Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Blending in above ground storage tanks with side-entering agitators

R.K. Grenville[a,*], J.J. Giacomelli[a], G.J. VanOmmeren[b], C.F. Hastings[a], M.J. Walters[a]

[a] Philadelphia Mixing Solutions Ltd., Palmyra PA, USA
[b] Department of Chemical Engineering, Rowan University, Glassboro NJ, USA

ARTICLE INFO

Article history:
Received 13 February 2018
Received in revised form 22 June 2018
Accepted 11 July 2018
Available online 27 July 2018

Keywords:
Mixing
Petroleum storage
Side-entering
Propeller
Stratified
Blend time

ABSTRACT

The blending of fluids in large, above ground storage tanks is widely practiced in the petroleum industry yet there have been very few studies of this mixing operation. The most demanding application is found when the tank contents have been allowed to stratify creating a light and heavy layer. The blend time in this case is defined as the time taken for the density of the fluid to become axially homogeneous.

Wesselingh (1975) measured blend times using brine and water to produce the heavy and light layers and measured conductivity changes to assess the blending process. He only looked at one propeller geometry but did study the effects of several important geometrical system properties, such as the ratio of propeller to vessel diameter and liquid depth to vessel diameter.

The study reported here uses Wesselingh's technique but examines the blending performance of four commercially available propellers. The results show that the Advanced Pitch propeller sold by Philadelphia Mixing Solutions Ltd. and Mixing Solutions Ltd. is significantly more efficient than the competitors' propellers when compared based on energy usage.

These results, and Wesselingh's, show that there are two operating regimes which are separated by a critical Froude number, Fr_C. At high Froude numbers ($Fr > Fr_C$) the dimensionless blend time is constant, and at lower Froude numbers ($Fr < Fr_C$) the dimensionless blend time is inversely proportional to Froude number. The implications for scale-up in both regimes are discussed.

1. Introduction

Side-entering agitators are widely used in the petrochemical industry for mixing the contents of above ground cylindrical storage tanks. These tanks have large diameters with depth to diameter ratios that are typically in the range of 30–40%. The diameter of the propeller is usually 1–3% of the vessel diameter and this results in very long blend times, in the order of several hours. In comparison, the ratio for top-entering agitators is usually 25–50% and, in the turbulent regime, blend times are in the order of seconds (Grenville and Nienow, 2004).

One reason for using side-entering agitators is that the vessels often have floating roofs so a top-entering agitator cannot be easily installed. Also, since the vessels have such large diameters, the structural steel required to mount a vertical agitator drive could be prohibitively expensive.

The operators of oil terminals must often blend grades of oil, with different physical properties, and need to achieve a required degree of homogeneity, which is specified by the customer, before the product can be released and shipped. Accurate knowledge of the blend time allows the operator to stop mixing, take a sample, then empty the vessel and prepare for the start of another batch. Mixing for longer than the true blend time prevents the next batch from being started, reducing the throughput of the terminal.

In the worst case the contents of the vessels are stationary and stratified into two or more distinct phases before the blending process starts. These are commonly called the light and heavy phases and differences in density, viscosity and/or temperature may exist. The blend time is defined as the time taken for the composition of the fluid to become uniform throughout the vessel. Although this mixing duty is

* Corresponding author.
E-mail address: rkgrenville@philamixers.com (R.K. Grenville).
https://doi.org/10.1016/j.cherd.2018.07.017

Nomenclature

D	Propeller diameter m
E	Energy input per mass or specific energy input J/kg
Fr	Densiometric Froude number ($=N^2 D/(g\,\Delta\rho/\rho)$)
Fr_C	Critical Froude number defined by Eq. (1) –
g	Acceleration due to gravity m/s^2
H	Total liquid depth m
H_H	Depth of heavy phase m
H_L	Depth of light phase m
h	Minimum of H_H and H_L m
k	Ratio (=H/T) –
k'	Ratio (=D/T) –
M	Mass of fluid kg
N	Propeller rotational speed s^{-1}
P	Power input by propeller W
Po	Propeller power number ($=P/(\rho N^3 D^5)$) –
Re	Reynolds number –
T	Vessel diameter m
X	Constant in Eqs. (17) and (18) –
Y	Constant in Eq. (19) –
α	Agitator shaft angle to vessel diameter deg
β	Constant in Eq. (4) and (14) –
γ	Exponent in Eqs. (4) and (14) –
δ	Exponent in Eq. (14) –
ε	Power input per unit mass or specific power input W/kg
ρ	Liquid density kg/m^3
ψ	Constant in Eq. (9) –
ω	Exponent in Eq. (9) –

extremely common at oil terminals and refineries there have been very few studies that have comprehensively examined how the blend time is affected by the geometry of the propeller and the properties of the fluids being mixed.

Hemrajani (2004) has discussed mixing in storage tanks with side-entering agitators and gives recommendations for power input per volume for various grades of crude oils. For light to medium crudes he recommended that the power input per volume should be 0.4 HP/kbbl (1.87 W/m^3) and this level of mixing is required to keep sludge suspended.

Rushton (1954) measured the blend time for furnace oil in a vessel that was 19.81 m in diameter with a liquid depth of 11.58 m. The agitator had a square pitch propeller 0.610 m in diameter operating at 420 RPM. Approximately 75% of the volume had a density of 887 kg/m^3 (28 API gravity) and 25% had a density of 867 kg/m^3 (31 API gravity). The time taken for the vessel contents to become completely blended was 12 h.

He also measured the time taken to blend tetraethyl lead (TEL) in a stratified gasoline storage vessel. This vessel was 36.58 m in diameter with a liquid depth of 12.19 m. The agitator had a square pitch propeller 0.711 m in diameter operating at 420 RPM. The TEL concentration was measured and, at the start, the concentration in the base of the vessel was 15.25 cc/gallon (0.401% vol.) and 0.20 cc/gallon (0.005% vol.) at the top. After two hours, the concentration was uniform throughout the vessel at 1.5 cc/gallon (0.396% vol.).

Oldhsue et al. (1956) measured blend times in vessels 1.07 and 6.09 m in diameter with liquid depth equal to the diameter. Cold water was introduced to the base of the vessel with warm water carefully added to create the stationary layers. No information was given about the propeller diameters or operating speeds of the agitators.

They concluded that the blend time is inversely proportional to the power input by the propeller per unit mass of the fluid, or specific power input, proportional to the density difference raised to the exponent 0.9 (for $0.03 < \Delta\rho/\rho < 0.07$) and proportional to the vessel to propeller diameter ratio (T/D) raised to the 2.3 but that the value of this exponent would be dependent on the geometry of the vessel (H/T).

Wesselingh (1975) measured blend times using conductivity probes in three vessels which were 0.55, 2.35 and 4.73 m in diameter. The vessels were partially filled with brine and then fresh water was gently added to create two stratified layers. At all scales, square pitch marine propellers were used with the vessel to propeller diameter ratio (T/D) varied from 19.0 to 58.7. The propeller speed was varied from 360 to 3000 RPM.

Most of the data were collected when the ratio of total depth to vessel diameter (H/T) was 0.42 but some experiments were carried out over a range of depths such that $0.077 < H/T < 0.697$. Also for most cases the depth of the two layers, H_H and H_L, were equal but this ratio was also varied for some experiments such that $0 < H_H/H < 1.0$, i.e. at the two extremes, the vessel was filled with the light or heavy fluid only.

The vessels had eight conductivity probes installed in various locations, apart from the smallest which had only one. The blend time was defined as the time taken for the conductivities measured at each probe to coincide after starting the agitator. Wesselingh plotted his data as the dimensionless blend time (the product of the blend time and propeller speed), $N\theta$, versus the densiometric Froude number, Fr. At high Froude numbers, above a critical value, $N\theta$ was found to be constant while below this critical Froude number $N\theta$ increased as Fr decreased. The critical Froude number was found to depend on the vessel to propeller diameter ratio and could be calculated from:

$$\log(Fr_c) = 1.40 + 0.04\left(\frac{T}{D}\right) \quad (1)$$

The dimensionless blend time was correlated by Eq. (2).

$$N\theta = 1500\left(\frac{T}{D}\right)^{1.3}\left(\frac{H}{T}\right)^{2.4}\left(\frac{h}{H}\right)\left(\frac{Fr_c}{Fr}\right)^{1.5} + 180\left(\frac{T}{D}\right)^{1.3}\left(\frac{H}{T}\right)^{0.8} \quad (2)$$

The second term on the right-hand side of Eq. (2) represents the "fixed" region where $N\theta$ is constant and the first term represents the "variable" region where $N\theta$ is a function of Froude number.

Wesselingh used his correlation to estimate the blend time in a full-scale vessel and, for the system described in his paper, concluded that the predicted blend time would be three days. He did not provide an explanation for this or a further analysis of the correlation's accuracy.

He also studied several other important aspects of side-entering agitator operation such as the total liquid depth, the shaft angle relative to the vessel diameter (i.e. angle α in Fig. 3) and the number of agitators.

Dakhel and Rahimi (2004) and Rahimi (2005) measured and developed a CFD model to predict the blend time in a vessel 44 m in diameter operating with a liquid depth of 13 m. The agitator had a three-bladed marine propeller supplied by Plenty, 0.65 m in diameter operating at 450 RPM. Two-thirds of the volume was occupied by heavy crude with density of 845 kg/m^3 and one-third by light crude with density of 833 kg/m^3. This gave a density difference, $\Delta\rho/\rho$, of 0.014. They reported that after 3 h it was difficult to distinguish between the measured densities while the CFD model predicted that the contents would be homogenous after 3.5 h. Rahimi (2005) used this CFD model to examine the effects of installing up to five propellers in the vessel. Substituting these dimensions and physical properties into Wesselinghs's (1975) correlation gives an estimated blend time of 81 h.

Giacomelli et al. (2014) tested the applicability of Wesselinghs's (1975) correlation by plotting his experimental data with full-scale blend time data measured by Rushton (1954) and Dakhel and Rahimi (2004). Wesseligh's correlation overpredicts the measured blend time in the large vessels so Giacomelli et al. (2014) re-correlated his data, collected in the variable regime, below the critical Froude number, and included the two full-scale data points. Their new correlation is:

$$N\theta = 12.48\,Fr^{-1.27}\left(\frac{T}{D}\right)^{2.47}\left(\frac{H}{D}\right)^{2.85}\left(\frac{h}{H}\right)^{1.04} \quad (3)$$

The correlation coefficient, r^2, is 0.913 with a relative standard deviation of ±46%. Substituting Dakhel and Rahimis' (2004) conditions into