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Izbira mešal za prenos toplote

Selection of Agitators for Heat Transfer

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Z mešanjem tekočin v posodah z mešalom opravljamo najrazličnejše naloge s področja prenosa snovi in toplote, zato ni čudno, da se je v praksi razvilo zelo veliko mešal, ki so bolj ali manj uporabna za posamezne naloge. V literaturi najpogosteje srečujemo priporočila za uporabo posameznih tipov mešal v določenem območju viskoznosti mešanih tekočin ali v določenem območju vrtilnih hitrosti mešala in jih je treba uporabljati s precejšnjo mero previdnosti. Ta priporočila se namreč nanašajo samo na eno nalogo, ki jo mešalo opravlja. Pri tem pa ne upoštevajo še drugih parametrov, pri čemer je treba posebej poudariti pomen porabe moči za pogon mešala, saj je nedvomno najprimernejše tisto mešalo, ki za izvedbo določene naloge porabi najmanj energije.

V našem sestavku se bomo omejili na možnosti pravilne izbire mešal za prenos toplote prek sten mešalne posode.

Mixing fluids in vessels with an agitator is performed in the most varied tasks in the field of mass and heat transfer, so it is not suprising that a great many agitators have been developed in practice, all applicable to a greater or lesser degree in individual tasks. In the literature, we most often find recommendations on the individual types of agitators in a predetermined viscosity range of mixed fluids or range of the agitator's rotation speeds, which need to be used with considerable caution. Namely, these recommendations refer only to one aspect of the task performed by the agitator, while no attention is usually paid to the remaining parameters, among wich special emphasis should be given to the importance of power consumption for driving the agitator. Undoubtedly, the agitator using least energy for the implementation of a determined task is the most suitable one.

Our paper will be limited to an examination of the possibility of an appropriate selection of agitators for heat transfer through the mixing vessel's wall.

ZVEZA MED PRENOSOM TOPLOTE IN PORABO MOČI

Vsa najpogosteje uporabljena mešala so bila doslej že raziskana glede na zmožnosti pospeševanja prenosa toplote prek stene posode [1], [2], [3], [4]. Znana je vrsta enačb, ki povezujejo bistvena števila z dimenzijo 1, najpogosteje v obliki:

$$\mathrm{Nu} = C\,\mathrm{Re}^m\,\mathrm{Pr}^n\left(\eta/\eta_{st}\right)^q \tag{1}$$

Te enačbe veljejo za določeno območje Reynoldsovih števil in za splošno uveljavljene standardne pogoje vgradnje mešala v mešalno posodo, s čimer so podana geometrijska razmerja med mešalom in mešalno posodo. Pri tem je treba spomniti, da je karakteristična dimenzija v Reynoldsovem številu premer mešala d, v Nusseltovem številu pa premer mešalne posode D, če se toplota seveda prevaja prek stene posode. Vrednost konstante C je za vsak tip mešala drugačna. Eksponent m pri Reynoldsovem številu običajno zavzema

1 CONNECTION BETWEEN HEAT TRANSFER AND POWER CONSUMPTION

Practically all the most frequently used agitators have already been investigated in terms of their capacity for the acceleration of heat transfer through vessel's walls [1], [2], [3], [4]. A series of equations is known, linking the relevant numbers with dimension 1, usually in the following form:

These equations are valid for a determined range of Reynolds numbers and for generally accepted standard conditions of integrating the agitator into the mixing vessel, by which the geometrical relations between the agitator and the mixing vessel are determined. At this point, it should be remembered that the charateristic dimension in a Reynolds number is the agitator's diameter d and in a Nusselt number, the mixing vessel's diameter D; of course, if heat is transferred through the vessel's walls. The value of vrednost 2/3 pri turbulentnem mešanju, pri laminarnem mešanju pa srečujemo vrednosti med 1/2 in 1/3. Eksponent n Prandtlovega števila ima praktično brez izjeme vrednost 1/3. Za eksponent q pri razmerju viskoznosti najpogosteje uporabljamo vrednost 0,14, vendar srečujemo tudi drugačne vrednosti [2].

Samo na temelju znanih medsebojnih odvisnosti bistvenih števil z dimenzijo 1 za računanje toplotne prestopnosti še ne moremo izbirati optimalnega tipa mešala za dano nalogo prenosa toplote, saj moramo pri tem upoštevati tudi porabo energije za pogon mešala. Različna mešala dosežejo v isti mešalni tekočini in isti mešalni posodi različne toplotne prestopnosti. Porabljajo pa tudi različno količino energije za pogon.

Porabo energije za pogon mešala prikazujemo v odvisnosti:

the constant C is different for every agitator type. The exponent number usually has the value 2/3 in turbulent mixing and values between 1/2 and 1/3 in laminar mixing. The exponent n of a Prandtl number has the value 1/3 practically without exception. For the exponent q in the viscosity ratio, we most often use the value 0.14, although we do meet other values [2].

Solely on the basis of the known interdependence of the relevant numbers with dimension 1 for calculation of heat fransfer coefficient, we cannot yet choose the optimum type of agitator for the given task of heat transfer, since we have to take into consideration also the consumption of energy for agitator's drive. In the same mixed fluid and the same mixing vessel, different agitators achieve different heat transfer coefficients and consume different quantities of energy for their drive.

The energy consumption for the agitator's drive is shown in the dependance:

$$\mathrm{Ne} = \mathrm{Ne}(\mathrm{Re}, \mathrm{Fr}) \tag{2}$$

Froudovo število Fr vpliva na porabo energije za mešanje samo v primeru, ko dobi gladina tekočine obliko znanega vrtinčnega lijaka, kar pa ni običajno, saj želimo praviloma obratovati tako, da se vrtinčni lijak ne pojavi. V primeru, če bi prišlo do vrtinčnega lijaka, v posodo namestimo motilnike toka. Porabo energije za pogon mešala zato lahko krajše popišemo:

The Froud number Fr influences the energy consumption for mixing only when the fluid's surface acquires the form of the well-known whirl funnel which, however, is not a usual occurrence, since we normally want to operate the agitator in such manner as to prevent creation of the whirl funnel. If a whirl funnel is nevertheless produced, baffles are placed in the vessel. The energy consumption for the agitator's drive can thus be described in abbreviated form as:

$$\mathrm{Ne} = \mathrm{Ne}(\mathrm{Re}) \tag{3}$$

To odvisnost običajno prikazujemo v obliki diagramov in je v literaturi splošno znana za vsa najpogosteje uporabljana mešala.

Če Reynoldsovo število potenciramo na tretjo potenco in upoštevamo, da je Newtonovo število $\mathrm{Ne} = P/(n^3 d^5 \rho)$, dobimo:

The above dependance is usually shown in the form of diagrams, and is generally known in literature for all the most frequently used agitators.

If the Reynolds number is involved to third power and if the Newton number $\mathrm{Ne} = P/(n^3 d^5 \rho)$ is accounted for, the following is obtained:

$$\mathrm{Re}^3 = n^3 d^5 \rho \, \frac{d\rho^2}{\eta^3} = \frac{P}{\mathrm{Ne}} \, \frac{d\rho^2}{\eta^3} \tag{4}$$

Pri standardnih pogojih vgradnje mešala v mešalno posodo je razmerje premerov posode in mešala za vsak tip mešala konstantno $D/d = \varkappa$. Višina tekočine je navadno enaka premeru posode $H = D$, prostornina mešalne tekočine pa je $V = \pi D^3/4$. Če te pogoje standardne vgradnje upoštevamo v Reynoldsovem številu enačbe (4), dobimo:

Under the standard conditions of integrating the agitator into the mixing vessel, the ratio between the diameters of vessel and the agitator is constant $D/d = \varkappa$ for every agitator type. The height of the fluid is usually identical to the vessel's diameter $H = D$, with the volume of mixed fluid resulting as $V = \pi D^3/4$. If these conditions of standard integration are accounted for the Reynolds number in equation (4), the following is obtained:

$$\mathrm{Re}^3 = \left(\frac{1}{\mathrm{Ne}} \, \frac{\pi}{4\varkappa}\right)\left(\frac{P}{V} \, \frac{D^4 \rho^2}{\eta^3}\right) \tag{5}$$

Ta oblika Reynoldsovega števila je zanimiva, ker se v njej pojavlja razmerje vložene energije oziroma za mešanje potrebne moči in prostornine mešane tekočine P/V. Čim manjše je to razmerje, tem bolj učinkovito je mešanje.

Prandtlovo število Pr in razmerje dinamičnih viskoznosti η/η_{st} za našo presojo odvisnosti prenosa toplote od tipa mešala nista pomembni, zato (1) zapišemo v obliki:

This form of recording the Reynolds number is interesting, since it implies a ratio between the input energy for mixing, and volume of mixed fluid P/V. The lower the ratio, the more effective the mixing.

The Prandtl number Pr and the ratio of dynamic viscosities η/η_{st} are not important for study of heat transfer dependence on the agitator type so equation (1) is written in the following form:

$$\frac{Nu}{Pr^{n}\left(\eta/\eta_{st}\right)^{q}} = C\, Re^{m} \qquad (6).$$

Nadomestimo še Reynoldsovo število z izrazom iz (5):

Then we also substitute the Reynolds number for the expression from (5):

$$\frac{Nu}{Pr^{n}\left(\eta/\eta_{st}\right)^{q}} = C\left(\frac{1}{Ne}\,\frac{\pi}{4\varkappa}\right)^{m/3}\left(\frac{P}{V}\,\frac{D^4\rho^2}{\eta^3}\right)^{m/3} \qquad (7).$$

Ta enačba že popisuje iskano odvisnost med prenosom toplote oziroma toplotno prestopnostjo α v Nusseltovem številu in potrebno močjo za pogon mešala na enoto prostornine tekočine P/V. Za prenos toplote je bolj učinkovito tisto mešalo, ki ima pri enaki potrebni moči na enoto voluma mešane tekočine P/V večjo toplotno prestopnost α oziroma večje Nusseltovo število Nu.

Izenačimo še desni strani (6) in (7) in dobimo:

This equation already describes the sought for dependence between heat transfer or the heat transfer coefficient α in the Nusselt number and the power for driving agitator per volume unit of mixed fluid P/V. The agitator which, under identical power required per volume unit of mixed fluid P/V, has a greater heat transfer cofficient α or a greater Nusselt number Nu, is more effective in heat transfer.

Equating also the right hand sides of (6) and (7), the result obtained is as follows:

$$\frac{P}{V}\,\frac{D^4\rho^2}{\eta^3} = \frac{Re^3}{\left(\frac{1}{Ne}\,\frac{\pi}{4\varkappa}\right)} = \frac{4\varkappa}{\pi}\, Ne\, Re^3 \qquad (8).$$

Če želimo ugotoviti odvisnost toplotne prestopnosti od potrebne moči za pogon mešala, moramo vrednotiti vsak tip mešala posebej. Izračun najenostavneje naredimo, če postopamo takole:

— Izberemo Reynoldsovo število Re in po (6) izračunamo:

If we want to discover the dependence of the heat transfer coefficient on the power required for driving the agitator, we have to evaluate every type of agitator separately. The calculation is simplest if the following steps are taken:

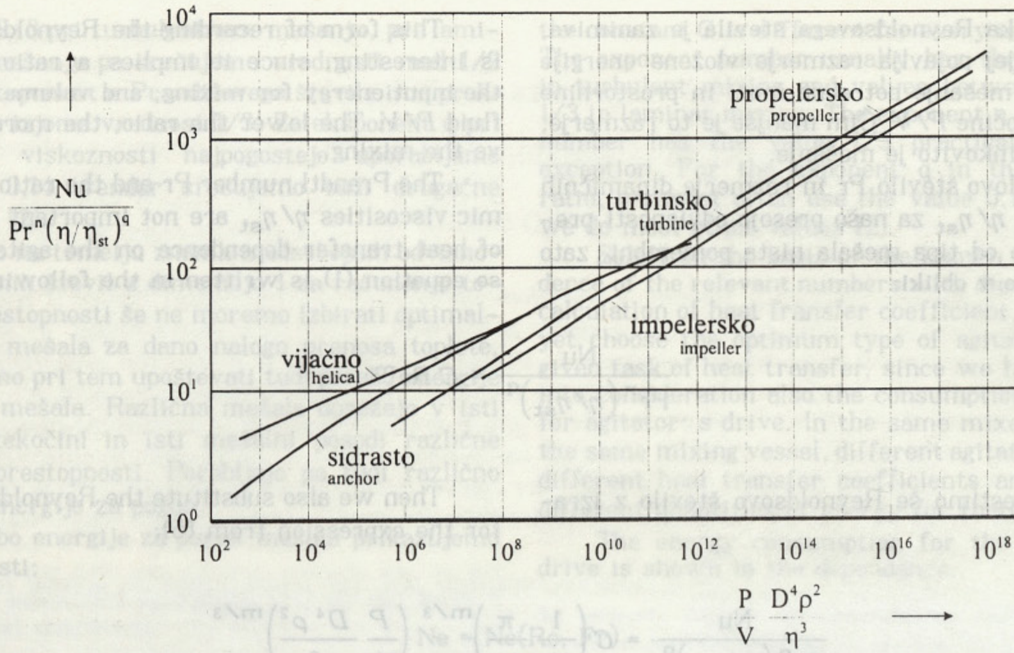
—Choose the Reynolds number Re and calculate using (6):

$$\frac{Nu}{Pr^{n}\left(\eta/\eta_{st}\right)^{q}}$$

— Iz diagrama porabe moči Ne = Ne(Re) odberemo izbranemu Reynoldsovemu številu pripadajoče Newtonovo število in po (8) izračunamo:

— in a diagram depicting power consumption Ne = Ne(Re), we read the Newton number to the chosen Reynolds number and calculate by (8):

$$\frac{P}{V}\,\frac{D^4\rho^2}{\eta^3}$$



Sl. 1. *Odvisnost Nu od P/V za nekaj mešal*

Fig. 1. *Dependance of Nu on P/V for some agitators*

Obe izračunani vrednosti vnesemo v diagram s prejšnjima koordinatama. Enačba (7) kaže, da je priporočljivo uporabiti logaritemsko mrežo. Rezultati računa so prikazani v diagramu na sliki 1.

V pretres smo vzeli naslednja mešala:

1) Turbinsko mešalo, 6 listov z motilniki ali brez njih:

— prenos toplote po Brooksu [5]:

$$Nu = 0{,}54\ Re^{2/3}\ Pr^{1/3}\left(\eta/\eta_{st}\right)^{0{,}14} \qquad 30 \leq Re \leq 400$$

$$Nu = 0{,}74\ Re^{2/3}\ Pr^{1/3}\left(\eta/\eta_{st}\right)^{0{,}14} \qquad 4\cdot 10^2 \leq Re \leq 3\cdot 10^5$$

— diagram porabe moči za pogon mešala smo vzeli po Rushtonu [6].

2) Propelersko mešalo, 3-listno:

prenos moči po Streku [1]:

$$Nu = 0{,}5\ Re^{2/3}\ Pr^{1/3}\left(\eta/\eta_{st}\right)^{0{,}14} \qquad 1{,}7\cdot 10^4 \leq Re \leq 9{,}2\cdot 10^5$$

— diagram porabe moči za pogon mešala smo vzeli po Rushtonu [6].

3) Impelersko mešalo z motilniki toka, razmerje premerov $\varkappa = 1{,}55$:

— prenos toplote po Dürichenu [7]:

$$Nu = 0{,}28\ Re^{2/3}\ Pr^{1/3}\left(\eta/\eta_{st}\right)^{0{,}20} \qquad 3\cdot 10^2 \leq Re \leq 7\cdot 10^5$$

— diagram porabe moči smo vzeli po Zlokarniku [3].

Both calculated values are then entered into the diagram with previous coordinates. Equation (7) indicates that the use of a logarithm net is advisable. The results of the calculation are shown in the diagram in Figure 1.

The following agitators were scrutinized:

1) Turbine agitator, 6 blades with or without baffles:

—heat transfer according to Brooks [5]:

— the diagram of power consumption for driving the agitator was taken after Rushton [6]

2) Propeller agitator, 3-blade:

— heat transfer according to Strek [1]:

— the diagram of power consumption for driving the agitator was taken after Rushton [6].

3) Impeller agitator with baffles, ratio of diameters $\varkappa = 1.55$:

— heat transfer according to Dürichen [7]:

— the diagram of power consumption was taken after Zlokarnik [3].

4) Sidrasto mešalo, razmerje premerov $\varkappa$ = 1,11:

— prenos toplote po Nagati [2]:

$$Nu = 1{,}5\ Re^{2/3}\ Pr^{1/3}\ \left(\eta/\eta_{st}\right)^{0{,}14} \qquad Re \leq 100$$

— diagram porabe moči je v isti literaturi.

5) Vijačno mešalo, razmerje premerov $\varkappa$ = 1,071, nagib vijačnice je ena:

— prenos toplote po Nagati [2]:

$$Nu = 4{,}2\ Re^{1/3}\ Pr^{1/3}\ \left(\eta/\eta_{st}\right)^{0{,}2} \qquad 1 \leq Re \leq 10^3$$

— diagram porabe moči je v isti literaturi.

Pri iskanju podatkov za prenos toplote in porabo moči smo naleteli na nemalo težav, saj je težko najti primere, ko se enačbe za prenos toplote in porabo moči nanašajo na enako obliko mešalnega sistema. Ker so oba pojava praviloma raziskovali različni avtorji, so za poskuse največkrat izbrali geometrijsko ne povsem enake kombinacije mešala in mešalne posode.

SKLEP

Pri vsakem mešanju tekočin razumljivo že od vsega začetka poznamo lastnosti tekočin, ki jo želimo mešati in geometrijsko obliko ter velikost mešalne posode. Iščemo torej najprimernejši tip mešala. Iz diagrama na sliki 1. lahko razberemo, katero mešalo zagotavlja največje toplotne prestopnosti pri enaki porabi energije oziroma pri enaki potrebni moči za pogon mešala. Vidimo, da so pri laminarnem mešanju zelo viskoznih tekočin najbolj učinkovita vijačna mešala, nato pa v smeri proti manj viskoznim tekočinam in turbulentnem mešanju sledijo sidrasta, turbinska in propelerska mešala. Natančneje lahko meje največje učinkovitosti posameznih tipov mešal odberemo iz diagrama na sliki 1.

4) Anchor agitator, ratio of diameters $\varkappa$ = 1.11:

— heat transfer according to Nagata [2].

— the diagram of power consumption is in the same literary source.

5) Helical agitator, ratio of diametres $\varkappa$ = 1.071, helical inclination is one:

— heat transfer according to Nagata [2]:

— the diagram of power consumption is in the same literary source.

We encoutered several difficulties in the search for data on heat transfer and power consumption, since it is difficult to find cases where equations for heat transfer and power consumption refer to the same shape of the system. Since the two phenomena were as a rule investigated by different authors, they usually chose for experiments geometrically not entirely identical combinations of agitator and mixing vessel.

CONCLUSION

In any mixing of fluids, we clearly know at the very start the features of the fluid which we want to mix and the geometry and size of the mixing vessel. Thus we look for the most appropriate type of agitator. It can be seen from the diagram in Figure 1 which agitator provides the greatest heat transfer coefficients at identical energy consumption or at indentical power required for the agitator' s drive, respectively. We can observe that in laminar mixing of highly viscouse fluids, helical agitators are the most effective, followed by anchor, turbine and propeller agitators when mixing less viscous fluids and when applying turbulent mixing. More precisely the limits of the greatest efficiency of individual types of agitators can be read from the diagram in Figure 1.

POMEN OZNAČB

- c — specifična toplota
- D — premer posode
- d — premer mešala
- g — zemeljski pospešek
- Fr = $n^2 d/g$, Froudovo število
- n — število vrtljajev mešala v sekundi
- Ne = $P/(n^3 d^5 \rho)$, Newtonovo število
- Nu = $\alpha D/\lambda$, Nusseltovo število
- P — moč
- Pr = $c\eta/\lambda$, Prandtlovo število
- Re = $nd^2 \rho/\eta$, Reynoldsovo število
- V — prostornina
- α — toplotna prestopnost
- η — dinamična prestopnost
- η_{st} — dinamična viskoznost pri temperat. stene
- λ — toplotna prevodnost
- ρ — gostota tekočine

SYMBOLS

- c — specific heat
- D — diameter of vessel
- d — diameter of agitator
- g — gravital acceleration
- Fr = $n^2 d/g$, Froud number
- n — rotations per second
- Ne = $P/(n^3 d^5 \rho)$, Newton number
- Nu = $\alpha D/\lambda$, Nusselt number
- P — power
- Pr = $c\eta/\lambda$, Prandtl number
- Re = $nd^2 \rho/\eta$, Reynolds number
- V — volume
- α — heat transfer coefficient
- η — dynamic viscosity
- η_{st} — dynamic viscosity at wall temperature
- λ — thermal conductivity
- ρ — fluid density

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