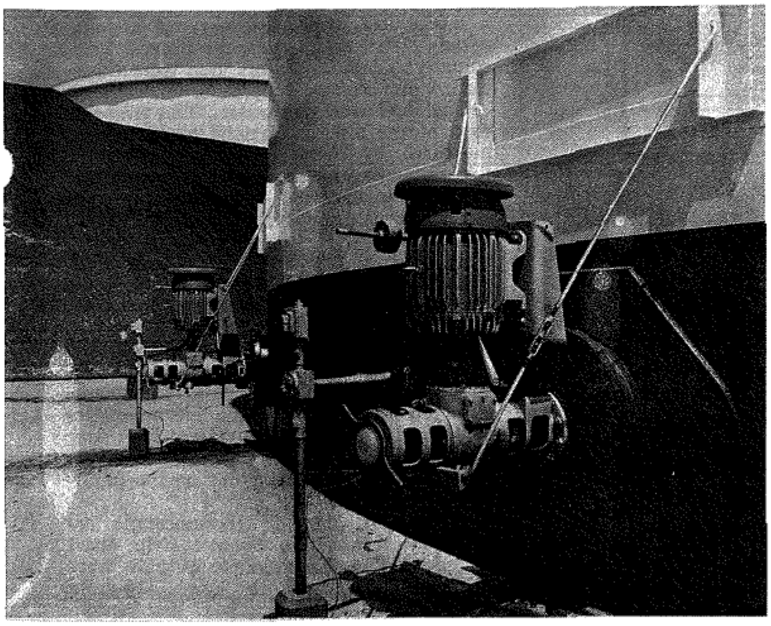

Side-entering propeller-type mixer on 80,000-bbl. gasoline blending tank. Two 25 hp. mixers placed on 120-ft. diam. × 40-ft. high tank.

The blending of liquids in large storage tanks where density stratifications exist is a daily operation in the petroleum refining and chemical industries. Nevertheless, the mechanics of the blending operation have not been sufficiently well understood. Here is a report of a study which took place in tanks as large as 70,000 gallons, and which showed that large impellers (with respect to tank sizes) give better results than small ones for the same power; that longer blending time at lower power levels does not consume more power.

blending of low-viscosity liquids with SIDE-ENTERING MIXERS

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Blending is a common operation in fluid mixing.* The manner in which blending takes place is varied, but the extremes are:

a. introducing a second miscible fluid into a first fluid in the vessel in such a manner that uniformity is produced almost instantaneously as the second fluid is introduced;

b. adding the second fluid in such a manner that the two liquids are initially stratified before blending progresses.

This report presents information concerning the second mode of blending, in which the two liquids are initially stratified before blending begins. This is by far the most difficult case, one which should yield useful limiting values for the effect of certain variables on the mixing operation.

The entire study was made with side-entering propeller-type mixers, positioned in the majority of the runs in the "standard off center" position. This position is illustrated in Figure 1. Tank sizes of 70,000, 500, and 100 gallons were used in the experiments. Fluid viscosity was between 0.3 and 1.0 centipoises.

Various systems have been used in the laboratory for measuring the effect of blending. Included are pH, color, electrical conductivity, concentration, refractive index, and density. In this particular study, uniformity of temperature was used as a measure of blending thoroughness. The use of hot and cold layers of the same fluid gave results similar to those obtained in blending of different fluids having the same physical properties as the hot and cold fluids. Blending times ranged from one minute to six hours. The effects of several mixing variables were studied and are reported and discussed as follows:

Results: Discussion and Conclusions

There was found to be a very sharp and distinct barrier between the two stratified layers. The mechanism by which this barrier is worn away seems to be a gradual erosion or wearing away of the barrier by the fluid in the part of the tank moved by the mixer.

Once the impeller action begins, the fluid motion begins quickly in the lower uniform area. No motion appears at the top surface of the upper stratified layer until the boundary layer reaches this surface.

Some preliminary experiments with injecting the second fluid behind the propeller indicate blending times several factors lower than that required for initially stratified systems.

The wearing away of the interface seems to be largely proportional to the volume of fluid passing across the interface. Thus, large impeller size to tank size ratios which give larger flow capacities for the same amount of power give shorter blending times for the same level of power than do smaller D/T ratios. There is apparently enough turbulence in low-viscosity systems that once any fluid from the second layer is incorporated into the first layer, it is immediately blended uniformly throughout.

The use of small diameter impellers, or more generally, small diameter fluid jets, would indicate more power for the same blending performance. This has been confirmed by the theoretical discussions of Folsom (*1*) and the experimental data of Fosset and Prosser (*2*). These authors give the conditions required to mix fluid in initially uniform layers and to prevent stratification throughout the entire system. Their results are in agreement with the results of this paper in that large diameter

* And yet few fundamental studies have been made in this area. Publications by Fox and Gex (*3*), and Vandervusse (*5*) are the major ones to date in this field. Articles on the use of fluid jets for mixing in which the fluid jet may be produced either by flow from a nozzle or from a mixing propeller have appeared in the literature (*1, 2*).

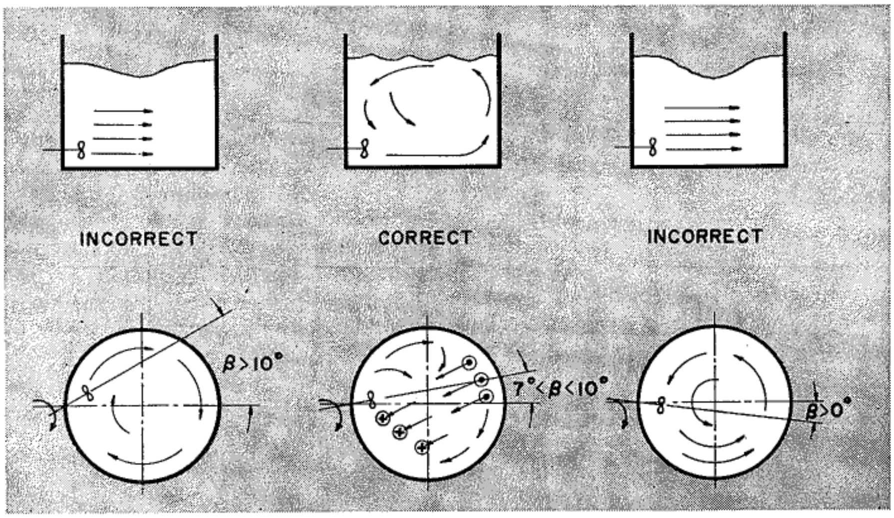

Fig. 1. Optimum positioning for side-entering propeller-type mixers.

fluid jets give better performance at lower horsepower than do small diameter fluid jets, whether the jet is produced by mixers or nozzles.

One important difference exists between the data presented here and the data of Fossett and Prosser on the use of nozzles. They have found (2) that the nozzle could not mix a tank initially stratified. Therefore, all their data are for injection of a second fluid into an initially uniform fluid, which requires much less power input than does the case of initially stratified layers presented here.

At no time in this investigation did data indicate that blending could not be obtained even at long time intervals with low power levels. There was some concern whether very low power levels would have all their energy dissipated in internal friction of the fluid without having a chance to cause blending throughout the system. Within the range of practical interest (blending times up to 12 and 16 hours) indications were that blending would proceed, and that these long blending times were entirely feasible.

Results: Summary

EFFECT OF DENSITY DIFFERENCE BETWEEN STRATIFIED LAYERS

The difference between hot and cold layers is essentially a difference in gravity. By varying the temperature difference and making duplicate blending runs, it was established that the blending time was proportional to the difference in gravity to the 0.9 exponent.

$$\theta \alpha (\Delta\rho/\rho_o)^{0.9}$$

The range of density differences used in the experimentation was from 0.3% to 7%.

EFFECT OF POWER

Power was varied by varying the speed of a given size impeller. The effect of power on blending time indicates that power and blending time are inversely proportional:

$$\theta \alpha (HP)^{-1}$$

where HP is the power input to the fluid. θ varied from one minute to six hours.

IMPELLER SIZE TO TANK SIZE RATIO

In the blending of low-viscosity fluids, the major effect seems to be one of pumping action throughout the tank. The use of large impellers at slow speed gives large values of flow and low values of fluid shear. In blending operations the impeller diameter to tank diameter ratio (D/T ratio) are normally relatively low and in all respects these studies were made to simulate blending on large scale installations.

The effect of D/T was correlated at constant power input to the mixer; therefore, large D/T inputs are associated with slow speeds to give the same power input as small impellers. With D/T values ranging from 0.03 to 0.11, the best exponent was found to be —2.3 at a liquid level to tank diameter ratio (Z/T) equal to 1.

$$\theta \alpha (D/T)_{HP}^{-2.3}$$

There is evidence that as the tank batches become shallower, the effect of D/T becomes less.

EFFECT OF MIXER POSITION

A mixer angle of 7° to 10° was used, as angles appreciably different from these values give inferior blending results.

Details of Experiments

EQUIPMENT

The mixing equipment used in this investigation consisted entirely of side-entering mixers, electrically driven through a mechanical means for varying impeller speeds. The shafts were positioned horizontally and the impellers used were three-bladed marine-type propellers.

The fluid used was water. The temperature of the fluid in various positions was measured by mounting copper-constantan thermocouples in the tank. The thermocouple temperatures were recorded on Brown thermocouple recorders.

Two types of thermocouple recorders were used in this work. One was a 16-point multi-channel recorder. With this instrument, up to 16 thermocouples could be placed in the tank and each thermocouple temperature would be recorded every four minutes. If less than 16 thermocouples were used in the tank, a temperature record of some of the thermocouples could be had at intervals of less than four minutes by connecting the thermocouple leads to more than one point on the multipoint recorder.

The second type of thermocouple recorder was a single channel strip chart recorder. The thermocouple outputs were fed to this recorder through a 16-point multiple contact switching box. The switching box was operated manually, so that the operator could record the temperature of any thermocouple point at any time and for as long a period of time as desired. With this recorder it was necessary to mark the chart paper with an identification of the thermocouple being recorded. Since the chart speeds were constant and known values for these recorders, the blending time could be determined by measuring the length of the chart that passed through the recorder from the beginning until the end of the run.

The tanks used in this investigation were flat bottomed, unbaffled, vertical cylindrical tanks. The tank diameters were 240 inches, 54 inches and 30 inches.

EXPERIMENTAL METHOD

To determine whether a blending operation has proceeded to homogeneity, it is necessary to be able to measure some fluid variable at various points in the tank. For this study the measurement of variation in temperature within the tank contents was investigated because of the following factors:

1. **Simplicity of measurement.**
2. **After a blend, fluids could be re-used because their properties could be adjusted by temperature adjustment.**

To determine if such a method were feasible, a 42-inch tank was set up and filled to a 21-inch depth with cold water. A layer of hot water was then floated on top of the cold by directing the stream of hot water onto a float, so that the water velocity was directed horizontally. It was found that a good separation of the hot and cold layers could be obtained. Figure 2 is a graph of the temperature changes in this tank when it was allowed to stand without mechanical agitation for a period of 48 hours. It can be seen that the temperatures of the hot and cold layers approached room temperature without any interchange between the two layers.

To determine the feasibility of the temperature method of measuring blending time, a flat-blade turbine mixer was placed in a tank of water in which hot and cold layers had been placed. It was found that the blending proceeded from the high density layer upward in the tank. As mixing proceeded, the interface moved upward and when it reached the position of the thermocouple, the temperature at that position dropped until it became equal to the temperature of the liquid in motion below the interface.

As a further check on this mechanism of blending, visual tests were made in which one of the layers was colored with a dye. In these demonstrations, it was easily seen that fluid flow due to the impeller was restricted to the lower or more dense layer, and that this fluid flow would eat away at the lower density material at the interface, thus raising the interface until a blend was obtained when the interface reached the surface of the liquid. The blending mechanism was found to be the same whether a top-entering mixer was used near the bottom of the tank as in the preliminary runs to explore the technique, or a side-entering propeller mixer was used near the bottom of the tank.

Figure 3 is a graph of the temperature changes in an experimental blending run in the 240-inch diameter tank. The mixing was accomplished with a side-entering propeller mixer.

Figure 4 is a graph taken from the literature (*4*), showing a blending operation in a stratified 20,000-barrel tank in which four charges of furnace oil of different API gravities were blended. In this case, the progress of the blend was determined by taking oil samples at various levels, determining the API gravity of the samples and plotting them against time. The temperature profile obtained in Figure 3 indicates that the same type of blending mechanism is obtained as was the case in Figure 4. It was concluded that the hot and cold layer technique using thermocouple probes would be a satisfactory method of measuring blending times.

In the experimental data reported here, the hot fluid was either 10% or 20% of the total. In studying any particular variable the proportion was kept constant. Experimental studies on the effect of this ratio indicated no detectable difference for these two percentages of hot fluid. Qualitative observations on higher percentages of the hot layer indicated that 50% of the total was the most difficult case.

PROCEDURE

To make a blending run, the following steps were taken:

a. The cold fluid was pumped into the tank to the desired depth.

b. The mixer was started and the desired rotational speed was set. The mixer was then stopped and the cold fluid was allowed to come to rest.

c. The layer of hot fluid was pumped into the tank using a float to prevent mixing at the interface.

d. The thermocouple recorder was started so that fluid temperatures throughout the tank could be measured before mixing began. The thermocouple recorder was then stopped.

e. The mixer and thermocouple recorder were started simultaneously.

f. The blend was allowed to proceed until temperatures throughout the tank reached an equilibrium value.

g. The length of the thermocouple recording chart between start of the mixer and the accomplishment of a blend was measured. Knowing the chart speed, this chart length was converted to a blending time.

VARIABLES

The variables studied in this investigation were:

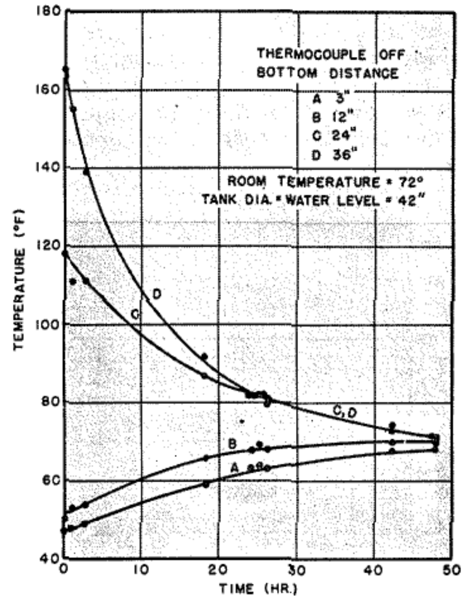

Fig. 2. Temperature changes in a stratified tank with no mechanical agitation.

a. Hot and cold layer temperature, and therefore the physical properties of the fluids.

b. Impeller diameter and impeller speed. These properties also varied the impeller horsepower input and D/T ratio.

c. Ratio of liquid depth to tank diameter.

d. Number of mixers and position of mixers on the tank periphery, including angle of entry.

Details of Experimental Results

EFFECT OF DENSITY DIFFERENCE

The first variable studied was the blending time at constant horsepower as a function of fluid density differences.

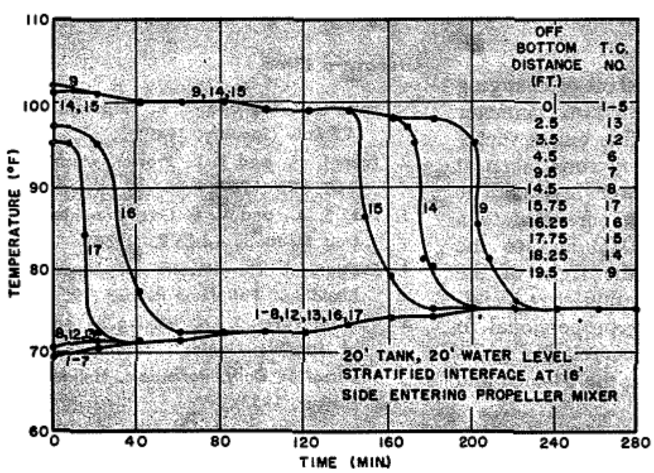

Fig. 3. Progress of blending in a 20-ft. diam. tank.

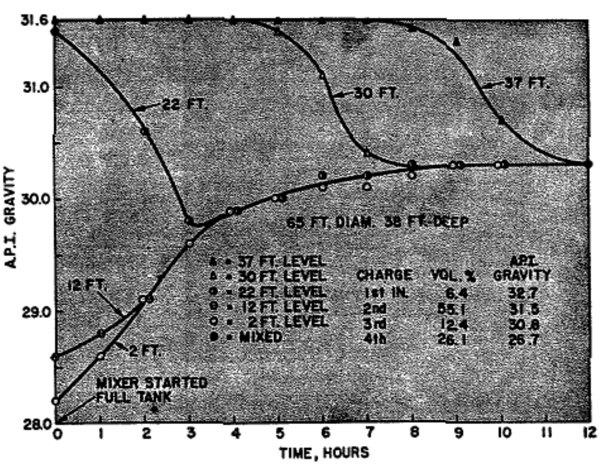

Fig. 4. Progress of blending in petroleum refinery tank (*4*).

A correlation was obtained by plotting blending time against the fractional density difference, $\Delta\rho/\rho_c$, on log-log paper, as shown in Figure 5. A slope of 0.9 was obtained. In order to extend the density difference further than could be done with hot and cold water, salt was dissolved in the cold layer. The squares on the figure represent the three runs made with the salt solution, and they fall fairly well on the correlating line. This slope of 0.9 was also obtained with different diameter impellers in other tank sizes. It was not possible with the particular method of obtaining warm water to obtain the same density difference in each run accurately. All subsequent data are corrected to $\Delta\rho/\rho_c = 0.02$. This correction takes the form

$$\theta_c = \theta\left(\frac{0.02}{\Delta\rho/\rho_c}\right)^{0.9}$$

where θ_c is the blending time used in the correlations, and θ is the actual blending time at whatever $\Delta\rho/\rho_c$ was used in the run. The density difference of 0.02 was chosen because it represents an average figure when blending tetraethyl lead into gasoline.

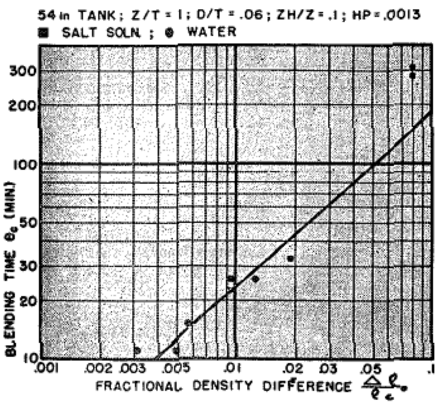

Fig. 5. Effect of fluid density difference on blending time at constant power input.

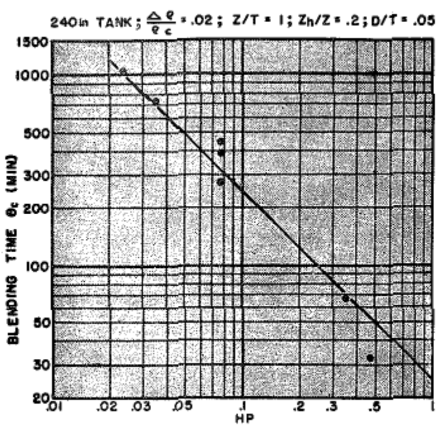

Fig. 6. Effect of mixer power input on blending time.

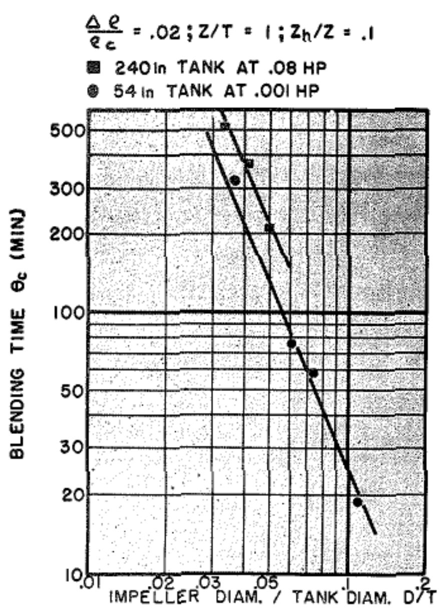

Fig. 7. Effect of D/T ratio upon blending time.

Table 1.—Effect of Mixer Entry Angle on Blending Time, θ_c

$\Delta\rho/\rho_c = 0.02$; Horsepower = 0.0011; $D/T = 0.06$; T = 54 in.; Z = 54 in.; $Z_h/Z = 0.1$

Angle up from horizontal	Angle to left of diameter			Angle to right of diameter	
	20°	10°	0°	10°	20°
10°			124 min.		
5°			...		
0°	195 min.	77.5 min.	105 "	235 min.	284 min.
−5°			155 "		
−10°			144 "		

EFFECT OF HORSEPOWER ON BLENDING TIME

Since standard propellers of known characteristics were used, the speed could be translated to power input to the liquid. Figure 6 shows a correlation of blending time vs. horsepower in the 240-inch tank. This correlation has a slope of −1, and indicates that for a given liquid system and impeller diameter, the total energy for blending is constant. Again, a similar slope was obtained with other impellers and other tank sizes when all other variables were held constant except impeller speed.

EFFECT OF D/T

Figure 7 shows the effect of changing the impeller diameter to tank diameter ratio. The points on this curve represent an average of many runs taken at various $\Delta\rho/\rho_c$ and power levels. The blending time was then corrected to a density difference of 0.02 and to the horsepower listed on the right of the figure using the correlation that blending time was inversely proportional to power. The resulting correlation gives a slope of −2.3 for both the 54-inch and the 240-inch tank.

It should be pointed out that this slope held only for a square batch in which the liquid level was equal to the tank diameter. With decreasing liquid level, this slope decreased. This correlation indicates that increasing the pumping capacity of the impeller aids the blending operation.

EFFECT OF MIXER POSITION

Most of the experimental work performed was done with the mixer shaft making an angle 7° to 10° to the left of the diameter. However, a few runs were performed in which this position was changed. Table 1 shows that this position is near the optimum since blending time increases as the position is changed from the optimum.

Notation

D = impeller diameter
HP = horsepower into liquid
T = tank diameter
Z = total liquid level
Z_h = level of hot liquid
ρ_c = density of cold layer
ρ_h = density of hot layer
$\Delta\rho$ = difference in density between hot and cold layer
$\frac{\Delta\rho}{\rho_c} = \frac{\rho_c - \rho_h}{\rho_c}$ = fractional density difference
θ = blending time (min.)
θ_c = blending time (min.) corrected to $\Delta\rho/\rho_c = 0.02$
β = angle of mixer from tank diameter drawn at point of shaft entry

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