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AN EFFECT OF DIFFERENT FACTORS ON HEAT TRANSFER PROCESS IN AN AGITATED VESSEL

WPŁYW RÓŻNYCH CZYNNIKÓW NA PROCES WYMIANY CIEPŁA W MIESZALNIKU

A b s t r a c t

Heat transfer process depends on many different factors. The type of heating/cooling surface area has an effect on the intensity of the heat transfer process. In the agitated vessel, a jacket or a coil can be used as heating/cooling surface area. When using coil as a heating/cooling surface area, its shape (helical or vertical) and its location in the vessel should be taken into account. The size of the vessel and the type of the agitator and its diameter also have the influence on heat transfer process. Moreover, except for geometrical factors, the fluid type and its physical properties are important in heat transfer process. The aim of the study presented in the paper was to compare intensity of heat transfer process as a function of different factors for the agitated vessel equipped with jacket or coil. This analysis was carried out on the basis of the own experimental results and literature data.

Keywords: *heat transfer process*, *agitated vessel*, *intensity of heat transfer process*

S t r e s z c z e n i e

Wymiana ciepła zależy od wielu różnych czynników. Na intensywność wnikania ciepła ma wpływ rodzaj zastosowanej podczas wymiany ciepła powierzchni grzejnej/chłodzącej, która w mieszalniku może być zabudowana w formie płaszcza bądź wężownicy. Używając wężownicy jako powierzchni grzejnej/chłodzącej, należy brać pod uwagę jej kształt oraz rozmieszczenie w zbiorniku. Również wielkość zbiornika oraz rodzaj i średnica mieszadła mają wpływ na wymianę ciepła. Poza czynnikami geometrycznymi na wartość współczynnika wnikania ciepła może mieć wpływ rodzaj cieczy użytej podczas procesu mieszania oraz jej właściwości fizyczne. Celem studiów prezentowanych w pracy było, na podstawie danych dostępnych w literaturze przedmiotu oraz wyników badań własnych, porównanie intensywności wnikania ciepła w funkcji różnych czynników dla zbiornika wyposażonego w płaszcz lub wężownicę.

Słowa kluczowe: *wymiana ciepła*, *mieszalnik*, *intensywność wnikania ciepła*

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1. Introduction

Tanks with agitators are used in the studies and in industrial practice when there are processes of exchange of momentum, heat or mass transfer in single or multiphases systems [1–3].

A lot of factors have an influence on the heat transfer process in an agitated vessel. These include: a surface and type of the heat transfer process, geometry of the agitated vessel, the type and size of the agitator used and the type of the liquid agitated.

Literature on the subject matter presents different types of heat exchange in the agitated vessel. The heat transfer process in the agitated vessels [1] may take place with the use of heating (cooling) jacket or coil. When using the coil as a surface of the heat exchange, it is necessary to take into consideration its helical or vertical shape. In case of coils, their location inside the agitated vessel is also important. The example ways of vertical tubular coils locations in the agitated vessel are presented in Fig. 1.

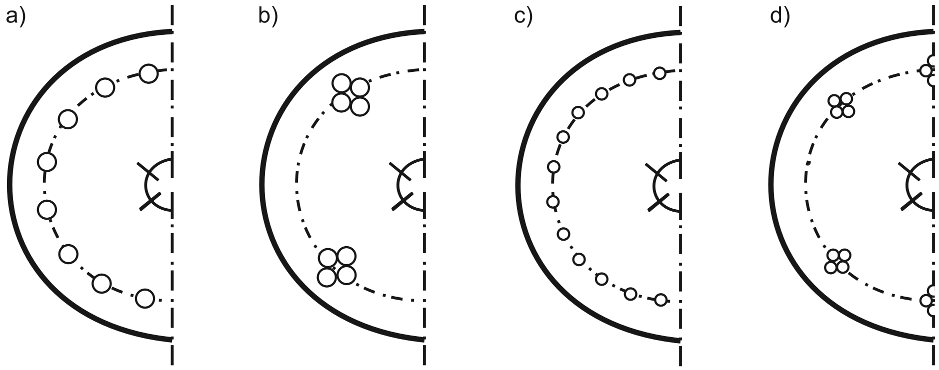


Fig. 1. Example ways of vertical tubular coils setup in the agitated vessel: a) sixteen-tube-vertical coil $J = 16$ – single tubes set up on the circumference of the agitated vessel; b) sixteen-tube-vertical coil set up in four blocks, four tubes in each block $J = 4 \times 4$; c) twenty-four-tube-vertical coil $J = 24$ – single tubes set up on the circumference of the agitated vessel; d) twenty-four-tube-vertical coil set up in six blocks, four tubes in each block $J = 6 \times 4$

The results of the heat transfer process are presented in the literature in the form of a dimensionless dependence [1]

$$\mathrm{Nu} = C\,\mathrm{Re}^{A}\,\mathrm{Pr}^{B}\,Vi^{E}\,f(d/D, h/D\ldots) \tag{1}$$

where:

Nu – Nusselt number

$$\mathrm{Nu} = \frac{\alpha \cdot l}{\lambda} \tag{2}$$

α – heat transfer coefficient [W/m^{2}K],

l – linear dimension [m],

λ – thermal conductivity of liquid [W/mK],
Re – Reynolds number

$$\mathrm{Re} = \frac{nd^2\rho}{\eta} \tag{3}$$

n – agitator speed [1/s],
d – agitator diameter [m],
ρ – density of liquid [kg/m^3],
η – dynamic viscosity of liquid, Pas
Pr – Prandtl number

$$\mathrm{Pr} = \frac{c_p \eta}{\lambda} \tag{4}$$

c_p – specific heat [J/kgK],
Vi – viscosity simplex

$$Vi = \frac{\eta}{\eta_w} \tag{5}$$

η_w – dynamic viscosity of liquid in the wall temperature [Pas],
$f(d/D, h/D\ldots)$ – a function including the influence of agitated vessel geometrical parameters.

The studies of the heat transfer process were discussed in the monography of Stręk [1] for the low viscosity liquid and in the monography of Kuncewicz [3] for the high viscosity liquid.

In the Nusselt number the linear dimension l is defined as an inner diameter of the agitated vessel D [4–7] when the agitated vessel is heated by the jacket. When the heat transfer process in the agitated vessel takes place by the use of the coil, the diameter of the agitated vessel D [8–21], the outer diameter of the coil tube d_w [22–31] or coil diameter D_w are taken as a linear dimension l.

Reynolds and Prandtl numbers, in the case of non-Newtonian liquids, may be defined differently. The example definition of both numbers are presented in Table 1, where m – flow index, k – consistency index [Ns^m/m^2], B – factor dependent on the type of the agitator, η_{ae} – apparent dynamic viscosity of liquid [Pas].

The geometry of the system, the type of a liquid and its turbulence have the influence on the constant value C and the exponents A, B, E in the equation (1). The A exponent value in Reynolds number changes in quite a wide range from 0.4 to 0.92 [11, 35]. The B exponent in Prandtl number most often equals 0.33 [1, 36]. The E exponent value with viscosity simplex Vi most often equals 0.14 [37]. The exponent value 0.2 is also used [26].

The aim of the study presented in this paper was to compare the intensity of the heat transfer process as a function of different factors for the agitated vessel equipped with jacket or coil. This analysis was carried out on the basis of the own experimental results and literature data.

Table 1

Definitions of Re and Pr number suggested by different authors

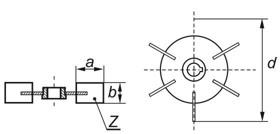
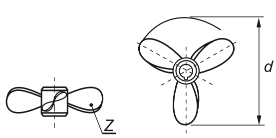
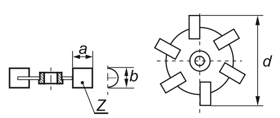
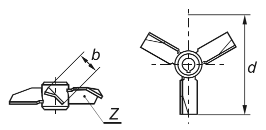
No.	Authors	Reynolds number	Prandtl number	Eq.
1	Edney et al. [27]	$\mathrm{Re} = \dfrac{n^{2-m} d^2 \rho}{k} B^{m-1}$	$\mathrm{Pr} = \dfrac{c_p k n^{m-1}}{\lambda} B^{m-1}$	(6)
2	Błasiński et al. [28]	$\mathrm{Re} = \dfrac{n^{2-m} d^2 \rho}{k} (4\pi)^{m-1}$	$\mathrm{Pr} = \dfrac{c_p k n^{m-1}}{\lambda} (4\pi)^{m-1}$	(7)
3	Pollard et al. [10], Suryanarayanan et al. [12], Sandall and Patel [32]	$\mathrm{Re} = \dfrac{n d^2 \rho}{\eta_{ae}}$	$\mathrm{Pr} = \dfrac{c_p \eta_{ae}}{\lambda}$	(8)
4	Hagedorn and Salamone [33]	$\mathrm{Re} = \dfrac{n^{2-m} d^2 \rho}{k}$	$\mathrm{Pr} = \dfrac{c_p k n^{m-1}}{\lambda}$	(9)
5	Mizushina et al. [34]	$\mathrm{Re} = \dfrac{n^{2-m} d^2 \rho}{k\left[2\pi\beta d / (D-d)\right]^{m-1}}$	$\mathrm{Pr} = \dfrac{c_p k \left[2\pi\beta d / (D-d)\right]^{m-1}}{\lambda}$	(10)

2. Data analysis

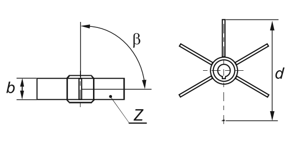
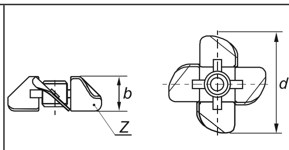
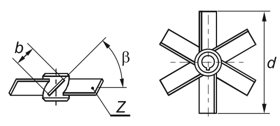
Seven different agitators were used in the analysis: Rushton (RT) and Smith (CD 6) turbine, pitched blade turbine of pitch β = 90° (T90) or β = 45° (T45), propeller (S), HE 3 and A 315. Geometrical parameters of the agitators are presented in Table 2.

Table 2

Geometrical parameters of the agitators

Agitator		Agitator	
	Rushton turbine (TR) $d = 0.33D$ $Z = 6$ $a = 0.25d$ $b = 0.2d$		Propeller (S) $d = 0.33D$ $Z = 3$ $S = d$ $b = 0.2d$
	Smith turbine (CD 6) $d = 0.33D$ $Z = 6$ $a = 0.25d$ $b = 0.2d$		HE 3 $d = 0.33D$ or $d = 0.5D$ $Z = 3$ $b = 0.19d$

Tab. 2. continuation

	Turbine (T90) $d = 0.33D$ $Z = 6$ $\beta = 90^{o}$ $b = 0.2d$		A 315 $d = 0.33D$ or $d = 0.5D$ $Z = 4$ $b = 0.5d$
	Turbine (T45) $d = 0.33D$ $Z = 6$ $\beta = 45^{o}$ $b = 0.2d$		

On the basis of the data [4-6, 15, 17], which describe two different types of heat transfer surfaces, presented in a general equation

$$\mathrm{Nu} = C\,\mathrm{Re}^{A}\,\mathrm{Pr}^{0.33}\,Vi^{0.14} \tag{11}$$

it is possible to define the influence of the heating surface on the intensity of the heat transfer. The influence of the heating surface on the intensity of the heat transfer was analysed on the basis of the data presented by Karcz [4], Karcz and Stręk [5], Cudak [6] and Stręk et al. [15] and Michalska [17]. The values of the constant C in the equation (11) are presented in Fig. 2 for the exponent by Reynolds number $A = 0.67$. The results for the jacketed agitated vessel of the diameter $D = 0.45$ m [4–6], and for the agitated vessel of the diameter $D = 0.6$ m equipped with the vertical tubular coil [15, 17] (which consisted of $J = 4$ tubes with the outer diameter of a single tube $d = 0.1D$ and the coil diameter $D_w = 0.9D$) are analysed. The Newtonian liquid was agitated. The values of C for agitators with three blades ($Z = 3$), i.e. propeller (S) and HE 3 impeller, as well as for the Rushton turbine (TR) and pitched blade turbine of pitch β ($\beta = 90°$ or $\beta = 45°$, $Z = 6$) are compared in Fig. 2. The diameter of the agitators equalled $d = 0.33D$. It was determined, that the intensity of the heat transfer for both the jacket and the vertical tubular coil changes depending on the type of the impeller used. When the surface of the heat exchange is the jacket, the highest intensity of the

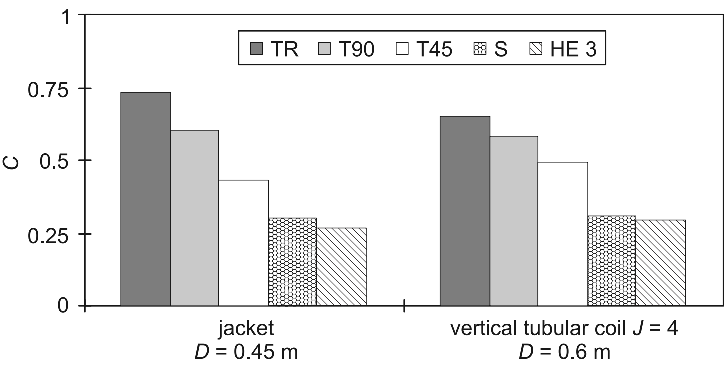


Fig. 2. Comparison of the constant C of the (11) equation for two different surfaces: the jacket and the vertical tubular coil

heat transfer was observed for the agitated vessel with the Rushton turbine (TR), and the lowest intensity of the heat transfer was obtained for the HE 3 impeller. A similar tendency was observed in the system, in which vertical tubular coil ($J = 4$) was the surface of the heat exchange. There were no significant differences in the value of the constant C of the equation (11) observed for the system in which the liquid is agitated with the same impeller and the surface type of the heat exchange changes. In the system where the heating surface is the jacket as well as the one where the heating surface is the vertical tubular coil ($J = 4$) there are minor differences in the value of constant C of the equation (11). It suggests that the intensity of the heat transfer process in the jacketed agitated vessel is similar to the intensity of the heat transfer obtained when the surface of the heat exchange is a vertical tubular coil consisting of $J = 4$ tubes.

The influence of the impeller diameter HE 3 and A 315 on the value of the constant C was analysed on the basis of the data presented by Michalska [17], for three example arrangements of the vertical tubular coil. The results presented in the work [17] were obtained in the agitated vessel of inner diameter $D = 0.6$ m, for the turbulent range of the Newtonian liquid flow. The vertical coil consisted of four ($J = 4$, $D_w = 0.9D$), sixteen ($J = 16$, $D_w = 0.7D$) or twenty four ($J = 24$, $D_w = 0.7D$) single vertical tubes arranged on the agitated vessel circumference. The values of constants C presented in Fig. 3, calculated for the exponent $A = 0.67$ at Re number indicate, that the minor effect of the impeller diameter on the intensity of the heat transfer process is observed in the case of the axial flow HE 3 impeller. The higher influence of the impeller diameter on the heat transfer process intensity is observed for the A 315 impeller. Bigger differences in constant values C are found for this impeller.

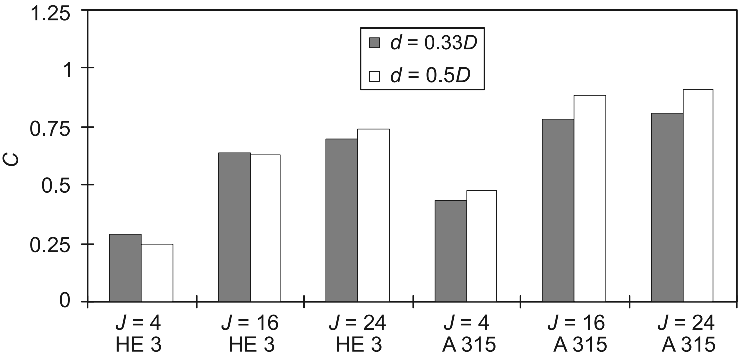


Fig. 3. Comparison of the constant value C of the equation (11) for the HE 3 and A 315 impeller of diameter equal $d = 0.33D$ or $d = 0.5D$ and three geometrically different setups of the vertical tubular coil

Arrangement of the vertical tubular coil in the agitated vessel also has an influence on the intensity of the heat transfer process. The constant values C of the equation (11) are presented in Fig. 4 (where the exponent by Reynolds number equalled $A = 0.8$) for different setups of the vertical tubular coil. In order to compare, the following data presented in works [16, 18, 19] were taken into account: vertical tubular coils consisting of sixteen

($J = 16$) or twenty four ($J = 24$) tubes set up singularly on the circumference of the vessel ($d_z = 0.027D$, $D_w = 0.7D$ for $J = 16$ and $d_z = 0.017D$, $D_w = 0.7D$ for $J = 24$) or vertical tubular coils grouped in four blocks four tubes in each block ($d_z = 0.027D$, $D_w = 0.64D$) in the case of coil consisting of sixteen tubes or grouped in six blocks, four tubes in each block ($d_z = 0.017D$, $D_w = 0.65D$) in the case of coil consisting of twenty four tubes. The liquid agitated was non-Newtonian liquid. The results were obtained for the transitional range of the liquid flow. The heat transfer process is more intensive when heat exchange takes place with the use of twenty-four-vertical tubular coil in comparison with sixteen-tubular coil in the agitated vessel. Vertical tubular coil singular tubes blocking has also influence on the heat transfer process intensity change. Not many changes in the heat transfer process intensity in the case of sixteen-tube-coil for the Rushton (TR) and Smith (CD 6) turbine agitated vessel. However in the case of the propeller (S) the differences are observed. Bigger intensity of the heat transfer process for the propeller (S) is visible when the vertical tubular coils are arranged singularly on the agitated vessel circumference. Similarly, it is possible to observe the changes in the heat transfer process intensity when the twenty-four-vertical coil is blocked in six blocks, four tubes in each block. In the case, when Smith turbine (CD 6) or the propeller (S) were used, the intensity of the heat transfer process decreases when the coil is set up in six blocks, four tubes in each block.

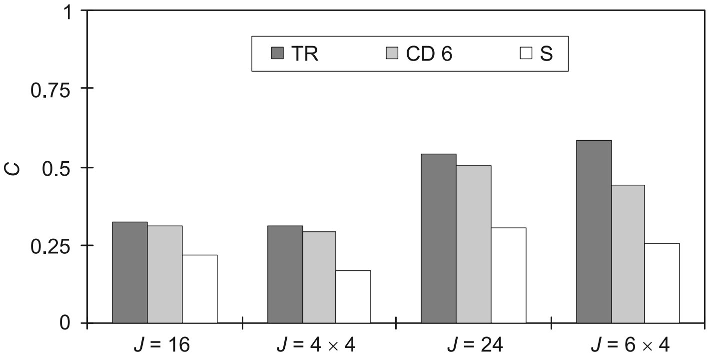


Fig. 4. Comparison of the constant value C of the equation (11) for Rushton turbine (TR), Smith turbine (CD 6) and the propeller (S) of the diameter $d = 0.33D$ and four geometrically different setups of vertical tubular coil

The type of the agitated liquid may also have an influence in the heat transfer process intensity. The constant value C in the equation (11) for Newtonian and non-Newtonian liquids obtained on the basis of data described in works [16, 17] is presented in Fig. 5. The results were obtained for the turbulent range of the Newtonian liquid flow and for the transitional range of the non-Newtonian liquid flow. It was stated that higher heat transfer process intensity takes place during agitation within the turbulent range of the Newtonian liquid in the vessel equipped with the vertical tubular coil consisting of four tubes ($J = 4$, $d_z = 0.1D$, $D_w = 0.9D$).

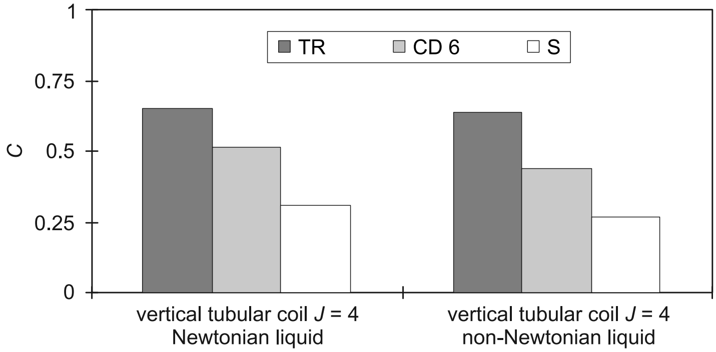


Fig. 5. Comparison of the constant value C of the equation (11) for Newtonian and non--Newtonian liquid and vertical tubular coil

3. Conclusions

Analysing data presented in literature [4–6, 15–19] with the use of the dimensionless equation (11), it is possible to confirm the influence of different factors on the heat transfer process intensity. In the case, when the heat transfer process takes place with the use of vertical tubular coil, the setup of this coil in the agitated vessel is important. Smaller values of the constant C of the equation (11) were obtained for the vertical tubular coils consisting of sixteen tubes (Fig. 4). The impeller set up in the agitated vessel, especially its type and diameter, is another element which has the influence on the heat transfer process intensity. Compared to the system with the propeller, for which heat transfer intensity is relatively low, greater level of this intensity is characteristic for the systems equipped with the pitched blade turbine (Fig. 2) and Rushton or Smith turbines (Figs. 2, 5). With the increase of A 315 impeller diameter, small increase in the value of the constant C of Eq. (11) is observed (Fig. 3). The liquid properties also have the influence on the heat transfer intensity. However, it is worth to notice that the analysis concerning heat transfer intensity in the agitated vessel should be extended about power consumption results, in order to estimate heat transfer efficiency.

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