Heat Transfer to Jackets with Close Clearance Impellers in Viscous Materials

C. K. COYLE, H. E. HIRSCHLAND, B. J. MICHEL and J. Y. OLDSHUE

Mixing Equipment Company, Inc., Rochester, New York and Greey Mixing Equipment Ltd., Toronto, Ontario

(Manufacturers of LIGHTNIN Mixers and Aerators)

"Viscous mixing" as defined here includes the range of 5000 to 500,000 centipoises at 5 sec-1 fluid shear rate. It was found that heat transfer coefficient with helical impellers were related to the clearance between the impeller and the tank wall and not influenced to any important degree by the speed or the fluid viscosity. The mechanism seems to be conduction through this stagnant film. "Convection-type" correlations are not useful in describing the effect of operating variables.

Le procédé dit "mélange visqueux" tel que défini dans cet article se situe dans les limites de 5000 a 500,000 centipoises lorsque la vitesse d'un fluide a cisaillement est 5 sec-1. Avec des roues à aubes du genre hélicoïdal on a trouvé que le coefficient de transfert de chaleur était en relation avee l'espace entre l'extrémité de l'aube et la paroi du réservoir; cependant la vitesse ou la viscosité du fluide ne l'affecte a aucun degré important. Le mécanisme semble se faire par conduction a travers la péllicule stagnante. Les corrélations de type "convection" n'ont été d'aucune utilité pour décrire l'éffet causé par les variables des operations expérimentales.

There were several objectives in this work:

1. To obtain heat transfer coefficients in jacketed mixing vessels with close-clearance impellers at viscosities over 10,000 centipoises, which is the highest viscosity reported in the literature to date (1).
2. To obtain heat transfer coefficients with helical type close-clearance impellers.
3. To determine the relative performance of anchor impellers.
4. To determine the relative performance of scraper blades for heat transfer.
5. To study heat transfer to Non-Newtonian fluids, which phenomenon has not been reported in the literature at these viscosities.
6. To get an indication of the difference in heat transfer and operating characteristics of open type impellers and helical impellers in a viscosity range where both can be used with satisfactory blending performance.

"Viscous Mixing" is a relative term. As defined in this report, "viscous mixing" occurs when the viscosity is in the range of 5000 to 500,000 centipoises at 5 seconds^{-1} fluid shear rate. Viscosity values given in this report always refer to 5 seconds^{-1} shear rate.

The laminar flow pattern associated with "viscous mixing" refers primarily to the flow pattern in the tank and a definition of "viscous mixing" actually depends upon impeller Reynolds number, which, in turn, is related to impeller diameter, impeller speed and fluid viscosity.

Experimental details

Two different size vessels were used, a 14-in. diameter vessel with a 13-in. diameter impeller, and a 30-in. diameter vessel with a 29-in. diameter impeller. The pitch of the helical impeller, based on the impeller diameter, was 0.5. The liquid level gave a liquid level-to tank diameter ratio, Z/T, of approximately 1.0. The tanks were jacketed. In the case of the 14-in. diameter tank, the jacket extended partially around the bottom and the clearance between the bottom blade and the bottom of the tank was maintained at 1/2-in. In the 30-in. tank, jackets existed only at the side walls and the clearance between the impeller and the tank wall was 1/2-in.

The fluids used were all organic materials having a wide variety of viscosities and pseudoplastic characteristics. The thermal conductivity of all the fluids used was 0.08 to 0.09 Btu/hr/°F/sq.ft./ft. The quantity of heat removed was determined during the batch runs by stopping the mixer and probing the interior of the tank very quickly. The temperature probes were withdrawn and the mixer operation continued. Two pre-determined locations were used and suitable averages taken to get the quantity of heat transferred at those points.

Water at approximately 50° to 70°F was circulated through the jacket and the average Δt during the course of the run was approximately 50°F. These runs were made from a tank temperature of about 140°F to 100°F. The data reported on Figures 1 and 2 were taken when the fluid was being cooled.

The quantity of heat transferred was measured by determining the temperature change in the known weight of fluid in the batch. The power consumption was measured by means of a strain gage torquemeter. The heat of mixing was included in the total heat removed from the batch during cooling.

Results

The data given in Tables 1 and 2 and Figures 1 and 2, show that neither speed nor viscosity plays an important role in determining the heat transfer coefficient. Once a relatively stagnant film exists on the tank wall, a heat transfer coefficient of between 4.0 and 4.5 Btu/hr°Fft^2 is obtained with the particular 0.5 inch radial clearance used here. There is very little that can be done to change this value at practical power levels and blend times.

The general conclusion from this study was that the heat transfer in the viscous range with close clearance impellers was primarily by a mechanism of conduction through a film whose effective thickness is related mainly to the clearance between the impeller and the tank wall. Convection type correlations extrapolated to this range of viscosity do not correlate these experimental results.

At a constant impeller-to-tank wall clearance, as the mixing tank is scaled up, there is normally an increase in the tip speed of the impeller and it is believed that this would tend to increase rather than decrease the heat transfer coefficient of larger systems at constant impeller-to-tank diameter wall clearances. The 29-in. diameter impeller in the 30-in. diameter tank tends to give a slightly higher coefficient than the 13-in. impeller in the 14-in. diameter tank, although this difference is small compared to the experimental scatter in the data. Shown for reference in Figures 1 and 2 are the heat transfer coefficients obtained with zero impeller speed.

At practical industrial operating power levels, speeds are in the range of 5 to 30 rpm. Two points are shown at 50 to 60 rpm, although the power level was so high that the heat dissipation from the mixer was so great that accurate heat transfer data could not be obtained.

As further evidence that there is a conduction film at the tank wall, it was observed that there was a slight decrease in heat transfer coefficients obtained when the fluid in the tank was heated rather than cooled. The thermal conductivity of organic

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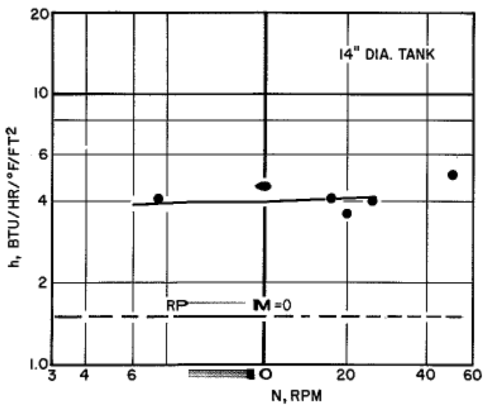

Figure 1 — Heat transfer versus impeller speed for helical impeller in 14-in. diameter tank.

Figure 2 — Heat transfer versus impeller speed for helical impeller in 29-in. diameter tank.

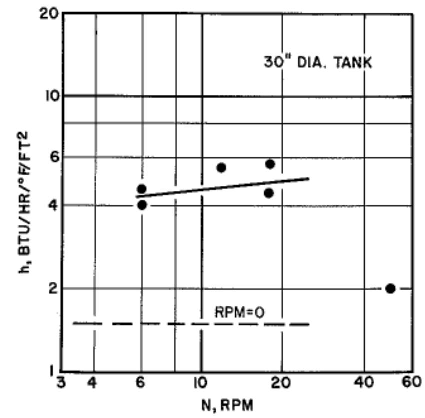

TABLE 1
HEAT TRANSFER DATA
14-in. dia. tank, 13-in. diameter helical impeller

N	Viscosity at shear rate 5 sec.$^{-1}$, 100°F	Viscosity Power Law exponent, n	h Btu/hr / °F,/sq.ft.
7	100,000	0.2	3.7
10	2,000	0.8	4.5
18	100,000	0.2	4.2
20	2,000	0.8	3.6
25	30,000	1.0	4.0
50	30,000	1.0	5.0

TABLE 2
HEAT TRANSFER DATA
30-in. dia. tank. 29-in. diameter helical impeller

N rpm	Viscosity at shear rate 5 sec.$^{-1}$, 100°F	Viscosity Power Law exponent, n	h Btu/hr / °F/sq.ft.
6	30,000	0.8	4.6
6	100,000	0.2	4.0
12	30,000	0.8	5.5
18	30,000	0.8	5.7
18	100,000	0.2	4.5
49	100,000	0.2	2.0

materials increases as temperature decreases, which would support the observation that cooling coefficients are higher than heating coefficients. In contrast, in the low viscosity mixing range where Nusselt number-Reynolds number correlations are used, heating coefficients are higher than cooling coefficients, which is logically explained by the change in viscosity at the heat transfer surface.

The anchor impeller, Table 4, gave a coefficient of approximately 75% of the helical impeller coefficient. This can be related to the fact that fluid blending and temperature uniformity in the central core of a tank are less effective with the anchor impeller than with the helical impeller. Observations and other studies on blending [2,3] lend additional support to the conclusion that lower temperature uniformity could exist with anchor impellers compared to helical impellers.

There was normally about a 50°F difference in temperature between the cooling water and the fluid in the tank. The temperature spread between two thermocouples, one out near the edge of the blade and one at the center of the tank near the shaft, ranged from 5 to 15°F with the helical impeller, while at the same speed and power, the anchor impeller gave differences from 10 to 20°F.

There are several ways to install scraper blades on production size anchor and helical impellers. In experiments reported in Table 1, scrapers were installed so that each area of the tank was scraped only once per revolution. A stiffener and a flexible blade adjusted to fit tightly against the wall were used. The heat transfer coefficients were about double the heat unscraped values.

The power consumption of the impeller with the scraper blade was approximately twice as high at a given speed as the power consumption when the impeller had a 1/2-in. clearance from the tank wall.

Open impellers in high viscosity materials

In some of the lower viscosity materials used in this test program, it was possible to use open impellers to achieve blending and fluid motion. A variety of different combinations were used, and the power levels varied from 4 to 20 times higher than those used with the helical impellers. These variations were due to different impeller size-to-tank size ratios and the small scale of the 14-in. diameter tank.

A coefficient of 4.5 Btu/hr/°F/sq.ft./ft. was obtained with the open impellers.

With open impellers in unbaffled tanks, there is some tendency to swirl even in "viscous mixing". There were no baffles used in this work since these tanks were small. In large tanks used in industry, tank baffles about one-half the standard width are placed off the tank wall. The spacing between the wall and the baffle may vary up to one-half the distance between the impeller tip and the tank wall.

It appears that the open impellers have a limiting wall film thickness in this viscosity range that corresponds to about what is obtained with a 1/2-in. radial clearance with close-clearance impellers.

Determination of non-Newtonian fluid properties

One of the relations used to express pseudoplastic properties is the "Power Law" [4], in which exponent "n" is 1.0 for Newtonian fluids, and falls to values less than 1 as pseudoplastic properties increase. In a mixing vessel, shear rates of 5 seconds^{-1} are quite typical and all viscosities in this paper are referred to this basis. The exponent "n" varies from 0.2 to 1.0. There are a variety of shear rates in a mixing vessel. One of the important shear rates is the average shear rate in the vicinity of the impeller which determines the "apparent" viscosity that

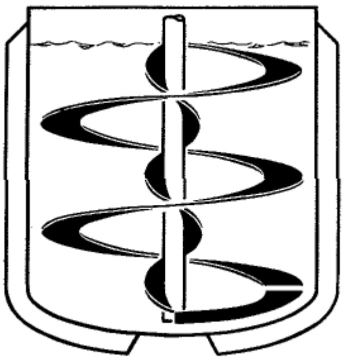

Figure 3 — Schematic view of helical impeller in jacketed tank.

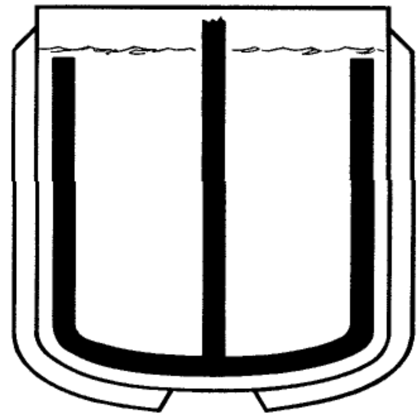

Figure 4 — Schematic view of anchor in jacketed tank.

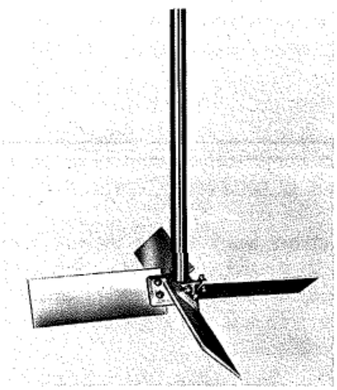

Figure 5—Axial flow turbine.

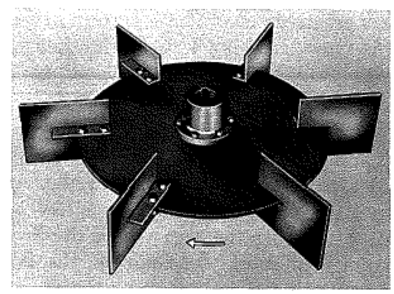

Figure 6—Flat blade turbine.

TABLE 3
EFFECT OF SCRAPER ATTACHED TO A HELICAL IMPELLER

N rpm	Viscosity at Shear Rate 5 sec.$^{-1}$, 100°F	Viscosity Power Law Exponent, n	$\frac{h_{scraper}}{h_{no\ scraper}}$	$\frac{HP_{scraper}}{HP_{no\ scraper}}$
25	30,000	1.0	2.0	2.0
50	30,000	1.0	2.3	2.0

TABLE 4
COMPARISON OF ANCHOR VERSUS HELICAL IMPELLER

N rpm	Viscosity at Shear Rate 5 sec.$^{-1}$, 100°F	Viscosity Power Law Exponent, n	$\frac{h_{anchor}}{h_{helical}}$	$\frac{HP_{anchor}}{HP_{helical}}$
7	100,000	0.2	0.8	1.0
18	100,000	0.2	0.7	1.0

the impeller "sees" in regard to the power consumption of the impeller.

All the impellers used in this program were calibrated with Newtonian fluids in the various vessels used. Reynolds number-Power number curves were obtained. Pseudoplastic fluids with a known viscosity versus fluid shear relationship were used. Power consumption was measured and the corresponding "apparent viscosity" was calculated. Thus, the corresponding fluid shear rate could be obtained. For the 17-in. impeller in the 18-in. tank, the average impeller shear rate was equal to 25 times the impeller speed.

TABLE 5
EFFECT OF SCRAPER ATTACHED TO AN ANCHOR

N rpm	Viscosity at Shear Rate 5 sec.$^{-1}$, 100°F	Viscosity Power Law Exponent, n	$\frac{h_{scraper}}{h_{no\ scraper}}$	$\frac{HP_{scraper}}{HP_{no\ scraper}}$
25	30,000	1.0	2.3	2.0
50	30,000	1.0	2.2	2.0

TABLE 6
JACKET HEAT TRANSFER – OPEN IMPELLERS

Impeller Type	Tank dia. T	Impeller Dia. D	N rpm	Viscosity at Shear Rate 5 sec.$^{-1}$, 100°F	Viscosity Power Law Exponent, n	h Btu/hr °F/ft^2	HP
Flat blade turbine	30-in.	16-in.	95	20,000	1.0	4.0	0.3
Axial flow turbine	14-in.	8-in.	430	2,000	0.8	4.1	0.25

There is also another average viscosity in the tank, that corresponding to the viscosity the process "sees" in relation to the blend time for a Newtonian fluid. The average process shear rate is not further discussed in this report.

TABLE 7
AXIAL FLOW TURBINE, $D/T=0.5$, COMPARED TO HELICAL IMPELLER, 1/2-IN. RADIAL CLEARANCE

Blend Time – equal

Heat Transfer Coefficient – equal

Impeller Type	Horsepower (Op. Cost) and (Mix. heat added)	N rpm	Torque	Initial Cost
Axial flow Turbine	1	1	1	1
Helical Impeller	1/4	1/8	2	3

Discussion

The laminar flow pattern associated with "viscous mixing" refers primarily to the flow pattern in the tank and the definition of the viscous mixing actually depends on the impeller Reynolds number which in turn is related to the impeller diameter, impeller speed and fluid viscosity.

As a comment on the upper viscosity range for the use of helical impellers, the fluid must have sufficient mobility to flow by gravity from any portion of the vessel surface where the anchor or helical impeller blades have pumped the fluids to a greater height to the area where the flow is flowing downward through the vessel. In addition, the fluid must have a certain adherence to the tank wall so the entire mass does not rotate with the impeller. The figure of 500,000 centipoises as an upper limit is very approximate, and could be as low as 100,000 centipoises and as high as several million centipoises depending upon this adherence factor.

In the 5,000 to 50,000 centipoises range, it is often possible for open impellers to achieve a satisfactory fluid motion, depending upon the size of the tank and the non-Newtonian nature of the fluid. In this area, the economics of the equipment dictate whether to use open impellers or close-clearance impellers. Above 50,000 centipoises, the close-clearance impeller predominates in utility.

Comparison of open impellers and close-clearance impellers

Table 7 shows the ratio between power, speed, torque and cost of open impellers and close-clearance impellers. When other impellers can be used with satisfactory results, the importance of power consumption in the heat removal step is normally the factor which would largely influence the final decision.

When the energy dissipated as heat by the impeller is an important percentage of the total heat to be removed, the helical impeller has a large advantage. This can offer considerable economies in heat transfer cycle times, and will allow other types of mixing effects to be used to advantage.

Conclusions and recommendations for further work

A uniform 1/4-in. thickness of material with a thermal conductivity of 0.09 Btu/ft/hr/°F can give a heat transfer coefficient of 4.5 Btu/ft²/hr/°F. It is our opinion that the heat transfer coefficient in viscous mixing is approximated by the rate of conduction through a stagnant film of approximately 1/2 the clearance between the impeller and the tank wall. Additional evidence for the conduction mechanism is that there is a slightly *higher coefficient for cooling than there is for heating.*

Since scale-up to larger tanks at a constant impeller-to-tank diameter clearance would result in higher tip speeds in the larger unit, the possibility exists for a slightly thinner film on large equipment and therefore a higher coefficient. This is quantitatively shown by comparing Figures 1 and 2.

Extrapolating Nusselt number-Reynolds number correlations down into the viscous range gives coefficients that vary with speed and viscosity and such an effect was not observed in this work.

Putting on a scraper that wipes the surface once per revolution tends to give twice the coefficient but also increases the power consumption by a factor of 2. The usefulness of scrapers depends upon the proportion of total heat coming from the mixer power input. Putting two scrapers on the impeller, so that the surface would be scraped twice per revolution, normally gives a still higher coefficient but was not studied in this particular report.

The anchor impeller does not give the same degree of temperature uniformity, which is thought to be one of the prime reasons why its heat transfer coefficient is about 25% less than that using a helical impeller at comparable speed and power levels.

Recommendations for further work should include investigation of other clearance ratios, and studies covering a wide range of viscosities, to indicate more precisely where the convection type correlations stop and the stagnant conduction film mechanism becomes predominant.

These are the first published data on heat transfer coefficients in this particular viscosity range with Newtonian and pseudoplastic fluids. Certainly other studies of comparable and different geometries and other fluid properties would add to the information on high viscosity heat transfer.

Nomenclature

D = impeller diameter
D/T = impeller diameter to tank diameter ratio
h = heat transfer
HP = horsepower
HP/Vol = horsepower per unit volume
k = thermal conductivity
N = impeller rotational speed, RPM
n = viscosity Power Law exponent
N_u = Nusselt number, hD/k
N_{Re} = Reynolds number, ratio of inertia force to viscosity force, $ND^2\rho/\mu$
T = tank diameter
t = temperature
Z = liquid level
Z/T = liquid level to tank diameter ratio
Δ = temperature difference, °F
ρ = specific gravity
μ = viscosity

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