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Optimization of geometry of helical ribbon impeller operating in the laminar flow of the liquid

Introduction

One of the requirements of mixing is a maximal shortening of the time of the process which demands little energy. In the case of screw and ribbon impellers the time of homogenisation generally depends on the circulation time. It must be added that both parameters depend on secondary circulation in a mixer.

Secondary circulation V_s in a mixer may be understood as the volumetric intensity of the liquid flow in the r-z plane (radial – axial) which is strictly connected with pumping capacity of impellers. It is assumed that secondary circulation in the mixer is two times higher than its pumping capacity [*Stręk, 1971*].

In practice, secondary circulation is considered to be the volumetric flux of the liquid flowing through a ring the inner diameter of which is indicated by the centre of the circulation loop. The external diameter of the ring is marked by the wall of the mixer. The ring is located in the plane normal to the axis of the mixer at the height of the circulation loop centre. Instead in the case of screw impellers the centre of circulation loop overlaps with the diffuser wall due to the fact that it constitutes a stationary element the mixed liquid circulates about.

The circulation time τ_c may be understood as the time which is necessary for an element of fluid Fig. 1 (moving with defined mean velocity $\bar{v}$) to achieve a distance equal to one full circulation loop in the mixer. The mean circulation time τ_c may be calculated dividing the mixer volume V_{zb} [m^3] by secondary circulation V_s [m^3/s]

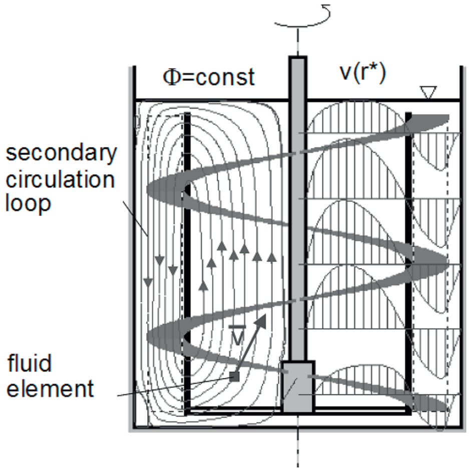

Fig. 1. Secondary circulation in a mixer, where: Φ – lines connecting points of equal dimensionless average axial velocity, r^* – dimensionless radius

$$\tau_c = V_{zb}/V_s, \tag{1}$$

The time of homogenisation τ_m [s] may be regarded as the time needed to obtain a defined degree of homogenization in the mixer being appropriate from the technological point of view. In the papers [*Szulc, 2004; Szulc and Kuncewicz, 2006*] it is stated that the homogenization time τ_m is strictly connected with the circulation time τ_c both in the turbulent and laminar flow by means of a simple functional equation. Furthermore, the homogenization time may be treated as the multiplication of the circulation time. The dependence may be defined using the following general equation

$$\tau_m = \beta\tau_c \tag{2}$$

where: β – proportionality coefficient.

The functional dependence, which may be found in the papers [*Szulc, 2004; Szulc and Kuncewicz 2006*] and define the relation between the homogenisation and circulation time in the laminar flow, shows a simple proportionality between the two parameters.

The value β [-] defines a number of circulation loops to be performed by an element of fluid so that the liquid obtains an adequately high degree of mixing. Thus, assuming, similarly as for the laminar flow, a simple relation between the values τ_m and τ_c on the basis of the available literature data [*Szulc, 2004*], the author established one's own value of the proportionality coefficient $\beta = \tau_m/\tau_c$. The way of how it had been obtained was defined in the study [*Szulc and Kuncewicz, 2006*] Nevertheless, such a value of the proportionality coefficient $\beta \cong 3.33$ should be regarded as an indicatory one. As evidenced in the paper [*Stręk, 1971*], the value of the proportionality coefficient β in the turbulent flow oscillates about 4÷5. The lower value of the coefficient obtained for the laminar flow is not equivalent to, generally being shorter, the times of homogenization when compared to the turbulent flow. Therefore, the values of the coefficients β should not be compared (the times of circulation attain many times smaller values in the turbulent flow).

Additionally, the time of homogenization τ_m and time of circulation τ_c may be defined using the appropriate modules of the homogenization time K_m

$$K_m = \tau_m N \tag{3}$$

and circulation time K_c

$$K_c = \tau_c N \tag{4}$$

The dimensionless number K_c defines such a number of mixer's rotations with which an element of liquid achieves a distance of one circulation loop.

The dimensionless time of homogenization, on the other hand, defines a number of mixer's rotations being necessary to obtain a defined degree of homogenization [*Szulc and Kuncewicz, 2006*].

An increase in secondary circulation brings about a decrease in circulation time which, in turn, contributes to a decrease in mixing time. Nevertheless, the drive of an impeller requires a supply of defined energy depending on the structure of the impeller, its geometrical parameters, rotation frequency and the physical-chemical properties of mixed liquid. Screw and ribbon impellers as a class of close-clearance impellers, generally consume a lot of energy. Furthermore, due to their purpose (for mixing of high viscous liquids) an increase in viscosity of liquid is connected with a linearly proportional increase in the mixing power.

Moreover, for the laminar regime of mixing, an increase in rotations of the impellers contributes to an increase in the mixing power to the second power of rotations $P \sim N^2$, and an increase in diameter increases the mixing power in proportion of $P \sim d^3$. The aforementioned factors contribute to the fact that there is no possibility of optional shortening of the mixing time by an optional manipulation of impeller's geometry or regulation of rotations. This is due to the fact that a relevant parameter, which has to be considered from the point of view of the homogenization time, is the mixing power. The mutual relationships between the mixing power and homogenization time prove the operating effectiveness of a given impeller. Hence, the smaller the power needed to obtain a predefined technological effect or the shorter homogenization time for

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given impellers with their unchanged power input, the more effective work of a given impeller.

On the basis of the aforementioned factors one may derive an energetic criterion of the mixing effectivity e_m which is the product of the homogenization time τ_m and mixing power P

$$e_m = \tau_m P \tag{5}$$

As a result, it defines the so-called energy of mixing, in other words an amount of energy that has to be provided to a defined system to obtain an appropriate, from the technological point of view, degree of homogenization.

In the laminar flow the dimensionless homogenization times K_m and circulation times K_c are constant and do not depend on the *Reynolds* number [-]. Thus, for this range of the *Reynolds* number the following dependence is valid $\tau_m = K_m / N$. In addition, knowing that in the laminar flow the dependence

$$NeRe = A \tag{6}$$

is valid,

where:

$$Ne = \frac{P}{N^3 d^5 \rho} \tag{7}$$

$$Re = \frac{Nd^2 \rho}{\eta} \tag{8}$$

the mixing power may be calculated from the following equation

$$P = AN^2 d^3 \eta \tag{9}$$

where:

d – the diameter of an impeller [m],
η – viscosity [Pa·s],
ρ – density [kg/m^3]

applying the classical definitions of the *Reynolds* number *Re* and power *Ne* described in [*Stręk, 1971; Szulc, 2004*]. Hence, the proposed energetic criterion e_m acquires the following form

$$e_m = P\tau_m = A\, K_m\, Nd^3 \eta \tag{10}$$

Just set the efficiency can be used to optimize the system impeller – mixer. The optimization in the case of the homogenization time defines the selection of system's geometry in such a way that with the unchanged power intake one could obtain the best intensity of mixing, i.e. the shortest mixing time. As evidenced in e_m equation the lower the value of effectivity e_m, the more effective operation of a given impeller.

The wide spread of experimental mixing time data explains the fact that even though, ribbon impellers have been widely used, no relationship has been proposed in the literature to correlate the variation of K_m with the geometrical variables of the ribbon impellers. The available literature investigating the helical ribbon mixing performance is quite diverse. The geometrical features of the helical ribbon impellers are one of the most studied aspects: single ribbon, double ribbon, for e.g.: [*Delaplace et al., 2000; Maingonnat et al., 2008; Rahimi et al. 2010; Dieulot et al., 2002.*]

The aim of this study was to optimize the work ribbon agitator working in the tank based on the proposed energy criterion, based on experimental data and model, for a given set of selected impellers.

Experimental

The investigations concerning the measurements of the velocity components in circumferential and axial directions, in the region of an impeller for ribbon impellers, in the laminar flow, were carried out. The main element of the measurement system was: the BSA *Doppler* laser anemometer (*Burst Spectrum Analyser*, *Dantec*). The examinations connected with mixing power were performed using a measuring apparatus MR-D1 (*IKA Labortechnik Staufen*) (measurement error -1.5%, the reproducibility of the results ±0.5%). A detailed description of the investigation and research stand is attached to the paper [*Szulc, 2004*].

The investigations were carried out for five ribbon impellers differing in terms of the diameter and pitch of a ribbon. In each case the ribbon impeller was centrally located inside the mixer and mounted at half of the height of the tank. The parameters of the impellers under scrutiny are summarized in Tab. 1.

Tab. 1. Parameters of helical-ribbon impellers

Impeller	Diameter of impeller *d* [m]	*d/D* [-]	Height *h* [m]	*h/D* [-]	A number of coils *i* [-]	Pitch of ribbon *p* [m]	*p/d* [-]	The ribbon angle *β* [°]
R1	0.28	0.959	0.26	0.890	1	0.260	0.929	72.6
R2	0.28	0.959	0.26	0.890	2	0.130	0.464	80.6
R3	0.28	0.959	0.26	0.890	3	0.087	0.311	83.7
R4	0.27	0.925	0.26	0.890	2	0.130	0.481	80.2
R5	0.26	0.890	0.26	0.890	2	0.130	0.5	79.8

The viscosity was measured using the *Rheotest 2* apparatus and *Hoeppler* viscometer.

A flat-bottomed glass tank of diameter $D = 0.292$ [m] was filled with liquid to the height equal to the diameter of the tank ($H/D = 1$).

The liquid investigated was the solution of *Optima* potato syrup of viscosity $0.43 \le \eta \le 8.06$ [Pa·s]. The density of the syrup ρ was 1350±5 [kg/m^3].

A change in the hydrodynamics of the system and simultaneously a change in the *Reynolds* number *Re*, was obtained by means of the change of rotations N of the impeller for the established viscosity η, or by means of a change in viscosity η for the driving system operating with a constant rotation frequency ω [1/s].

Results and discussion

In accordance with the aim of the study the evaluation of the operation effectiveness of the investigated ribbon impellers was performed from the homogenisation time point of view and based on a 3D solution of the TSN (three-dimensional numeric simulation) dimensionless model presented in the study and the experimental investigations.

In Tab. 2 one may find the dimensionless numbers K_s, K_c, K_m, circulation time τ_c and homogenization time τ_m for the investigated ribbon impellers, obtained on the basis of the experimental mean axial velocity distributions in a radial direction presented in the papers [*Szulc, 2004; Szulc and Kuncewicz, 2006*]. The way of calculation of those velocities has been described. The prerequisite to obtain their numeric values was the definition of secondary circulation in the mixer V_s [m^3/s]. The calculation of V_s slightly differs for screw impellers or ribbon impellers but in both cases the value V_s is given in the form of the dimensionless number of secondary circulation K_s defined by the equation

$$K_s = \frac{V_s}{Nd^3} \tag{11}$$

In Tab. 2 one can find the experimental results of the dimensionless numbers K_s, K_c, K_m as well as the circulation times τ_c and homogenization times τ_m obtained for the ribbon impellers under scrutiny in the selected areas of the mixer (in the all areas of the tank). To calculate the homogenization time τ_m the value of the coefficient $\beta = 3.333$ defined by the Eq. (2) was used.

$$V_{s1} = 2\pi \int_{r(\bar{u}_v=0)}^{R_2} (r\bar{u}_v(r))dr \tag{12}$$

$$V_{s2} = 2\pi \int_{r_p}^{r(\bar{u}_v=0)} (r\bar{u}_v(r))dr \tag{13}$$

where:

V_{s1} – the volumetric intensity of the liquid flow in the area of the ribbon impeller and in the close-clearance area near the tank wall,
V_{s2} – the volumetric flow of the liquid in the area of the liquid [m^3/s],
R_2 – the inner radius of the tank [m],
$\bar{u}_v$ – the mean actual axial velocity [m/s],

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r_p – the external radius of the shaft in the tank [m].

Due to minor measurement errors, the experimental values of secondary circulation for the region of the impeller with close-clearence region and liquid only slightly differed, thus in further sections of the chapter the mean values of secondary circulation obtained from both regions were applied to evaluate the effectivity of ribbon impellers operation. Those values in combination with the model values obtained in an analogous way, but on the basis of the solution of the presented 3D model [*Szulc, 2004*], are summarized in Tab. 3.

Tab. 2. The experimental dimensionless numbers K_s , K_c, K_m and circulation times τ_c and homogenization times τ_m for ribbon impellers for $N = 1$ [s^{-1}] and liquid viscosity η = 10 [Pa·s]

d [m]	d/D	i [-]	p/d	Imp. a.	V_{s1} [m^3·s^{-1}]	K_s	τ_e [s]	τ_m [s]	K_c	K_m
				Liq. ar.	V_{s2} [m^3·s^{-1}]	K_s	τ_e [s]	τ_m [s]	K_c	K_m
0.280	0.959	1	0.964	Imp. a.	0.00167	0.0705	11.7	39.0	12.4	41.4
				Liq. a.	0.00163	0.0691	12.0	39.9	12.7	42.3
0.280	0.959	2	0.482	Imp. a.	0.00110	0.0466	17.7	59.0	18.8	62.6
				Liq. a.	0.00108	0.0456	18.2	60.5	19.2	64.1
0.280	0.959	3	0.321	Imp. a.	0.00071	0.0301	27.5	91.5	29.1	97.0
				Liq. a.	0.00066	0.0277	29.8	99.3	31.6	105
0.270	0.925	2	0.500	Imp. a.	0.00107	0.0505	18.3	60.8	19.4	64.5
				Liq. a.	0.000974	0.0459	20.1	66.9	21.3	70.9
0.260	0.890	2	0.519	Imp. a.	0.00083	0.0437	23.6	78.7	25.0	83.4
				Liq. a.	0.00097	0.0514	20.1	67.0	21.3	71.0

According to the expectations, the shortest times of homogenization were obtained for the impeller of the greatest diameter. This fact was connected with the highest value of secondary circulation V_s for this impeller (Tab. 2). What is more, the shortest times of homogenization for the pitch of the ribbon $p = 0.260$ [m] were obtained for the impellers of constant diameter $d = 0.280$ [m] due to the fact that it is this type of an impeller that displayed the highest secondary circulation, which is in agreements with the experimental results [*Kuncewicz et al., 2005*]. It must be underlined that Tab. 2 does not encompass the energy consumption of the individual impellers.

Tab. 3. Experimental and model mean values of homogenization times $\bar{\tau}_m$ and dimensionless numbers $\bar{K}_m$ of ribbon impellers for $N = 1$ [s^{-1}] and liquid viscosity $\eta = 10$ [Pa·s]

d/D	Diam.of an impeller d [m]	Number of coils i [-]	p/d	Exp. $\bar{K}_m$	Mod. K_m	Exp. $\bar{\tau}_m$ [s]	Mod. τ_m [s]
0.959	0.280	1	0.964	41.8	43.3	39.4	40.9
0.959	0.280	2	0.482	63.4	65.3	59.8	61.6
0.959	0.280	3	0.321	101.2	101.7	95.4	96.2
0.925	0.270	2	0.500	67.7	70.3	63.8	66.3
0.890	0.260	2	0.519	77.2	76.3	72.8	72.0

In Fig. 2 the experimental mean dimensionless values of the homogenisation times $\bar{K}_m$ and model values K_m (obtained on the basis of the Author's own model (3D) described in [*Szulc, 2004*] in a diameter pitch function p/d for the screw impeller of diameter invariant $d/D = 0.959$ are compared. Analogously, in Fig. 3 the mean experimental and model values of the homogenization times K_m in a diameter invariant function d/D for the impeller of coil number $i = 2$ are compared.

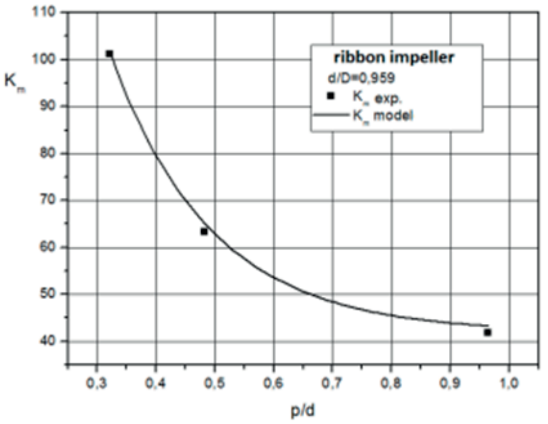

Fig. 2. Comparison of dimensionless homogenisation times K_m in a pitch invariant function *p/d* for a ribbon impeller

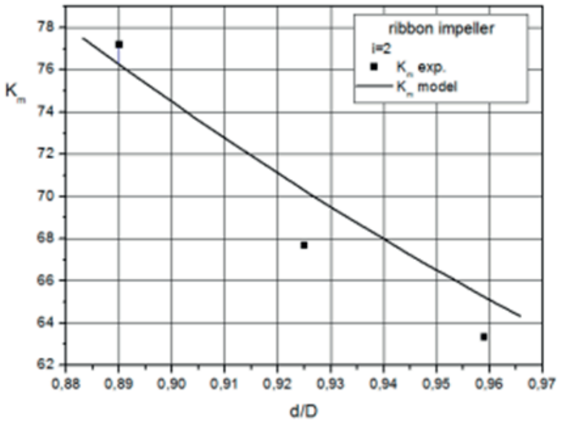

Fig. 3. Comparison of mean dimensionless homogenization time $\bar{K}_m$ in a diameter invariant function *d/D* for a ribbon impeller

The mean differences between the experimental and model values K_m are ~8% and the value of K_m decreases with an increase in pitch and diameter of a ribbon which is in agreement with the conclusions in the literature on the subject [*Carreau et al., 1976; Chavan and Ulbrecht, 1973; Delaplace et al., 2000; 2006; Dieulot et al., 2002; Fradette et al., 2007; Ho and Kwong, 1973; Ihejirika, and Ein-Mozaffari, 2007; Kaminoyama et al., 1999; Kuncewicz et al., 2001; Kuncewicz and Pietrzykowski, 2001; Kuncewicz et al., 2003; Kuncewicz et al., 2005; Maingonnat et al., 2008; Rahimi et al. 2010; Nagata et al., 1956; Niedzielska, 2004; Novak, 1970; Prokopec and Ulbrecht, 1970; Sanjuan-Galindo et al., 2011; Seichter, 1981; Seichter et al., 1981; Serwiński and Błasiński, 1960; Stręk, 1971; Szulc, 2004; Szulc and Kuncewicz, 2006; Takahashi et al., 1982*].

As it has been previously mentioned, the evaluation of screw impeller operating effectivity regarding the homogenization times requires the mixing power to be considered.

Tab. 4. Mean experimental and model values of homogenization times τm, mixing power and an energetic criterion em for the investigated ribbon impellers, for $N = 1$ [s^{-1}] and liquid viscosity $\eta = 10$ [Pa·s]

d/D	d [m]	i	p/d	Re	$\bar{\tau}_{m\exp.}$ [s]	$\tau_{m\mathrm{mod.}}$ [s]	P [W]	Exp. $e_m = (\bar{\tau}_m P)$ [J]	Model $e_m = (\tau_m P)$ [J]
0.959	0.280	1	0.964	10.6	39.48	40.86	50.49	1993.3	2063.0
0.959	0.280	2	0.482	10.6	59.76	61.56	69.80	4171.7	4297.3
0.959	0.280	3	0.321	10.6	95.41	96.20	85.61	8168.3	8236.0
0.925	0.270	2	0.500	9.8	63.86	66.32	51.77	3305.8	3433.1
0.890	0.260	2	0.519	9.1	72.82	71.95	43.41	3161.3	3123.5

In Tab. 4 the experimental and model values of the mixing times τ_m, mixing power P and the values of the introduced energetic mixing criterion $e_{m\,=}\,\tau_m P$ [J] are summarized. The criterion allows to find an optimal system regarding both the power and time of homogenization. The analysis is devoted to finding the energetic extremum of the minimum of the function.

$$e_m = (\tau_m P)_{p/d}^{d/D} \rightarrow \min . \tag{14}$$

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From the analysis of Tab. 4 it may be concluded that an optimal ribbon impeller regarding the effectivity criterion was the impeller of diameter invariant *d/D* = 0.959 and pitch invariant being equal *p/d* = 0.964 (the frame in bold). The key element in this case was too high value of secondary circulation V_s for this ribbon (Tab. 2). The pitch of the impeller is approximate to the value of the optimal pitch ratio described in the subject literature [*Szulc, 2004*] as *p/d* ≅ 0.5 and *d/D* = 0.95. The above considerations imply that the ribbon impellers of too small diameters should not be used due to the fact that their small size contributes to the formation of the incomparably small secondary circulation in the mixer.

Conclusions

The analysis allows to draw the following conclusions:

- On the basis of a simple proportionality of the circulation and homogenization times and using the 3D model solutions (proposed in the study [*Szulc, 2004*]) the optimization of ribbon impellers regarding the homogenization time may be carried out.
- In the case of ribbon impellers the homogenization time increases with a decrease in the pitch of a ribbon and decrease in impeller's diameter (within the investigated changes of the geometrical parameters of the impeller).
- In the case of ribbon impellers the mixing power increases with a decrease in the clearance between the edge of the impeller and internal wall of the tank and with a decrease in the ribbon pitch of the impeller.
- The optimal parameters regarding the homogenization times may be attributed to the ribbon impeller, the diameter and screw pitch ratio of which were only slightly different from *d/D* ≅ 0.959 and *p/d* ≅ 0.964.
- It has been stated that, in practice, the ribbon impellers of too small diameters should not be used due to the fact that their small size contributes to the formation of incomparably small secondary circulation in the mixer.

REFERENCES

Carreau P.J., Patterson I., Yap C.Y., 1976. Mixing of viscoelastic fluids with helical-ribbon agitators - I. Mixing time and flow patterns. *The Can. J. Chem. Eng.* **54**, 135-142. DOI: 10.1002/cjce.5450540303

Chavan V.V., Ulbrecht J., 1973. Power correlations for close-clearance screw impellers in non-newtonian liquids, *Ind. End. Chem. Process Des. Develop.,* **12**, 472-476

Delaplace G., et al., 2000. Circulation and mixing times for helical ribbon impellers. Review and experiments. *Experiments in Fluids,* **28**, 170-182. DOI: 10.1007/s003480050022

Delaplace G., et al., 2006. An analytical model for the prediction of power consumption for shear-thinning fluids with helical ribbon and helical screw ribbon impellers. *Chem. Eng. Sci.* **61**, 3250–3259. DOI: 10.1016/j.ces.2005.11.069

Dieulot J.-Y., Delaplace G., Guerin R., Brienne J.-P., Leuliet J.-C., 2002. Laminar mixing performances of a stirred tank equipped with helical ribbon agitator subjected to steady and unsteady rotational speed. *Chem. Eng. Res. Des.,* **80**, nr 4, 335-344. DOI: 10.1205/026387602317446371

Fradette L., et al., 2007. CFD phenomenological model of solid–liquid mixing in stirred vessels. *Comp. Chem. Eng.* 31, 334–345. DOI: 10.1016/j.compchemeng.2006.07.013

Ho F.C., Kwong A., 1973. A guide to designing special agitators. *Chem. Eng.* nr 7, 94

Kaminoyama M., Watanabe M., Nishi K., Kamiwano M., 1999. Numerical simulation of local heat transfer coefficient in stirred vessel with impeller for highly viscous fluids, *J. Chem. Eng. Japan*, **32**, nr 1, 32-30. DOI: 10.1252/jcej.32.23

Ihejirika I., Ein-Mozaffari F., 2007. Using CFD and Ultrasonic Velocimetry to Study the Mixing of Pseudoplastic Fluids with a Helical Ribbon Impeller. *Chem. Eng. Technol.,* **30**, nr 5, 606–614. DOI: 10.1002/ceat.200700006

Kuncewicz C., Pietrzykowski M., 2001. Hydrodynamic model of a mixing vessel with pitched-blade turbines. *Chem. Eng. Sci.*, **56**, nr 15, 4659-4672. DOI: 10.1016/S0009-2509(01)00119-1

Kuncewicz C., Pietrzykowski M., Szulc K., 2001. Modelowanie hydrodynamiki mieszalnika dla mieszadeł wstęgowych pracujących w ruchu laminarnym, *Inż. Chem. Proc.* **22**, 461-481

Kuncewicz C., Szulc K., Budzyński P. 2001. Modelowanie przepływu cieczy wysokolepkiej w mieszalniku dla mieszadeł ślimakowych*, Inż. Chem. Proc.* **22**, 3C, 837-842

Kuncewicz C., Szulc K., Kurasiński T., 2003. Hydrodynamika cieczy wysokolepkiej wewnątrz mieszalnika z mieszadłem ślimakowym bez dyfuzora, *Inż. Ap. Chem*. **42**, nr 3s, 107-108

Kuncewicz C., Szulc K., Kurasiński T., 2005. Hydrodynamics of the tank with a screw impell*er*, *Chem. Eng. Proc.* **44**, 766-774, DOI: 10.1016/j.cep.2004.08.006.

Maingonnat J.F., Doublier J.L., Lefebvre J., Delaplace G., 2008. Power consumption of a double ribbon impeller with newtonian and shear thinning fluids and during the gelation of a iota-carrageenan solution. *J. Food Eng.* 87, 82–90. DOI: 10.1016/j.jfoodeng.2007.11.015

Rahimi M., Kakekhani A., Alsairafi A.A., 2010. Experimental and computational fluid dynamic (CFD) studies on mixing characteristics of a modified helical ribbon impeller. *Korean J. Chem. Eng.*, 27, nr 4, 1150-1158. DOI: 10.1007/s11814-010-0222-7

Nagata S., Yanagimoto M., Yokoyama T., 1956. Studies on the mixing of high viscous liquids. *Mem. Fac. Eng.* Kyoto Univ. **18**, 444-460

Niedzielska A., 2004. *Modelowanie wymiany ciepła dla mieszadła wstęgowego*. Praca doktorska. Politechnika Łódzka, Łódź

Novak V., 1970. *Thesis,* Prague Institute of Chemical Technology, Prague

Prokopec L., Ulbrecht J., 1970. Rührleistung eines Schraubenrührers mit Leitrohr beim Mischen nichtnewtonscher Flüssigkeiten. *Chem.-Ing.-Tech.* **42**, 530-534. DOI: 10.1002/cite.330420804

Sanjuan-Galindo R., Heniche M., Ascanio G., Tanguy P.A., 2011. CFD investigation of new helical ribbon mixers bottom shapes to improve pumping. *Asia-Pac. J. Chem. Eng.;* 6, 181–193. DOI:10.1002/apj.537

Seichter P., 1981. Process characteristics of screw impellers with a draught tube for newtonian liquids. Pumping capacity of the impeller, *Coll. Czech. Chem. Commun*., **46**, 2020-2031

Seichter P., Dohnal J., Rieger F., 1981. Process characteristics of screw impellers with a draught tube for newtonian liquids. The power input, *Coll. Czech. Chem. Commun*., **46**, 2007-2020,

Serwiński M., Błasiński H., 1960. *Chem. Stos*, **3-4**, 325,

Stręk F., 1971. *Mieszanie i mieszalniki*, WNT, Warszawa

Szulc K., 2004. *Modelowanie przepływu w mieszalniku – zakres laminarny, mieszadła wstęgowe i ślimakowe*, Rozprawa doktorska, Politechnika Łódzka, Łódź

Szulc K., Kuncewicz Cz., 2006. Modelling of mixing time for ribbon impellers. *Inż. Chem. Proc*. **27**, 567-577

Takahashi K., Sasaki M., Arai K., 1982. Effects of geometrical variables of helical ribbon impellers on mixing of highly viscous newtonian liquids, *J. Chem. Eng. Japan,* **15**, 217-224. DOI: 10.1252/jcej.15.217

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