Mixing in Viscous Liquids

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

Mixing Equipment Company, Rochester, New York

Detailed data are reported for blend time and turnover time with a 17-in. impeller operating in an 18-in. diameter tank. Above 1,500 centipoises, viscosity had no effect on blend time at constant speed. Blend time was inversely proportional to speed.

The inner flight of a helical impeller is of value when blending pseudoplastic fluids but has no effect on blend time with Newtonian fluids. The ratio of blend time to turnover time is given, as well as the effect of several different helical impeller geometry variables.

The primary observations made in this study were blend time and turnover time in viscous fluids with helical impellers. Viscous mixing is a relative term. As defined in this report, viscous mixing lies in the range of 5,000 to 500,000 centipoises at 5 $sec.^{-1}$ fluid shear rate. This is a typical shear rate as defined by the apparent viscosity that a 17 in. single, outer flight helical impeller in an 18-in. tank, ½ in. clearance, experiences related to the power consumption of the impeller at 12 rev./min.

Turnover time is defined as the time required for suspended particles to make a complete circuit in the tank from top to bottom and return. Particles of approximately 2 to 30 mesh were used. The tanks were transparent, the fluids were translucent, and times were recorded for several different particles in the system and suitable averages obtained.

For the blending runs, 5g. of brilliant yellow dye were mixed into 200 cc. of material from the tank and were added at the same spot on the surface of the tank. This was approximately at a spot on a diameter equal to 0.5 T. For each run, visual observation was made of the time for color uniformity to be produced.

In several runs, both turnover time and blend time were measured to obtain the relationship between them. In other runs, one or the other was used, since it was found that either could be used to establish the effect of mixing parameters.

In this report, visual blend time was used as referred to above. There are many questions unanswered concerning the relationship of other methods of determining blend time compared with the visual method used here. Discussions of various methods of determining blend time which contain additional references are given by Hoogendoorn and den Hartog (*3*) and Sykes and Gomezplata (*6*). Visual blend time was used because it is a reliable, consistent technique which allows the flow pattern to be observed. Bourne (*1*) and Nagata (*5*) describe work on flow patterns with helical impellers.

Every attempt was made to keep the experimental technique consistent so that the relative effect of mixing variables could be reliably evaluated.

In general, blend time determined by taking point analytical readings of such items as pH, concentration, or

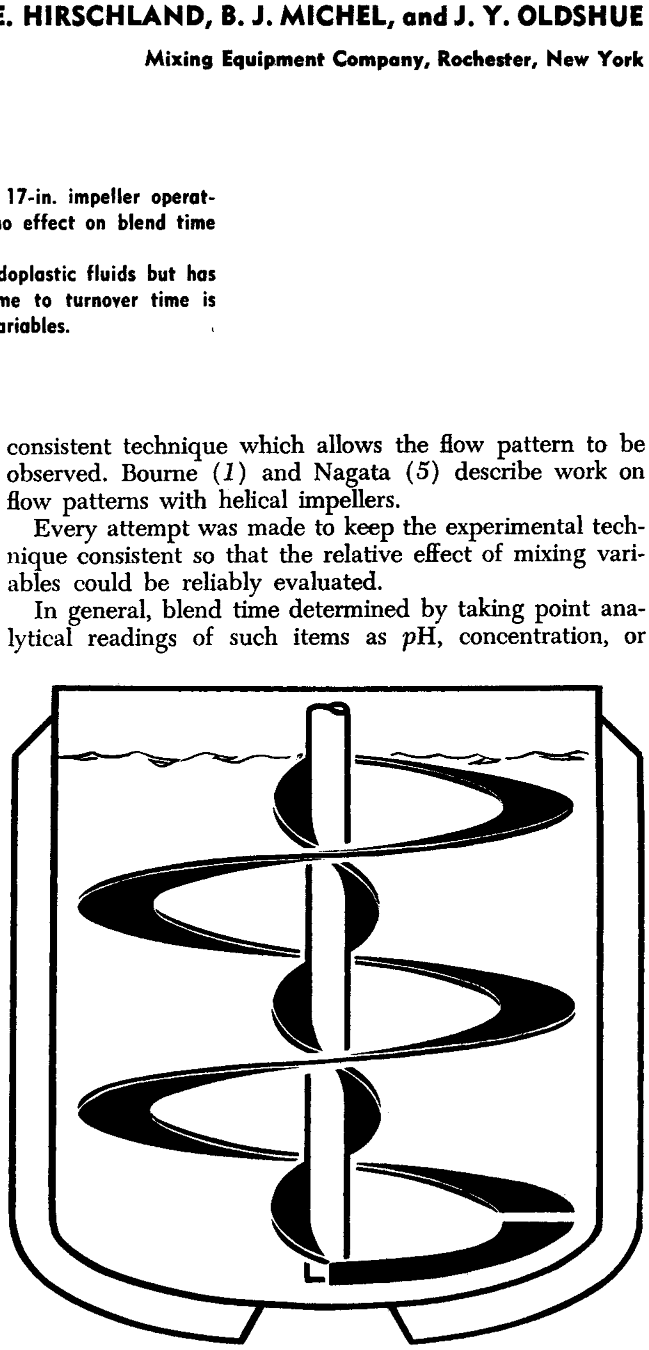


Fig. 1. A schematic view of a helical impeller in a jacketed tank.

refractive index will indicate a longer blend time than the visual blend time reported here. Blend times three to six times longer, by using analytical methods of determining blend time compared with this visual method, have been obtained in other studies in this laboratory.

The impellers used were helical impellers in which the outer flight had a blade width of one-twelfth of the impeller diameter, and the pitch of the outside helical flight was varied as shown in the tables. This pitch was expressed as a ratio to the impeller diameter. When an inner helix was used, it had an absolute pitch equal to the absolute pitch of the outer flight. The diameter of the inner helix was $0.35D$. Figure 1 illustrates a typical helical impeller. The majority of the tests described here were run with a 17-in. diameter helical impeller in an 18-in. diameter tank. Some data are reported for a 29-in. diameter impeller in a 30-in. diameter tank.

In all cases, the rotation was such that the outer flight pumped upward and the fluid could flow downward in the center of the tank.

EFFECT OF SPEED AND VISCOSITY ON BLEND TIME: NEWTONIAN FLUIDS

Blend time was inversely proportional to impeller speed as shown in Figure 2. This agrees with reports from other investigators (2, 5), using a variety of impeller tank configurations and fluids.

A series of experiments with corn syrup solutions of various viscosities is shown on Figure 2. In initial runs,

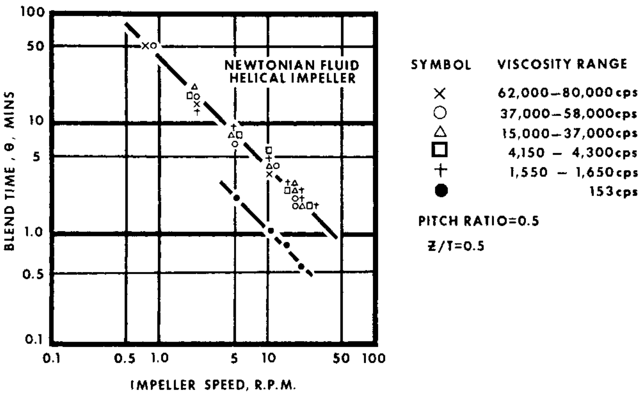


Fig. 2. Effect of speed and viscosity on the blend time for helical impellers in Newtonian fluids, 18-in. diameter tank with 17-in. diameter helical impellers.

temperature was carefully controlled to keep viscosity constant for several different experiments. However, it was determined that viscosity did not affect the blend time achieved at a given impeller speed in the range of 1,500 to 80,000 centipoises in the 18-in. tank reported on Figure 2.

Some of the data on this figure show viscosity groupings in which the viscosity was allowed to vary during a series of runs at different speeds.

Several runs at 153 centipoises show that viscosity does have an effect below a certain point. All runs used in analyzing the effect of mixing variables were made above 1,500 centipoises in the area where viscosity does not have an effect.

The area in which viscosity does have an effect probably is not a function of viscosity alone, but would involve impeller speed and impeller diameter as well.

TABLE 1. COMPARISON OF BLEND TIME AND TURNOVER TIME

Ratio of blend time to turnover time for 1% carbopol solution, 29-in. diameter impeller in 30-in. diameter tank.

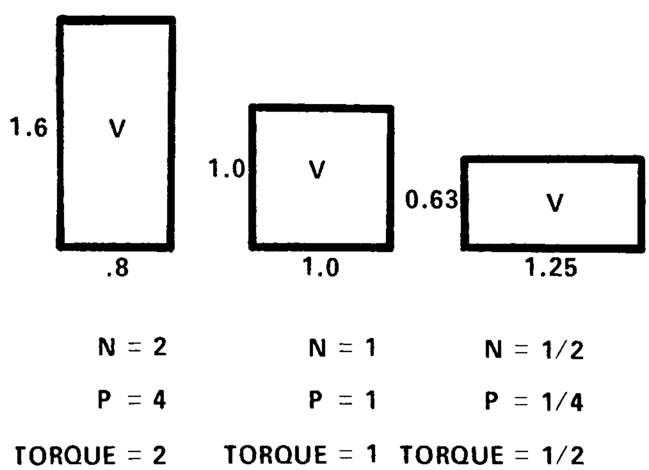
Speed, rev./min.	Z/T	Blend time / Turnover time
7.5	1.4	3.3
7.5	1.0	3.0
7.5	0.5	3.3

TURNOVER TIME VS. BLEND TIME

In a series of runs, shown in Table 1, it was found that blend time was approximately three times the turnover time for a given configuration and type of fluid. This held for both Newtonian and pseudoplastic fluids. In several of the mixing evaluations, turnover time was evaluated to study the effect of other mixing variables.

The turnover time was measured by taking a suitable average from stopwatch readings of the time required for particles to make one complete circuit in the tank, from top to bottom, and return.

TABLE 2. EFFECT OF TANK PROPORTIONS ON POWER AND TORQUE WITH A CONSTANT LIQUID VOLUME AND CONSTANT BLEND TIME (Relative values)



EFFECT OF LIQUID DEPTH-TO-TANK DIAMETER RATIO

The helical impeller normally extends essentially to full liquid depth. If the liquid depth is increased, the power consumed by the impeller at constant speed is increased in proportion.

Figure 3 indicates that the blend time at constant speed is also directly proportional to the liquid depth-to-tank diameter ratio, Z/T, over the range 0.5 to 1.5. Table 2 shows that at higher Z/T's it takes more power for a given volume of fluid to get a given blend time than it does at smaller Z/T ratios. This indicates that on a given application, the cost of the mixer and impeller and the cost of the tank and other process considerations must be evaluated to determine the proper Z/T ratio. Table 2 shows that shallow batches require less power and less torque for a given volume of fluid within the range studied, 0.5 to 1.5. Thus it can be concluded that to find opti-

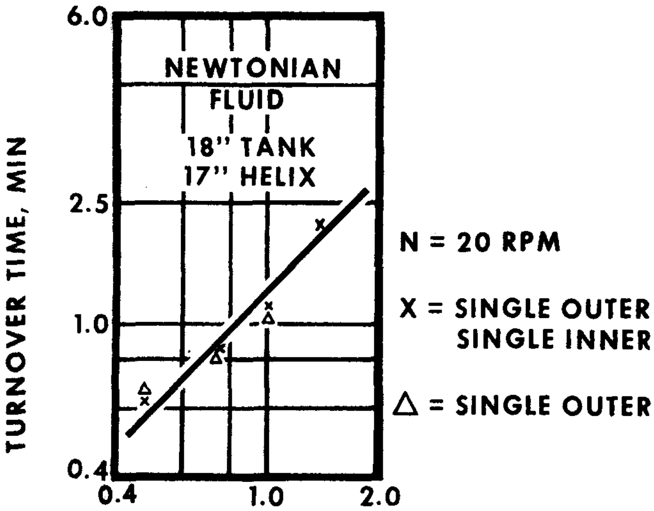


Fig. 3. Effect of Z/T ratio and of adding or removing single inner time; helical impeller in non-Newtonian fluids.

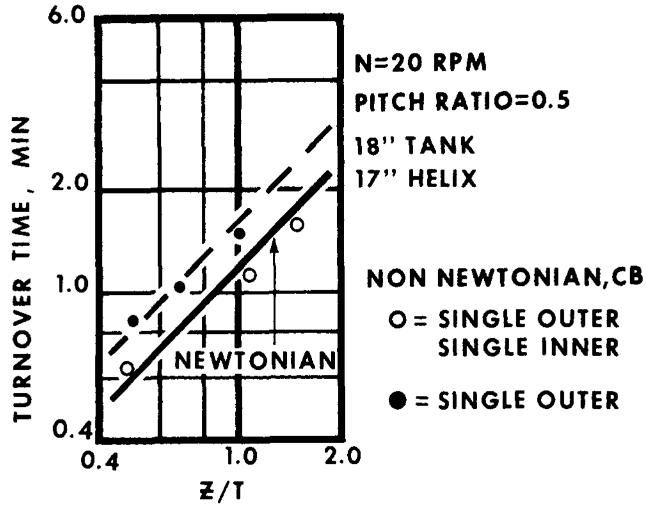


Fig. 4. Effect of adding or removing inner helical flight on turnover time; helical impeller in non-Newtonian fluids.

mum installation cost, Z/T ratios should be considered down to small values, since even though power and mixer cost may be lower, the cost of the vessel becomes higher at very low Z/T ratios.

EFFECT OF PSEUDOPLASTIC FLUIDS USED

Table 3 describes the two different pseudoplastic fluids used. The power law stating that

$$(\text{shear stress}) = K(\text{shear rate})^n$$

was used to describe the pseudoplastic properties. The exponent n is 1.0 for Newtonian fluids and approaches lower numbers as the pseudoplastic tendencies increase (*4*).

Figure 4 illustrates that with a helical impeller having both an outer flight and an inner flight, the turnover time is the same for this pseudoplastic fluid as it is for the Newtonian fluid.

The inner flight on a helical impeller has a negligible effect on the power consumption, but, if it is removed, it increases the turnover time in pseudoplastic fluids.

Figure 5 shows that blend time for pseudoplastic fluids with an outer and an inner flight is the same as that for Newtonian fluids, while the blend time for a helical impeller without an inner flight in pseudoplastic fluids is much higher, confirming the results shown in Figure 4.

EFFECT OF GEOMETRY OF HELICAL IMPELLER

Table 4 summarizes many of the salient points on the effect of geometry variations, which are as follows:

1. *Effect of inner flight.* As mentioned previously, the inner flight does not decrease the blend time in Newtonian fluids but does significantly decrease the blend time for pseudoplastic fluids compared with a helical impeller without the inner flight.

2. *Effect of two outer flights.* The use of two outer flights spaced 180 deg. relative to each other gives a lower speed for a given blend time as compared with a single outer flight. However, the power consumed by the impeller with two outer flights is approximately the same at this lower speed compared with the impeller with one outer flight at its corresponding higher speed. Therefore, for equal blend time, the impeller with two outer flights requires a higher torque because of the lower speed, and thus a larger size of mixer drive as compared with an impeller with a single outer flight, even though the horsepower is approximately the same. There may be requirements such as heat transfer characteristics or mechanical construction that would indicate a preference for two outer flights over one outer flight in a particular case.

3. *Pitch ratio.* A pitch ratio of 0.9 compared with 0.5 gives satisfactory performance in Newtonian fluids but gives very poor turnover in pseudoplastic fluids. As the pitch ratio of a single outer flight helical impeller is increased from 0.5 to 0.9, the power consumption at a given speed and viscosity decreases and approaches the power consumption of a hypothetical single blade anchor impeller. By analogy, the power consumption of a helical impeller with two outer flights would decrease as pitch ratio is increased from 0.5 to 0.9 and approach the power consumption of a two-bladed conventional anchor impeller. The anchor impeller normally does not have any tendency to pump from top to bottom, which is consistent with the observation that the 0.9 pitch ratio impeller does not blend as effectively as the 0.5 pitch ratio.

TABLE 3. FLUIDS USED IN THIS STUDY

C.S.,	corn syrup, Newtonian, 1,550 to 80,000 centipoises
CB,	1% carbopol, 40,000 to 50,000 centipoises at 5 sec.$^{-1}$ $n = 0.2$
CMC,	2% carboxymethylcellulose 7,000 to 8,000 centipoises at 5 sec.$^{-1}$ $n = 0.6$

THE SHEAR RATE OF SINGLE OUTER FLIGHT HELICAL IMPELLERS

By using pseudoplastic fluids which have a known viscosity vs. shear rate relationship, the average shear rate around the impeller as determined by the power consumption of the impeller can be measured.

Metzner and Otto (*4*) have reported a coefficient of 11 for the shear rate of a six flat blade turbine compared with the operating speed. In equation form:

$$(\text{average impeller shear rate}) = 11 \text{ (impeller speed)}$$

In several different pseudoplastic fluids, six flat blade turbines were operated as well as the 17 in. single outer

TABLE 4. RELATIVE EFFECT OF PITCH RATIO AND SINGLE OR DUAL OUTER HELICAL FLIGHTS ON SPEED AND TORQUE FOR EQUAL BLEND TIME

Constant blend time No. of flights Outer	Inner	Pitch ratio*	Fluids Newtonian Speed	torque (Relative values)	Non-Newtonian Speed	torque
1	1	0.5	1.0	1.0	1.0	1.0
1	0	0.5	1.0	1.0	1.4	1.4
2	1	0.5	0.7	1.25		
2	0	0.5	0.7	1.25		
2	1	0.9	1.3	0.9	poor turnover	
2	0	∞		Anchor impeller		

* Based on outer flight diameter.

flight helical impeller with a pitch ratio of 0.5. The coefficient relating shear rate for the helical impeller to the operating speed was determined as 25 in an 18-in. diameter tank.

POWER CONSUMPTION

Power consumption varies directly with viscosity at the average shear rate of the impeller. Shear rate from an impeller and the viscosity of the fluid at that shear rate are important to properly calculate the power consumption of the mixer. Estimating the viscosity of pseudoplastic fluids from data obtained on viscosimeters that do not have shear rates comparable to the impeller used in the installation can easily introduce values differing by a factor of 2 or 3 from the correct viscosity.

The process performance of the helical impeller is not affected by the actual viscosity, but the power, size of drive, and cost of the equipment is almost a direct multiplier based on the viscosity that the impeller experiences at its average shear rate.

COMPARISON BETWEEN OPEN IMPELLERS AND HELICAL IMPELLERS

Open impellers, such as flat blade turbines and axial flow turbines, can often achieve a satisfactory blend of materials in some ranges of viscosity which are also effectively handled by helical impellers.

Table 5 illustrates some general observations on the relationship between open impellers and helical impellers when both can accomplish satisfactory results. It illustrates a typical difference between power, speed, torque, and cost for axial flow turbines and helical impellers that will accomplish a given degree of blending. Usually the amount of heat generated by the mixer compared with the total heat removal required is a prime consideration in making a decision between the axial flow turbine and the helical impeller.

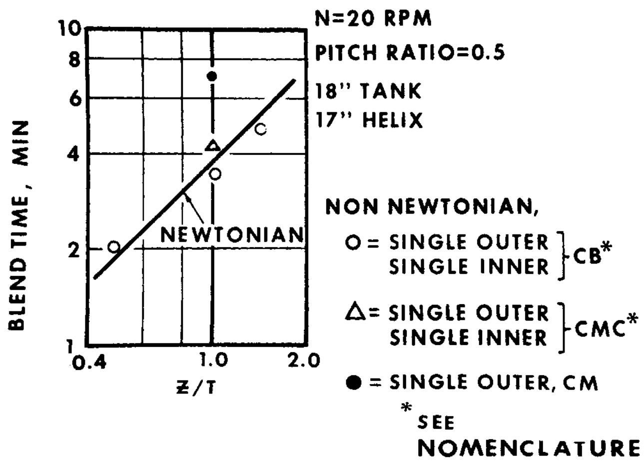


Fig. 5. Effect of pseudoplastic fluids on blend time.

TABLE 5. COMPARISON OF AN AXIAL FLOW TURBINE AND A HELICAL IMPELLER FOR EQUAL BLEND TIME AND EQUAL HEAT TRANSFER CHARACTERISTICS

Blend time—equal
Heat transfer coefficient—equal

Impeller type	hp.	Speed	Torque	Initial cost
	Relative values			
Axial flow turbine	1	1	1	1
Helical impeller	1/3 to 1/10	1/15 to 1/6	1.5 to 3.0	2.5 to 3.5

Ranges for a helical impeller compared to an axial flow turbine are from field observations with both Newtonian and non-Newtonian fluids from 10,000 to 50,000 centipoises at 5 sec.$^{-1}$.

There is also a difference in scale of mixing of the blending produced by higher speed axial flow turbines and the lower speed helical impeller. Scale of mixing is the minimum volume of a sample in which nonuniformity can be detected by the particular analytical device being used. The open impellers give a much smaller scale of mixing on the blend produced, and this can be of value depending upon the uniformity required.

When helical impellers are used for large scale tank blending, there are occasions when it is desirable to reduce the scale of mixing of the blend produced by passing the output through a high speed line blender which will give a smaller scale of uniformity that can be of advantage for future processing of the stream.

NOTATION

D = impeller diameter
D/T = impeller diameter to tank diameter ratio
K = arbitrary constant
N = impeller rotational speed, rev./min.
n = viscosity Power Law exponent
T = tank diameter
V = volume
Z = liquid level
Z/T = liquid level to tank diameter ratio
θ_B = blend time
θ_T = turnover time

LITERATURE CITED

1. Bourne, J. R., "Some Characteristics of Helical Impellers in Viscous Liquids," Inst. Chem. Engrs., England (1965).
2. Gray, J. B., *Chem. Eng. Prog.*, **59**, No. 3 (Mar., 1963).
3. Hoogendoorn, C. J., and A. P. den Hartog, *Chem. Eng. Sci.*, **22**, No. 12, 1689-99 (1967).
4. Metzner, A. B., and R. E. Otto, *AIChE J.*, **3**, No. 3 (1957).
5. Nagata, S., M. Yanagimoto and T. Yokoyama, *Chem. Eng. Japan*, **21**, No. 5 (1967).
6. Sykes, Paul, and Albert Gomezplata, *AIChE J.*, **11**, No. 1 (1965).

Manuscript received December 30, 1968; revision received March 13, 1969; paper accepted March 17, 1969. Paper presented at AIChE Los Angeles meeting.