# Efficiency of the Heat Transfer Process in a Jacketed Agitated Vessel Equipped with an Eccentrically Located Impeller*

J. KARCZ and M. CUDAK

*Department of Chemical Engineering, Technical University of Szczecin,*
*PL-71 065 Szczecin*
*e-mail: joanka@carbon.tuniv.szczecin.pl*

Received 30 March 2002

The paper presents the results of an experimental study on the efficiency of the heat transfer process in a jacketed, unbaffled agitated vessel of different slenderness, equipped with eccentrically located HE 3 impeller or propeller. The efficiency of the process was evaluated on the basis of the measured values of the heat transfer coefficient and power consumption. The measurements were carried out in the turbulent flow of a Newtonian liquid. Liquid aspect ratio of the agitated vessel was varied from 0.5 to 1.5 and the eccentricity of the impeller shaft was in the range from 0 to 0.53. The measured quantities were approximated analytically.

Vertical shaft with an impeller is usually located in a centric position inside the cylindrical agitated vessel. Sometimes the shaft can be displaced to a certain distance $e$ from the vertical axis of the vessel. Eccentric location of the impeller in the agitated vessel can be useful in some cases. Agitation of viscous liquid in the agitated vessels without baffles can be given as an example. In the case of liquid agitation in the cascade of large vessels, single construction of the drive can be used for mounting of two impeller shafts in the neighbouring vessels.

In comparison with the unbaffled agitated vessel with the centrally located impeller shaft, the depth of the free surface vortex around the shaft decreases in the unbaffled agitated vessel with the eccentrically located shaft. Moreover, the effects of the agitation observed in the agitated vessel of such geometry are partially similar to those, which were found in the baffled agitated vessel with centrally located impeller [1—4].

An effect of the eccentricity $e/R$ of the impeller shaft on the power consumption was studied by *Dyląg* and *Brauer* [5], *King* and *Musket* [6], and *Paszek* [7]. *Medek* and *Fort* [8] experimentally analyzed the effect of the parameter $e/R$ on the efficiency of the agitator, which was defined as the ratio of the pumping capacity to the power consumption. *Rzyski* [9] studied the efficiency of the high-speed impellers within the transitional range of the fluid flow. The dependence of the mixing time of the liquid on the eccentricity of the impeller shaft was investigated by *Seichter et al.* [10]. Cavitation effects in eccentric-cylinder flows of Newtonian and non-Newtonian liquids were analyzed by *Ashrafi et al.* [11]. *Karcz* and *Cudak* [12, 13] studied the effect of the eccentricity of the shaft with the propeller agitator on the heat transfer coefficient in the jacketed agitated vessel.

The purpose of the studies presented was to investigate the efficiency of the heat transfer process in the jacketed, unbaffled agitated vessel of different slenderness, equipped with the eccentrically located HE 3 impeller or propeller. The efficiency of the process was analyzed on the basis of the measurements of the heat transfer coefficients and power consumption obtained for the agitated vessel.

## EXPERIMENTAL

The studies of heat transfer process and power consumption were carried out in the jacketed agitated vessel equipped with the eccentrically located shaft of impeller. The vessel of inner diameter $D = 0.45$ m was filled with liquid up to the height $H$ equal to $0.5D$, $D$ or $1.5D$. Eccentricity $e/R$ (where $R = D/2$) was varied within the range of $\langle 0; 0.53\rangle$. The measurements were conducted for the centric position of the shaft in the unbaffled vessel ($e/R = 0$) and for the four eccentric positions of the shaft ($e/R = 0.13$, 0.27, 0.4, and 0.53). The liquid was agitated using the impellers of the diameter $d = 0.33D$ with $Z = 3$ blades, generating the axial circulation of the fluid in the vessel. The HE 3 impeller working at the down-pumping mode and propeller with the pitch $S = d$ acting as

*Presented at the 29th International Conference of the Slovak Society of Chemical Engineering, Tatranské Matliare, 27—31 May 2002.

the up-pumping agitator were used. Maximum width of the propeller blades was equal to $b = 0.2d$. The distance between the impeller and flat bottom of the agitated vessel was equal to $h = 0.33D$. The experiments were carried out within the turbulent regime of the Newtonian liquid flow in the agitated vessel. Machine oil, with the viscosity of about $4.5 \times 10^{-3}$ Pa s at temperature of 70 ℃, was agitated.

Mean heat transfer coefficients $\alpha$ were measured under steady-state conditions. The agitated vessel was equipped with a jacket, a flat nonheated bottom, and an eccentrically located agitator. Vertical wall of the vessel of thickness 5 mm was made of copper. The driving system of the agitator consisted of the belt transmission and an electric motor coupled with a steering unit. Agitator speeds were measured by means of the electronic counter, which was connected with the potential source and reed relays as sensors being placed above the magnet.

The liquid circulated in the system *via* an overflow of the agitated vessel, an intermediate vessel, liquid cooler, circulating pump, a rotameter, and a pipe in the flat bottom of the agitated vessel. Heating jacket was filled with steam of temperature about 102 ℃ and a condensate was collected in the condenser pots. All temperatures in the agitated vessel were measured with the accuracy ±0.1 ℃ with the thermocouples connected to a point recorder.

Torque, needed to calculate the power consumption was determined by means of the strain gauges method. Measuring system consisted of a torsional sleeve with the strain gauges, a converter, and Hottinger's amplifier.

Heat transfer coefficient $\alpha$ on the side of the agitated liquid was determined from the thermal resistance equation which relates overall heat transfer coefficient $k$ with the wall thermal conductivity $\lambda$ and film heat transfer coefficients on both sides of the heat transfer surface area. The coefficient $k$ can be calculated when heat flux $Q$, heat transfer surface area $F$, and driving difference of temperature $\Delta t_{\mathrm{m}}$, are known. Heat flux $Q$ was determined from the thermal balance equation, which was formulated for the circulating flow $G$ of the liquid, heated in the agitated vessel from the inlet temperature $t_1$ up to outlet temperature $t_2$. Difference between mean bulk temperature $t_{\mathrm{m}}$ of the agitated liquid and steam temperature $t_{\mathrm{p}}$ was calculated as mean difference of temperature $\Delta t_{\mathrm{m}}$. Thermal equilibrium at a given measurement was reached after 30—40 min.

## RESULTS AND DISCUSSION

The effects of the shaft eccentricity within the range $e/R \in \langle 0; 0.53 \rangle$ and the liquid aspect ratio within the range $H/D \in \langle 0.5; 1.5 \rangle$ on the heat transfer coefficient $\alpha$ were evaluated on the basis of 560 experimental data. These data were obtained in the turbulent regime of the Newtonian fluid flow ($Re \in \langle 10^4; 3 \times 10^4 \rangle$) in the jacketed agitated vessel without baffles. For the comparative purposes, the results of the measurements of the heat transfer coefficient in the baffled vessel with the centrally located impeller were also used. The results of the studies were described by means of the equation

$$Nu = \frac{\alpha D}{\lambda} = C\,(e/R, H/D)\,Re^{A} Pr^{0.33} Vi^{0.14} \qquad (1)$$

where

$$Re = \frac{nd^2\rho}{\eta} \quad Pr = \frac{c_p \eta}{\lambda} \quad Vi = \frac{\eta}{\eta_w} \qquad (2)$$

The dependences $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re)$ for a given position of the HE 3 impeller ($e/R$ = const) and varying liquid aspect ratio ($H/D \neq$ const) are presented in Fig. 1. The results obtained show that the heat transfer coefficient decreases with the increase of the parameter $H/D$.

The dependences $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re)$ for a given liquid aspect ratio equal to $H/D = 0.5$ and various positions of the HE 3 impeller in the agitated vessel ($e/R \neq$ const) are presented in Fig. 2. As the data in Fig. 2 show, heat transfer coefficients reach the greatest values for the most eccentric position of the impeller shaft in the agitated vessels without baffles.

All the results of measurements of the heat transfer coefficients for the agitated vessel without baffles were approximated by means of eqn (*1*), in which statistically evaluated exponent $A = 0.67 \pm 0.1$ was used. Assuming mean value of the $A = 0.67$ in eqn (*1*), the following equations were proposed for the agitated vessel equipped with the HE 3 impeller

$$Nu = \frac{\alpha D}{\lambda} = 0.24 Re^{0.67} Pr^{0.33} Vi^{0.14} \left(\frac{H}{D}\right)^{-0.23} \cdot$$
$$\cdot \left[1.51 \left(\frac{e}{R}\right)^2 - 0.316 \left(\frac{e}{R}\right) + 1\right] \qquad (3)$$

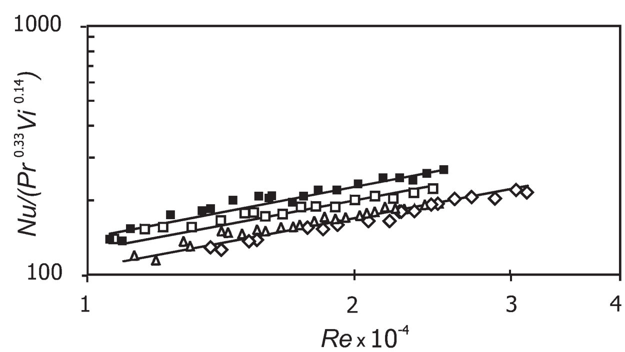


**Fig. 1.** The dependence $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re)$ for the unbaffled agitated vessel with the HE 3 impeller; $H/D \neq$ const; $J = 0$; filled squares – $e/R = 0$, $H/D = 0.5$; squares – $e/R = 0.13$, $H/D = 0.5$; triangles – $e/R = 0.13$, $H/D = 1$; diamonds – $e/R = 0.13$, $H/D = 1.5$.

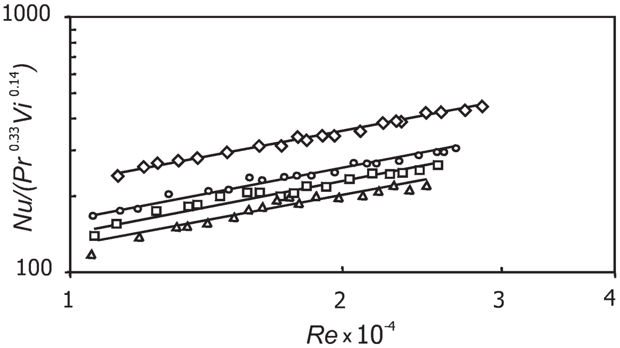


**Fig. 2.** The dependence $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re)$ for the baffled and unbaffled agitated vessel with the HE 3 impeller and constant $H/D = 0.5$: diamonds – $J = 4$, $e/R = 0$; squares – $J = 0$, $e/R = 0$; triangles – $J = 0$, $e/R = 0.27$; circles – $J = 0$, $e/R = 0.53$.

and for the agitated vessel equipped with the propeller

$$Nu = \frac{\alpha D}{\lambda} = 0.217 Re^{0.67} Pr^{0.33} Vi^{0.14} \left(\frac{H}{D}\right)^{-0.16} \cdot \left[1.628\left(\frac{e}{R}\right)^2 - 0.189\left(\frac{e}{R}\right) + 1\right] \quad (4)$$

Eqns (3) and (4) approximate the experimental data with the mean relative error of 9 % and describe these data in the turbulent regime of the liquid flow ($Re \in \langle 1 \times 10^4; 3 \times 10^4 \rangle$), the eccentricity of the impeller shaft $e/R \in \langle 0; 0.53 \rangle$, and liquid aspect ratio $H/D \in \langle 0.5; 1.5 \rangle$.

An analysis of the experimental data shows that the intensity of the heat transfer process depends strongly on the shaft eccentricity $e/R$ in the jacketed unbaffled agitated vessel, equipped with the propeller or HE 3 impeller. Assuming $H/D$ = const, heat transfer coefficients increase by about 36 % or 26 % in both agitated vessels, respectively, with the increase of the eccentricity within the range of the $e/R \in \langle 0; 0.53 \rangle$. These coefficients decrease by about 18 % or 25 %, respectively, within the range of the parameter $H/D \in \langle 0.5; 1.5 \rangle$ and for a given eccentricity ($e/R$ = const).

Experimental studies of the power consumption for the agitated vessel without baffles revealed that power number $Ne$ strongly depends on the eccentricity $e/R$ of the impeller shaft. Power number $Ne$ increases with the increase of the parameter $e/R$ reaching for the most eccentricity the value comparable with the data ascribed to the baffled vessel.

An efficiency of the heat transfer process in the jacketed agitated vessel with the eccentrically located impeller was analyzed on the basis of the equation proposed by *Stręk* and *Karcz* [14]

$$Nu = \frac{\alpha D}{\lambda} = \left(\frac{\pi}{4}\right)^{A/3} K (Re_{P,V})^{A/3} Pr^{0.33} Vi^{0.14} \quad (5)$$

The coefficient $K$ in eqn (5) defined as

$$K = \left(\frac{H}{D}\right)^{A/3} \left[\frac{C}{Ne\,(D/d)^{A/3}}\right] \quad (6)$$

where $Ne = P/n^3 d^5 \rho$ denotes power number, depends only on the geometrical parameters of the agitated vessel. In eqn (5), the modified Reynolds number depending on the power consumption per volume $P/V$ is expressed as follows

$$Re_{P,V} = \frac{(P/V)\, D^4 \rho^2}{\eta^3} \quad (7)$$

The dependences $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re_{P,V})$ for the agitated vessels of the liquid aspect ratio $H/D = 0.5$ and $H/D = 1$, equipped with the centric or eccentrically located impellers, HE 3 or propeller, are presented in Figs. 3 and 4. The function $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re_{P,V})$ reaches the greatest level for the most eccentric position of the impeller shaft in the agitated vessel without baffles. The data for the baffled vessel of the liquid aspect ratio $H/D = 0.5$ with the shaft at the centric position, are lying above the experimental points representing correlation for the vessel without baffles.

The results of the measurements of the heat transfer coefficient $\alpha$ completed with the data of the power consumption $P$ were approximated in the form of eqn (5), in which the value $A/3 = 0.67/3 = 0.22$ was assumed. The following correlations were obtained for the agitated vessel equipped with the HE 3 impeller

$$Nu = \frac{\alpha D}{\lambda} = 0.197 \left(\frac{\pi}{4}\right)^{0.22} (Re_{P,V})^{0.22} Pr^{0.33} \cdot Vi^{0.14} f_1\left(\frac{H}{D}\right) f_2\left(\frac{e}{R}\right) \quad (8)$$

where

$$f_1\left(\frac{H}{D}\right) f_2\left(\frac{e}{R}\right) = \left[-0.211\left(\frac{H}{D}\right)^2 + 0.423\left(\frac{H}{D}\right) + 1\right] \cdot \left[1.276\left(\frac{e}{R}\right)^2 - 0.195\left(\frac{e}{R}\right) + 1\right] \quad (9)$$

and for the agitated vessel equipped with the propeller

$$Nu = \frac{\alpha D}{\lambda} = 0.205 \left(\frac{\pi}{4}\right)^{0.22} (Re_{P,V})^{0.22} \cdot Pr^{0.33} Vi^{0.14} f_1\left(\frac{H}{D}\right) f_2\left(\frac{e}{R}\right) \quad (10)$$

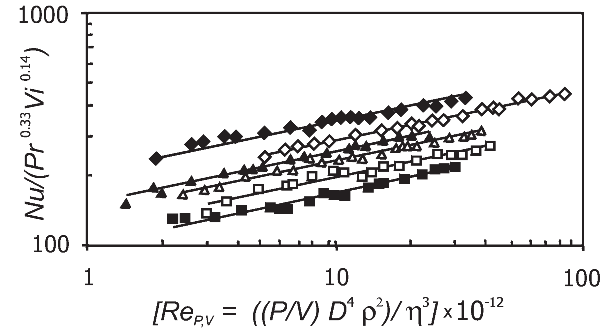


**Fig. 3.** The dependence $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re_{P,V})$ for the liquid aspect ratio $H/D = 0.5$: diamonds – $J = 4$, $e/R = 0$; squares – $J = 0$, $e/R = 0$; triangles – $J = 0$, $e/R = 0.53$. Opened symbols – HE 3 impeller; full symbols – propeller agitator.

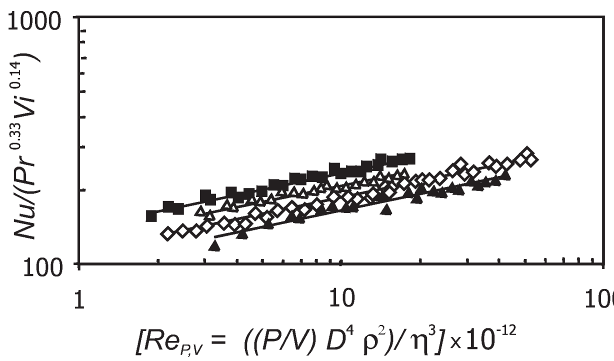


**Fig. 4.** The dependence $Nu/(Pr^{0.33}Vi^{0.14}) = f(Re_{P,V})$ for the liquid aspect ratio $H/D = 1$ and HE 3 impeller: diamonds – $J = 4$, $e/R = 0$; filled triangles – $J = 0$, $e/R = 0$; opened triangles – $J = 0$, $e/R = 0.4$; filled squares – $J = 0$, $e/R = 0.53$.

where

$$f_1\left(\frac{H}{D}\right) f_2\left(\frac{e}{R}\right) = \\ = \left[-4.09 \times 10^{-2}\left(\frac{H}{D}\right)^2 + 0.137\left(\frac{H}{D}\right) + 1\right] \cdot \\ \cdot \left[1.968\left(\frac{e}{R}\right)^2 - 0.466\left(\frac{e}{R}\right) + 1\right] \qquad (11)$$

Eqns (*8*) and (*10*) approximate the results of the measurements with the mean relative error of 5.5 % and 4 %, respectively. The dependences $Nu/(Re_{P,V})^{0.22}Pr^{0.33}Vi^{0.14} = K(e/R, H/D)$ described by means of eqns (*8*) and (*10*) show that the criterion $K$ depends strongly on the impeller eccentricity $e/R$. Liquid aspect ratio $H/D$ affects the coefficient $K$ only slightly. Comparing the systems with the eccentrically located HE 3 impeller working at down-pumping mode, and propeller (up-pumping mode), it can be stated that the direction of the liquid circulation in the agitated vessel affects the efficiency of the heat transfer process insignificantly.

On the basis of the experimental data obtained, the jacketed vessel of the liquid aspect ratio $H/D = 1$ in which HE 3 impeller is located at the position $e = 0.53R$ can be proposed as the best for the effective realization of the heat transfer process (Fig. 4). If the HE 3 impeller in this agitated vessel will be substituted by propeller agitator, the efficiency of the heat transfer would decrease only slightly.

*Acknowledgements. Financial support for the study was provided partially by the National Grant Foundation (Grant KBN 7 T09C 029 21).*

## SYMBOLS

| | | |
|---|---|---|
| $A$ | exponent in eqn (*1*) | |
| $b$ | width of impeller blade | m |
| $C$ | constant in eqn (*1*) | |
| $c_p$ | specific heat capacity | J kg$^{-1}$ K$^{-1}$ |
| $D$ | inner diameter of the vessel | m |
| $d$ | diameter of the agitator | m |
| $e$ | eccentricity of the impeller shaft | m |
| $F$ | heat transfer surface area | m$^2$ |
| $G$ | liquid flow | kg s$^{-1}$ |
| $H$ | liquid height in the vessel | m |
| $h$ | off-bottom clearance of the impeller | m |
| $J$ | number of baffles | |
| $K$ | optimization criterion | |
| $k$ | overall heat transfer coefficient | W m$^{-2}$ K$^{-1}$ |
| $n$ | agitator speed | s$^{-1}$ |
| $Ne$ | $Ne = \dfrac{P}{n^3 d^5 \rho}$; power number | |
| $Nu$ | $Nu = \dfrac{\alpha D}{\lambda}$; Nusselt number | |
| $P$ | power consumption | W |
| $Pr$ | $Pr = \dfrac{c_p \eta}{\lambda}$; Prandtl number | |
| $Q$ | heat flux | W |
| $R$ | radius of the agitated vessel (= $D/2$) | m |
| $Re$ | $Re = \dfrac{n d^2 \rho}{\eta}$; Reynolds number | |
| $Re_{P,V}$ | $Re_{P,V} = \dfrac{(P/V)\,D^4 \rho^2}{\eta^3}$; modified Reynolds number | |
| $S$ | pitch of the propeller | |
| $t$ | temperature | K, ℃ |
| $V$ | volume of liquid | m$^3$ |
| $Vi$ | $Vi = \dfrac{\eta}{\eta_w}$ | |
| $Z$ | number of agitator blades | |
| $\alpha$ | heat transfer coefficient | W m$^{-2}$ K$^{-1}$ |
| $\eta$ | dynamic viscosity | Pa s |
| $\lambda$ | thermal conductivity | W m$^{-1}$ K$^{-1}$ |
| $\rho$ | liquid density | kg m$^{-3}$ |

## REFERENCES


1. Nagata, S., *Mixing. Principles and Applications.* Kodansha, Tokyo, 1975.
2. Stręk, F., *Agitation and Agitated Vessels* (in Polish). Wydawnictwa Naukovo-Techniczne, Warszawa, 1981.
3. Tatterson, G. B., *Fluid Mixing and Gas Dispersion in Agitated Tanks.* McGraw-Hill, New York, 1991.
4. Novak, V. and Rieger, F., *IChEME Symp. Series 136*, 283 (1994).
5. Dyląg, M. and Brauer, H., *Verfahrenstechnik 10*, 637 (1976).
6. King, R. and Musket, J., in *5th European Conference on Mixing.* Wuerzburg, Germany, 1985.
7. Paszek, E., *Inż. i Ap. Chem.* (in Polish) *37,* 17 (1998).
8. Medek, J. and Fort, I., in *5th European Conference on Mixing.* Wuerzburg, Germany, 1985.
9. Rzyski, E., *Inż. Chem. Proc.* (in Polish) *2*, 379 (1981).
10. Seichter, P., Pesl, L., Slama, V., and Mazoch, J., in *14th Int. Congress of Chem. and Proc. Eng. CHISA*. Prague, Czech Republic, 2000.
11. Ashrafi, N., Binding, D. M., and Walters, K., *Chem. Eng. Sci. 56*, 5565 (2001).
12. Karcz, J. and Cudak, M., in *Proceedings of the 28th International Conference of the SSChE*, Tatranské Matliare, Slovak Republic, 2001.
13. Karcz, J. and Cudak, M., *Inż. Chem. Proc.* (in Polish) *22*, 633 (2001).
14. Stręk, F. and Karcz, J., *Inż. Chem. Proc.* (in Polish) *5*, 111 (1984).