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Heat transfer investigations in a liquid that is mixed by means of a reciprocating agitator

Introduction

Mixing is probably the most frequently used chemical engineering operation in industry [Masiuk *et al.*, 2008]. On a macroscopic scale, the improvement of mixing process can be achieved by using various types of mixers or agitators. In chemical engineering and related fields, a mixing process may be realized by means of reciprocating mixers. With a reciprocating mixer often less mixing time for homogenization of the liquid is required in comparison with the stirred vessels [Masiuk *et al.*, 2008]. Moreover, the lower shear stress produced by a reciprocating agitator is important for biochemical processes. The application of reciprocating mixers is applied only a few engineering operations [Kamieński and Wójtowicz 2003; Ni *et al.*, 2003; Hirata *et al.*, 2007; 2009; Lin and Thibault, 2013]. Moreover, this type of agitator may be applied in order to enhance the heat transfer rate in the mixed liquid [Fu *et al.*, 2009; Mackley *et al.*, 1990; Masiuk, 1991; Masiuk 1996a,b; Ratushnyan and Chou 2003; Wu and Lau, 2005; Djedjula, 2008; Singh and Ramaswamy 2015; 2016; Singh *et al.*, 2015].

In the present report, the experimental investigations have been conducted to explain the influence of a novel type of reciprocating agitator on the heat transfer enhancement. Moreover, the influence of geometrical configuration of the tested agitator on the heat transfer rate was experimentally determined.

Experimental

Laboratory set-up. All experimental measurements of the heat transfer process using the novel type of agitator were carried out in a laboratory set-up (see Fig. 1).

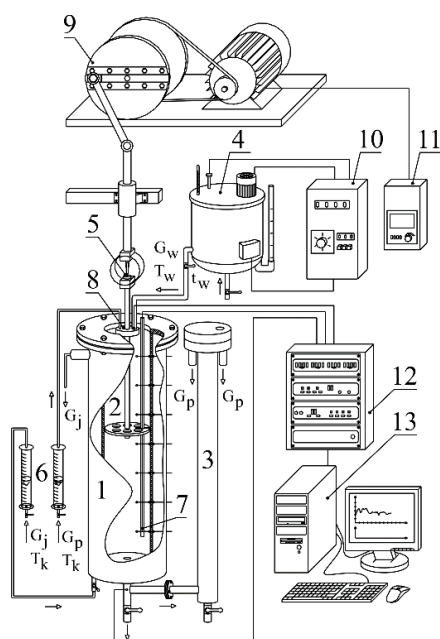


Fig. 1. Experimental set-up: 1 - tubular vessel, 2 - perforated plate agitator, 3 - external overflow, 4 - temperature controller for heating liquid feed, 5 - hardened ring with inductive transducer, 6 - flow meters, 7 - temperature sensors, 8 - distributor of cold liquid, 9 - electromechanical eccentric drive, 10 - power cube, 11 - controller of motor speed, 12 - system of temperature sequential sampling, 13 - personal computer

The investigations were performed using the vertical cylindrical vessel (0.205 m in inner diameter and 1.035 m in height) equipped with the heating jacket (0.308 m in outer diameter). The liquid height in vessel was equal to 0.955 m. The applied experimental system consisted of the electrical and thermal instrumentation to measure the heat transfer process in the mixed liquid.

The average heat transfer coefficient from the heating jacket wall to the liquid (tap water) in the agitated vessel was measured for steady state conditions. The temperature measurements were carried out by using the set of the microprocessor sensors. These sensors were applied for the investigations of the temperature distribution in the bulk of the mixed liquid, both sides of the heating wall, heating steam as well as the temperature of inlet and outlet streams of the medium flowing throughout the vessel. Signals from the temperature sensors were recorded by means of the multifunction computer meter CX-701.

Type of agitator. The mixing process was carried out by means of the novel type of agitator [Masiuk and Rakoczy, 2009]. The experimental measurements were performed using different configuration of the tested agitator (see Fig. 2).

The reciprocating agitator consisted of a single horizontal plate with four circular holes located in the moving plate in which rotating turbines were installed. The turbines were covered by the cups mounted on the upper side of the plate. The mounting of the cups enabled to rotate them around such that the direction of the cups openings could be changed. Three main arrangements of the cups of the tested agitator were investigated: open towards the axis of the vessel (Fig. 2a), open towards the heating wall (Fig. 2b) and removed (Fig. 2c).

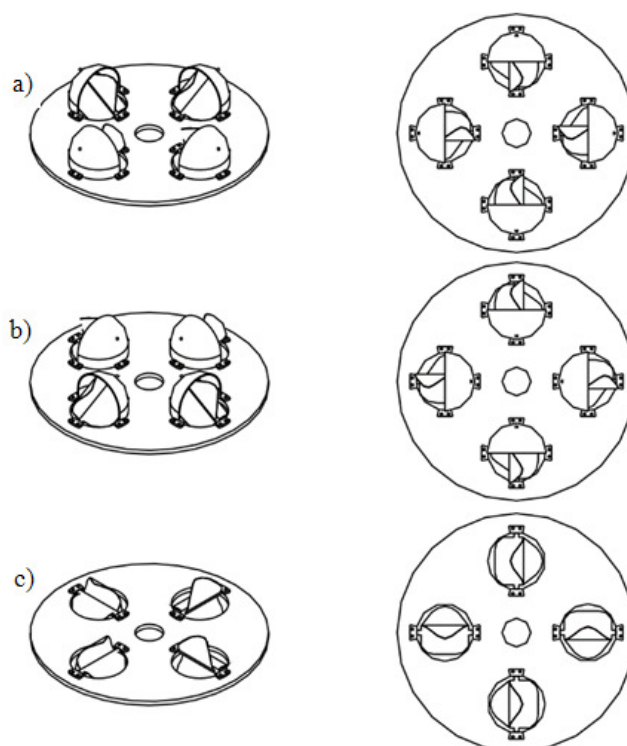


Fig. 2. The geometrical configuration of the tested reciprocating agitator

Range of tests. The flow rate of the mixed liquid (tap water) ranging between 0.0139 and 0.0556 kg·s⁻¹ was measured with a rotameter. The frequency of the reciprocating movement of the agitator was changed between 0.003 and 0.509 s⁻¹. The amplitude was varied between 0.04 and 0.23 m.

Results

The heat transfer coefficient is calculated on the basis of the assuming that the heat introducing through the heating jacket of the mixer is equal to the heat removed with the liquid. Based on the above assumption the averaged heat transfer coefficient, α_m , was calculated from the following relationship:

$$\alpha_m = \frac{F_{in-out} \lambda_w (T_{out} - T_{in})}{F_{in} s (T_{in} - T_l)} \quad (1)$$

where:

- F_{in-out} – mean inside and outside area of inner tube, [m²]; F_{in} – inside area of inner tube, [m²];
- s – tube wall thickness, [m];
- T_{out} – mean temperature of outside wall, [°C];
- T_{in} – mean temperature of inner wall, [°C];
- T_l – mean temperature within mixed liquid, [°C];
- α_m – mean heat transfer coefficient, [W·m⁻²K⁻¹];
- λ_w – thermal conductivity of heating wall material, [W·m⁻¹K⁻¹].

The relationship between the heat transfer coefficient and the mixing conditions may be expressed by means of the well-known *Nusselt* type equation [Hobler, 1986]:

$$Nu = f(Re, Pr) \quad (2)$$

In the case of the reciprocating mixers, this relation may be defined as follows [Masiuk, 1996a]:

$$Nu = f\left(Re_{flow}, Re_{rec}, Pr, \frac{Pr}{Pr_w}\right) \quad (3)$$

where:

- Nu – *Nusselt* number;
- Pr – *Prandtl* number;
- Pr_w – *Prandtl* number at wall temperature;
- Re_{flow} – *Reynolds* number for axial flow;
- Re_{rec} – *Reynolds* number for reciprocating agitator.

The above Eq. (2) may be rewritten in the following form:

$$\frac{\alpha_w D_m}{\lambda_w} = f\left(\frac{w_w D_m}{\nu}, \frac{2\pi A f d_h}{\nu}, \frac{c_p \rho}{\lambda_w}, \frac{c_p \rho}{\lambda_w |_{T_{in}}}\right) \quad (4)$$

where:

- A – amplitude of reciprocating movements of agitator, [m];
- c_p – specific heat of liquid, [J·kg⁻¹K⁻¹];
- d_h – hydraulic diameter of agitator, [m];
- D_m – inner diameter of tubular mixer vessel, [m];
- f – frequency, [s⁻¹];
- T_{in} – mean temperature of inner wall, [°C];
- w_w – velocity of liquid inside mixer, [m·s⁻¹];
- α_w – mean heat transfer coefficient at wall temperature, [W·m⁻²K⁻¹];
- λ_w – thermal conductivity of heating wall material, [W·m⁻¹K⁻¹];
- ν – kinematic viscosity of liquid, [m²s⁻¹];
- ρ – density of liquid, [kg·m⁻³].

In the case of the constant *Reynolds* number for axial flow

($Re_{flow} = \text{const}$), the general relation (3) is given by the relation:

$$Nu = p_1 Re_{rec}^{p_2} Pr^{p_3} \left(\frac{Pr}{Pr_w}\right)^{p_4} \rightarrow \frac{Nu}{Pr^{p_3} \left(\frac{Pr}{Pr_w}\right)^{p_4}} = p_1 Re_{rec}^{p_2} \quad (5)$$

where: p_1 and p_2 , are constants (these parameters are computed employing the *Matlab* software and the principle of least squares). The p_3 and p_4 are equal to 0.45 and 0.25, respectively [Masiuk and Rakoczy, 2007].

The obtained values of the parameters p_1 and p_2 are collected in Table 1. Moreover, the calculated values of the coefficient of determination are also presented in this table.

Table 1. The values of the parameters of Eq. (5) for the tested configuration of the reciprocating agitator

Re_{flow}	Configuration a (Fig. 2a)			Configuration b (Fig. 2b)			Configuration c (Fig. 2c)		
	p_1	p_2	R^2	p_1	p_2	R^2	p_1	p_2	R^2
620	11.52	0.33	0.91	8.96	0.40	0.95	11.89	0.35	0.90
1240	8.04	0.38	0.90	12.01	0.39	0.92	11.44	0.37	0.93
1830	6.42	0.41	0.95	29.35	0.32	0.93	8.31	0.41	0.94
2390	10.69	0.37	0.92	24.98	0.34	0.94	19.35	0.34	0.95

where R^2 is the coefficient of determination

In order to establish the effect of the dimensionless reciprocating *Reynolds* numbers on the heat transfer process, the typical experimental data obtained in this work are graphically illustrated in the log-log system in Fig. 3.

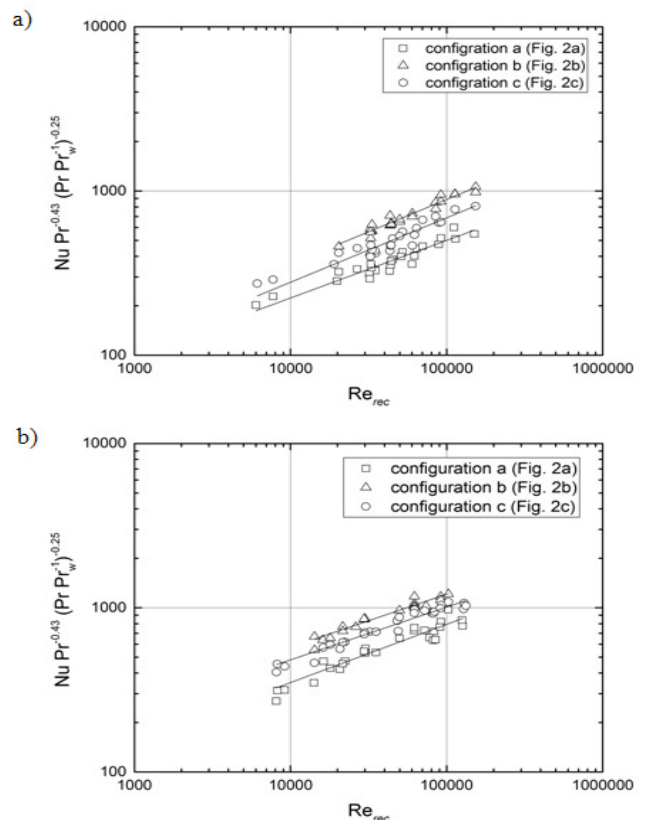


Fig. 3. The typical example of the effect of reciprocating *Reynolds* numbers on heat transfer process for the various values of *Reynolds* number for axial flow: a) $Re_{flow} = 620$, b) $Re_{flow} = 2390$

Figure 3 shows that the values of the *Nusselt* number for the tested configuration b (see Fig. 2b) of the reciprocating agitator are greater than the values of this dimensionless number obtained in this work for the other configurations of the agitator (see Fig. 2a and 2c). It should be noticed that the augmentation of the heat transfer ratio is connected with the flow regime. This configuration is allowed to produce the mixed liquid stream toward to the heating wall of the mixer. As follows from the analysis of Fig. 3, this construction of agitator is more effective for the tested region of the dimensionless *Reynolds* number for the axial flow. This leads to the conclusion that the heat transfer rate is mainly dependent on the geometrical configuration of the reciprocating agitator.

Conclusions

Several significant concluding remarks from the present investigations may be summarized as follows:

- It is shown that the geometrical configuration of the tested reciprocating agitator have a perceptible influence on the heat transfer from the wall of the heating jacket to agitated fluid flowing through the vessel. The mixer with the novel type of agitator is suitable for heat transfer process in the liquid system.
- From the results presented here it follows that the best heat transfer is obtained for the configuration b of the tested reciprocating agitator (see Fig. 2b). It was observed that the heat transfer coefficient for this configuration of agitator was about 300% higher as compared to the configuration a (see Fig. 2a) and configuration c (see Fig. 2c).
- It was found that modification of the dimensionless *Reynolds* number for the axial flow helped 1.2÷1.5 times improvement in the heat transfer coefficient.
- Thus, overall, it can be concluded that the tested reciprocating agitator has potential to provide efficient heat transfer rate during the process.

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