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Short communication

Heat transfer to viscous Newtonian and non-Newtonian fluids using helical ribbon agitator

C.L. Rai, I. Devotta, P.G. Rao*

Chemical Engineering Division, Central Leather Research Institute, Adyar, Chennai 600020, India

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Abstract

Heat transfer rates in agitated vessels has been investigated for some Newtonian and non-Newtonian fluids mixed in a flat bottomed vessel equipped with a helical ribbon agitator. Heat transfer rates from jacket to bulk liquid were determined for different stirrers, rheological properties and operating conditions. The heat transfer coefficient for the liquid inside the vessel is calculated based on the experimental data and an empirical correlation is developed to predict the heat transfer coefficient for the specified operating conditions. The correlation includes the influence of the *H*/*T* ratio on the heat transfer coefficient, which has not been studied so far. Investigations on the effect of position of impeller in the vessel indicate that the heat transfer coefficient is maximum when the impeller is placed slightly above the centre. Heat transfer rates were also investigated in gassed systems, both in the presence and absence of agitation. The results indicate that the heat transfer coefficient initially increases substantially with the superficial velocity of the gas and then increases rather slowly at higher gas flow rates. It also indicates that the heat transfer coefficient does not increase substantially when aeration is coupled with agitation as compared to only aeration. The marginal increase is relatively higher at lower gas flow rate as compared to the increase at higher flow rate.

Keywords: Heat transfer rates; Helical ribbon agitator; Impeller; Newtonian and non-Newtonian fluids

1. Introduction

In many chemical process industries, mixing and heat transfer in agitated vessels is an important operation in both batch and continuous processes. Agitated vessels are generally used for processing liquid systems and are suitable for carrying out reaction at isothermal conditions where heat of reaction is high. Generally, heating or cooling is effected by jacketing the vessel. The rate of heat transfer is a function of the physical properties of the agitated liquid, the heating or cooling medium, vessel geometry and most importantly on the degree of agitation.

The type of agitators used depends on the properties of the fluid to be mixed, especially the viscosity. Helical ribbon agitators have been used industrially in systems involving viscous and non-Newtonian fluids. This type of agitator provides good mixing efficiency [1] of the fluid near the wall and also provide vertical mixing of fluid. Hence, studies of mixing [2–4], heat transfer [5–10] power consumption [11,12,19,20] using helical ribbon agitators have attracted many researchers, both theoretically and experimentally, in the past.

Shamlou and Edwards [6] studied the temperature gradient inside the vessel agitated with helical ribbon impeller using thermocouple at different location in the vessel. They presented a generalised relation for critical Reynolds number (Re) as a function of fluid properties as well as impeller and vessel geometry. They also developed correlations for heat transfer coefficient for two ranges of Re. They found that for Re>10, the heat transfer coefficient is independent of the impeller geometry.

2. Dimensional analysis

2.1. Newtonian liquids

Forced convective heat transfer may be conveniently correlated in the familiar form

$$\mathrm{Nu} = f(\mathrm{Re}, \mathrm{Pr}, \mathrm{Vi}, \text{geometrical parameters}) \tag{1a}$$

* Corresponding author. Tel.: +91-44-4916706; fax: +91-44-4911589.
E-mail address: clrimd@md2.vsnl.net.in (P.G. Rao)

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where Nu is the Nusselt number ($h_j T/k$), Re the Reynolds number ($\rho ND^2/\mu$), Pr the Prandtl number ($C_p\mu/k$) and Vi is the Viscosity ratio (μ/μ_w). Physical properties C_p, μ, ρ and k are evaluated at the bulk fluid temperature and μ_w is determined at the mean wall temperature. The relationship between the variables in Eq. (1a) has been established from experimental measurements. It is reported in the following form:

$$\mathrm{Nu} = A\mathrm{Re}^a\mathrm{Pr}^b\mathrm{Vi}^d(\text{shape factor})^e \tag{1b}$$

The exponent of Pr is reported as 1/3. The exponent of the viscosity ratio is established as 0.14 in work of Sieder and Tate [13]. The value of the geometric constant A in Eq. (1b) is a function of impeller type and system geometry.

2.2. Non-Newtonian liquids

In non-Newtonian fluids, all the dimensionless quantities can be defined using the average apparent viscosity μ_a in the place of viscosity, μ. It is based on the average shear rate in the vessel. For helical ribbon agitators, the average shear rate γ_a for c/D ratios (0.4, 0.5) can be calculated from the following equation [11]:

$$\gamma_a = \frac{\pi}{\sqrt{2}}\left[\frac{D}{T-D}\right]N \tag{2}$$

In the present work, heat transfer rates in agitated vessel from jacket to bulk are presented in the medium range Re of practical significance using helical ribbon impeller. A general correlation has been provided for design purposes. This correlation gives the influence of the H/T ratio on the heat transfer coefficient, which was not studied so far. The effect of impeller position in stirrer tanks on the heat transfer rates are also investigated. Further, heat transfer to aerated fluid in stirred tanks has been studied for some impellers [14–16]. However, there has been no heat transfer studies with helical ribbon agitator in aerated stirred tanks.

3. Experimental

A 0.115 m diameter vessel was used in the experiments. Information on vessels, accessories and dimensions are given in Table 1. Newtonian fluids like castor oil, glycerine and lube oil were used. Aqueous solutions of CMC (3 and 9%) and PAAm (0.5%) were used as non-Newtonian fluids. The properties of the fluids are presented in Table 2. The agitator was driven by a 0.22 kW motor. The speed of the agitator was measured by non-contact type tachometer. For the non-Newtonian fluid used, the Re and Pr numbers are based on the effective viscosity, which was determined by 'Roto Visco Haake Viscometer'. A PT-100 thermocouple was placed at the middle of the liquid height between the vessel wall and impeller to measure the bulk temperature. Preliminary studies using thermocouples at various locations in the vessel confirmed no measurable temperature gradients in the fluid at all operating speeds. Also, using the correlation for critical Re [6], it was found the Re_c were well below the Re used in this work. Heating was done by hot water in the vessel jacket by water bath circulator provided with temperature indicator cum controller.

Table 1
Details of the two impellers used in the present work

Parameter	Stirrer 1	Stirrer 2
Diameter, D (mm)	80	75
Height, h (mm)	200	70
Pitch, p (mm)	80	70
No. of blades, n_b	1	3
Width of the blade, w (mm)	10	10

3.1. Effect of impeller position

Experiments were performed by changing the position of impeller, i.e. by changing the distance between the bottom of the vessel and the centre of the impeller. These experiments were done for two speeds using castor oil and all the other parameters were unchanged.

3.2. Effect of H/T ratio

Experiments were also performed by changing the height of the fluid in the vessel. These were also performed at two speeds using lube oil. The impeller were placed exactly at the centre of the fluids in each case. All other parameters were unchanged.

Table 2
Properties of the Newtonian and non-Newtonian fluids used in the present work

Fluid used	Viscosity, μ		Thermal conductivity, k (kcal/h m°C)	Heat capacity, C_p (kcal/kg°C)	Density, ρ (kg/m^3)
	K' (kg/m h)	n			
Glycerine	732	1	0.248	0.66	1682
Castor oil	789	1	0.15	0.48	961
Lube oil	248	1	0.11	0.5	854
3% CMC	111	0.87	0.516	1.003	1000
9% CMC	871	0.80	0.516	1.003	1131
0.5% PAAm	90	0.73	0.516	1.0	1000

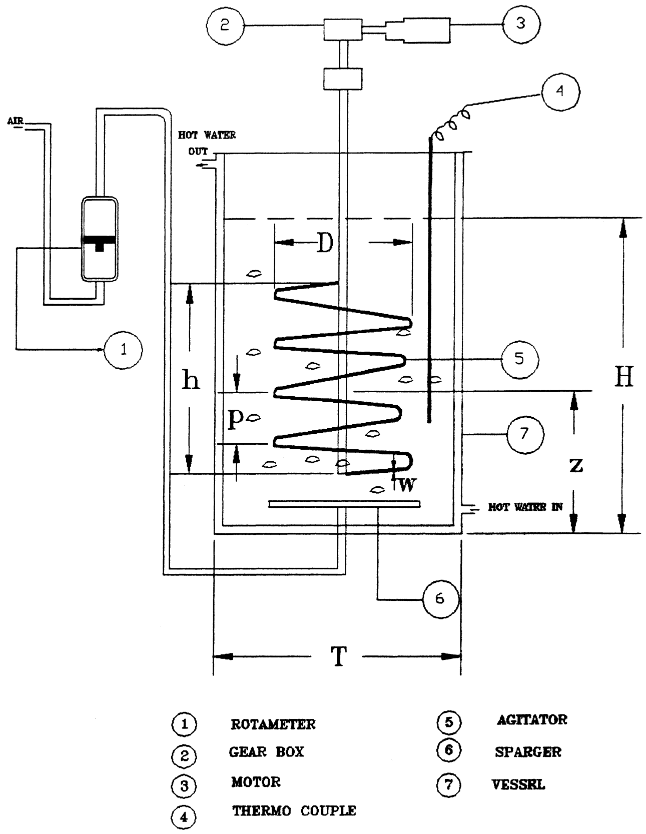

Fig. 1. Experimental set-up.

3.3. Effect of aeration

The experimental set-up for aerated stirred tank is shown in Fig. 1. Clean air from the compressor was introduced into the vessel through a ring sparger kept at the bottom of the vessel. The air flow rate into the stirrer tank is measured using a rotameter. Aeration experiments were performed with lube oil and 9% CMC solution, both in the presence and absence of agitation. Neither the sparger geometry nor the properties of the gas were varied. The heat taken away by the air is also taken into account in the calculation of heat transfer coefficient [15].

4. Results and discussion

4.1. Effect of impeller position

The effect of impeller position is the distance from the bottom vessel to the centre of the impeller on Nu. All the other parameters such as agitator speed, height of the fluid, etc. are unchanged. The results show that when the distance Z/H is small, i.e. the impeller is placed close to the bottom of the vessel, the heat transfer coefficient and hence Nu is low. As the distance is increased, Nu increases. However, when the distance is increased further, Nu starts decreasing, thus showing an optimum distance at which Nu is maximum. The optimum distance corresponds to Z/H, approximately equal to 0.55, i.e. the heat transfer coefficient is maximum when the impeller is placed approximately at the centre. This trend is found for two different speeds of impeller, viz. 50 and 100 rpm. When the impeller is placed close to the bottom of the vessel, the mixing localised at the bottom of the vessel and the mixing is insufficient at the top portion of the vessel. This results in low heat transfer coefficient when the impeller is placed close to the vessel bottom. As the distance increases, mixing becomes more and more vigorous and uniform throughout the vessel. Hence, the heat transfer coefficient increases. However, when the distance from the bottom becomes very large, again, the mixing is localised on the top portion resulting in lower heat transfer coefficient.

4.2. Nu–Re

It has been seen that Nu versus Re use two types of stirrers for glycerine. The obvious trend of increase in Nu is with increase in Re. The least square fit of the experimental data is found to be reasonably good for both the cases. Further, it can be seen that the stirrer 2 gives higher heat transfer coefficient compared to stirrer 1. Similarly for other fluids, viz. lube oil, castor oil, 3% CMC, 9% CMC and 0.5% PAAm, respectively. However, in the case of non-Newtonian fluids the stirrer 1 gives slightly higher heat transfer coefficient compared to stirrer 2.

4.3. Effect of H/T ratio

Fig. 2 shows a log–log plot of $\mathrm{Nu}/\mathrm{Re}^{a}\mathrm{Vi}^{0.14}\mathrm{Pr}^{0.33}$ versus H/T (ratio of height of the fluid to the tank diameter). Here, the constant 'a' is the slope of Nu versus Re plot for the corresponding fluids. The powers Vi and Pr are taken as 0.14 and 0.33 as these are well established in the literature

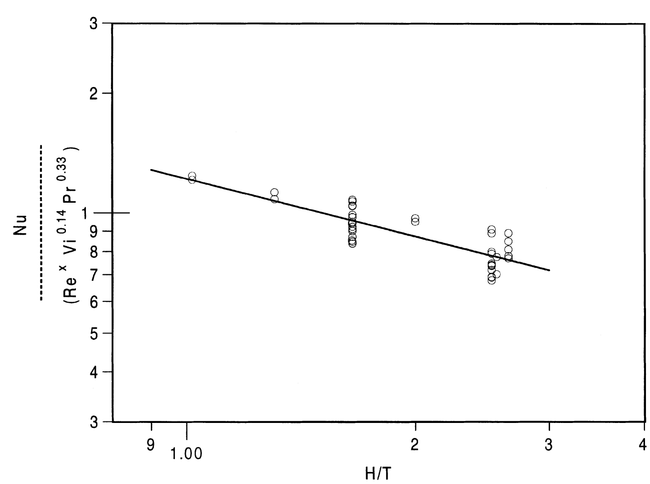

Fig. 2. H/T correlation for helical ribbon agitator.

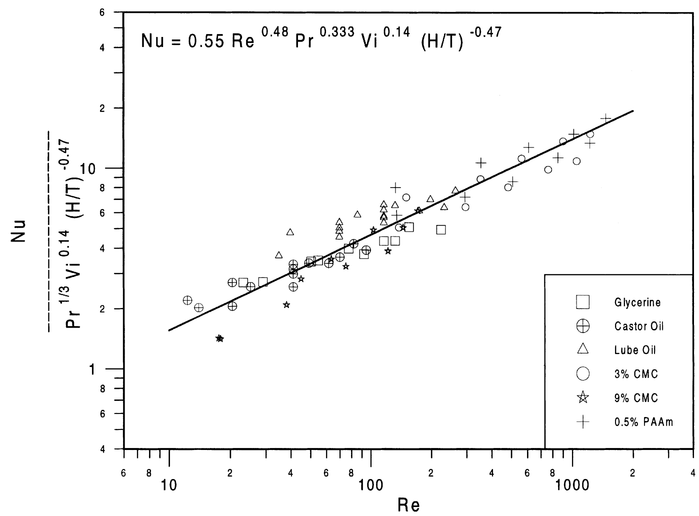

Fig. 3. Heat transfer correlation for helical ribbon agitator.

for helical ribbon agitator. The plot shows that the value of $Nu/Re^{x}Vi^{0.14}Pr^{0.33}$ decreases with increase in *H*/*T* ratio with a slope of −0.47.

4.4. Heat transfer correlation

The experimental data from the present work summarised in Fig. 3 can be correlated in empirical form as

$$Nu = 0.55Re^{0.48}Pr^{0.33}Vi^{0.14}\left(\frac{H}{T}\right)^{-0.47} \quad (4)$$

with coefficient of determination (R^2) equal to 0.9 and the standard error of the estimate (σ^2) equal to 0.037. The new parameters introduced in correlation is *H*/*T* which influence the heat transfer coefficient appreciably. The work of Chapman et al. [17] with flat blade turbine impeller showed the power of *H*/*T* ratio to be −0.56. The exponent of Re in Eq. (4) is close to 1/2 reported by the earlier workers for similar Re range used in this work. [7,8,18]. The correlation can be used to determine heat transfer coefficient for vessels with geometric deviation from standard configuration. However, the correlation can be used only in the range of Re studied, as the heat transfer coefficient strongly depends on the impeller geometry when Re<10 [6].

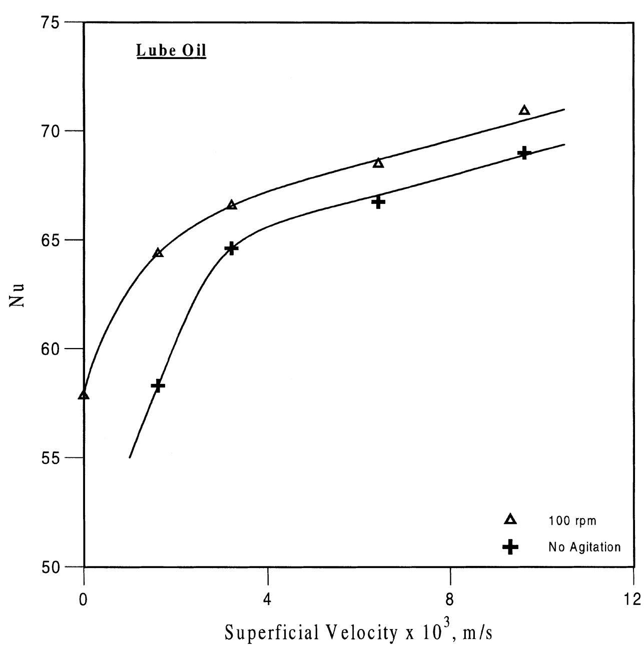

Fig. 4. Effect of aeration on the heat transfer coefficient in presence and absence of agitation for lube oil.

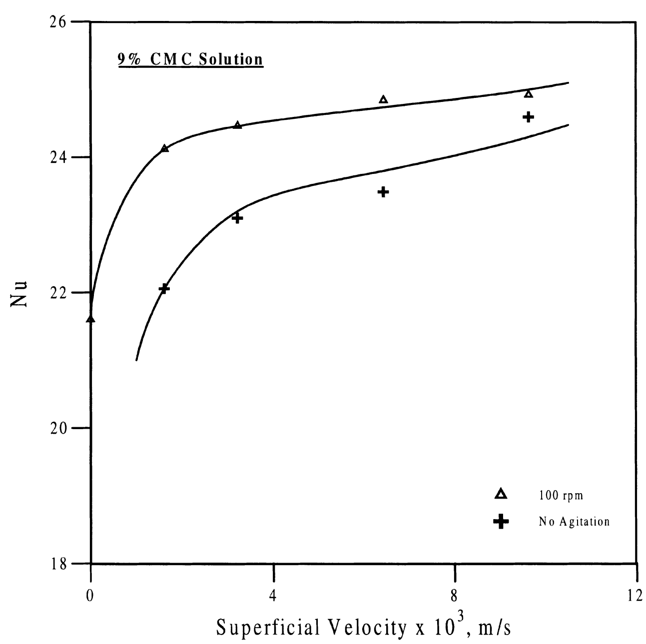

Fig. 5. Effect of aeration on the heat transfer coefficient in presence and absence of agitation for 9% CMC solution.

4.5. Effect of aeration

Fig. 4 shows the effect of aeration on heat transfer correlation or Nu in the presence and absence of agitation. At 100 rpm, it can be seen that the Nu initially increases substantially with increase in superficial velocity and rather slowly at higher superficial velocities of the gas. Similar trend can be also observed in the absence of agitation. Further, it can also be noticed that in the presence of aeration, there is no remarkable increase in Nu value with agitation. The increase is relatively higher at lower gas flow rate as compared to the increase at higher flow rate. The heat transfer coefficient corresponding to agitation at 100 rpm without aeration has been attained in absence of agitation with a velocity of 0.0016 m/s (corresponding to 1 l/min of gas flow rate). Fig. 5 also shows similar trend for 9% CMC solution.

5. Conclusion

- Temperature profiles with respect to time and heat transfer coefficient for different diameters of impeller has been investigated.
- The influence of H/T ratio on the heat transfer rate has been studied.
- A generalised correlation has been obtained for vessel with geometric deviations from standard configuration.
- The maximum heat transfer coefficient is attained when the impeller is placed approximately at the centre.
- Increase in superficial velocity of the aerated gas increases the heat transfer coefficient appreciably, especially at lower gas flow rate.
- Aeration coupled with mechanical agitation has not given substantial improvement in heat transfer coefficient both for Newtonian and non-Newtonian fluids.
- Viscoelastic material reduces the heat transfer coefficient.

6. Nomenclature

A, a, b, d, e	constants in Eq. (1b)
C_p	specific heat capacity of the fluid
c	clearance between impeller tip and vessel wall
D	impeller diameter
h	impeller height
h_j	heat transfer coefficient
H	height of the fluid in the vessel
k	thermal conductivity of the fluid
K'	constant in the power law equation (consistency index)
n	exponent in the power law equation (flow behaviour index)
n_b	number of blade in the impeller
p	pitch
T	tank diameter
w	width of the impeller blade
Z	distance between the centre of the impeller and the bottom of vessel.

Dimensionless quantities

Nu	Nusselt number ($h_j T/k$)
Pr	Prandtl number ($C_p\, \mu/k$)
Re	Reynolds number ($\rho N D^2/\mu$)
Re_c	critical impeller Reynolds number ($\rho N_c D^2/\mu$)
Vi	viscosity ratio (μ/μ_w)

Greek symbols

γ_a	average shear rate
μ	Newtonian viscosity
μ_a	average apparent viscosity for non-Newtonian fluids
μ_w	viscosity at the wall
ρ	density of the fluid

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