THF addition positively affected the drop size of the dispersed phase and the triacylglycerol (TAG) conversion degree. The plug flow through the RPC and simple kinetic models were verified. The mass transfer limitation was observed in the initial part of the reactor (only for THF contents of ≤10 %), whereas the chemical reaction-controlled regime was in the upper reactor part, which included a fast irreversible second-order reaction and/or reversible second-order reaction (only at the THF content of 30 %). The TGA content of around 80 % at the reactor exit indicated that the overall biodiesel production process should be conducted in a series of two RPCs with the separation of glycerol after each reactor. This process configuration was patented nationally in 2014 [91]. A 98–100 % TAG conversion was achieved at the exit of the second reactor. However, a TAG purity of 96.2 % was obtained in the same RPC using KOH (1 % of the oil loading), waste pig-roasting lard, and methanol (1:4.5 mol mol$^{-1}$) at 60 °C, a retention time of 10 min, and a capacity of 120 kg day$^{-1}$ [20]. In this case, the first-order model for both the reaction and the mass transfer and the model of the changing reaction mechanism and TAG mass transfer were proved. Continuous KOH-catalyzed methanolysis of rapeseed oil at 30 °C was performed in a cocurrent upflow RPC of 2.5 cm or 16.6 cm diameter and a gravitational separator providing the TAG conversion degrees at the exit of the plant of 98 % [92,93]. Residence times of the reaction mixture in the reactors and separators were 13 min and about 3 h, respectively.

## 5. CONCLUSION

Reciprocating plate columns (RPCs) have been investigated and applied in Serbia from 1970 to 2020 at the laboratory level as contactors and reactors. Hydrodynamic and mass-transfer characteristics of RPCs are reviewed, such as the

PVCB, power consumption, dispersed-phase holdup, axial dispersion, volumetric oxygen mass transfer coefficient, liquid mass transfer coefficient, and specific interfacial area. Serbian researchers have used RPCs as multiphase contactors for liquid-liquid extraction and gas absorption, bioreactors in alcoholic fermentation, polysaccharide and enzyme biosyntheses, and reactors for biodiesel production.

### Nomenclature

| | |
|---|---|
| $a$ / m$^2$m$^{-3}$ | specific interfacial area |
| $A$ / m | amplitude of reciprocating motion |
| $A_c$ / m$^2$ | cross-sectional column area |
| $Af$ / m s$^{-1}$ | reciprocating intensity |
| $C_0$ | orifice coefficient |
| $D_l$ / m$^2$ s$^{-1}$ | axial dispersion coefficient |
| $D_c$ / m | column diameter |
| $d_o$ / m | plate opening diameter |
| $d_{3,2}$ / m | Sauter-mean bubble diameter |
| $f$ / Hz | frequency of reciprocating motion |
| $g$ / m s$^{-2}$ | gravitational acceleration |
| $k_l$ / m s$^{-1}$ | liquid mass transfer coefficient |
| $k_la$ / s$^{-1}$ | volumetric mass transfer coefficient |
| $L$ / m | length of the tie-rod |
| $l_c$ / m | column length |
| $m_e$ / kg | emulsion mass |
| $n_p$ | number of plates |
| $p$ / Pa | instantaneous pressure |
| $p_1$, $p_2$ / Pa | pressures at the top and bottom of the column, respectively |
| $\Delta\overline{p}$, $\Delta P$ / Pa | average and maximum pressure variation at the column bottom, respectively |
| $P$ / W | instantaneous power consumption |
| $\overline{P}$, $P^*$ / W | average and maximum power consumption, respectively |
| $P_g^*$ / W | maximum gassed power consumption |
| $P_{g.cr}^*$ / W | critical maximum gassed power consumption |
| $s$ | the ratio of the radius (equal to the amplitude of reciprocating motion *A)* of the disk to the length of the tie-rod, ($A$ / $L$) |
| $s_e$ / m | equivalent plate length |
| $t$ / s | time |
| $u_c$ / m s$^{-1}$ | superficial continuous phase velocity |
| $u_d$ / m s$^{-1}$ | superficial dispersed phase velocity |
| $u_g$ / m s$^{-1}$ | superficial gas velocity |
| $u_l$ / m s$^{-1}$ | superficial liquid velocity |
| $u_s$ / m s$^{-1}$ | velocity of the plate stack, $= A\ \omega \sin[\omega t\ (1 + s \cos \omega t)]$ |
| $u_{s,m}$ / m s$^{-1}$ | maximum plate stack velocity |
| $u_R$ / m s$^{-1}$ | slip velocity |
| $V_l$ / m$^3$ | liquid volume |
| $z_1$ and $z_2$ / m | top and bottom of the column, respectively |

### Greek symbols

| | |
|---|---|
| $\varepsilon$ | fractional free plate area |
| $\varepsilon_d$ | dispersed phase holdup |
| $\varepsilon_g$ | gas holdup |
| $\varepsilon_s$ | solid phase content |
| $\rho_L$ / kg m$^{-3}$ | liquid density |
| $\sigma$ / N m$^{-1}$ | liquid surface tension |
| $\omega$ / s$^{-1}$ | angular frequency ($2\pi f$) |

### Abbreviations

| | |
|---|---|
| i.d. | internal diameter |

## SUPPLEMENTARY MATERIAL

Additional data are available electronically at https://www.ache-pub.org.rs/index.php/HemInd/article/view/1110, or from the corresponding author on request.

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# Kolona sa vibracionom mešalicom – fundamentalna istraživanja i primena u Srbiji od 1970. do 2020. godine

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(Pregledni rad)

*Izvod*

U grupi višefaznih kontaktora i reaktora, značajno mesto zauzima reaktor sa vibracionom mešalicom (RVM) koji se sastoji od niza perforiranih pločica pričvršćenih na zajedničkom vratilu, koje se kreću gore-dole. Ovakva konstrukcija reaktora maksimizira pozitivne efekte mehaničkog mešanja i minimizira ili elimiše negativne efekte karakteristične za kontaktore i reaktore kolonskog tipa. U RVM, najveće zadržavanje dispergovane faze postiže se pri njenoj manjoj brzini strujanja zbog uticaja mehaničkog mešanja na usitnjavanje mehurova ili kapi. Zato ovaj uređaj može biti najprihvatljiviji kontaktor za izvođenje složenih procesa u višefaznim sistemima. U radu su opisana fundamentalna istraživanja i primena RVM u Srbiji u poslednjih pedeset godina, od 1970. do 2020. godine. Analizrane su hidrodinamičke i mesenoprenosne karakteristike, kao što su promena pritiska na dnu reaktora, snaga mešanja, zadržavanje dispergovane faze, aksijalna disperzija, koeficijent prenosa mase u tečnosti, specifična međufazna površina i zapreminski koeficijent prenosa mase. Takođe, opisana je primena RVM kao reaktora u bioprocesima i procesima proizvodnje biodizela.

*Ključne reči:* povratno-periodično mešanje, promena pritiska, snaga mešanja, zadržavanje dispergovane faze, aksijalna disperzija, zapreminski koeficijent prenosa mase