Incipient Vortex Formation in Baffled Agitated Vessels

MICHAEL W. CLARK and THEODORE VERMEULEN

Lawrence Radiation Laboratory, Berkeley, California

This note deals with an experimentally observed anomalous behavior in the power requirements of agitated liquids using four-bladed flat-paddle impellers in baffled tanks.

Very early in the published literature on mixing-power requirements, one finds the introduction of dimensionless variables to describe system behavior. White and co-workers (9) used the paddle type of impeller in unbaffled tanks, and presented their data for power consumption, P, in the following form:

$$P = k\, L^a\, n^b\, \mu^c\, \rho^d\, T^e\, W^f\, H^g \quad (1)$$

Later experimenters rearranged these results, as well as their own, in terms of a dimensionless power number, N_{PO}:

$$N_{PO} = Pg_c/n^3\, L^5\, \rho = k(L^2 n\rho/\mu)^\alpha\, (W/L)^\beta\, (H/L) \quad (2)$$

As work was extended into baffled tanks in the turbulent-flow region ($L^2 n\rho/\mu > 10^3$) (2, 4, 6), it was generally found that the power number remained constant over a wide range of variation of the Reynolds number, although this constant differed for the various geometrical systems investigated. In order to minimize this variation of N_{PO} with the geometrical parameters, an alternate known form of the power number, $N_{PW} = Pg_c/n^3 L/W\rho$, may be utilized.

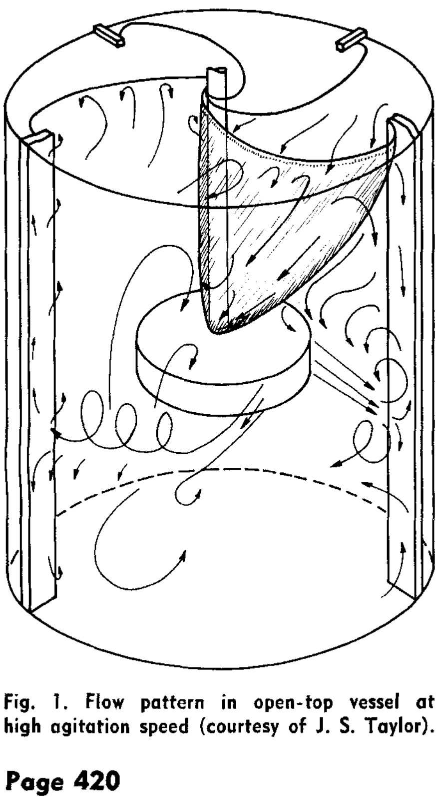

Fig. 1. Flow pattern in open-top vessel at high agitation speed (courtesy of J. S. Taylor).

Numerous investigators have found that the power requirement for unbaffled systems shows a continuous decrease of N_{PO} with increasing N_{Re} that is owing to circularity of the fluid motion and to the consequent vortexing. In view of this result, it appears reasonable for a fully baffled tank that a continuous increase of the volume-ratio L^2W/T^2H should bring the system into a region where the tank baffling is overcome, and where circularity in the liquid motion is again approached. This region should be characterized by a sudden decrease in the curve of N_{PO} or N_{PW} vs. impeller speed.

This effect has been encountered in an experimental program in which the impeller size was continuously increased in a fully baffled open-top tank 10 in. in diameter. The parameters which were varied systematically included impeller width, diameter, speed, and depth. The tank diameter was fixed at 10 in.; the liquids used were water and carbon tetrachloride; and the liquid depth was held at 10 in. for all experimental runs. Once the decrease of N_{PO} at high impeller speeds was observed, the next problem was to fix the real cause for the decrease. In order to rule out the possibility of its being due only to the circular motion of the fluid, the experiment was also carried out in a closed tank. Here the characteristic reduction in power number did not occur. The phenomenon can therefore be attributed to introduction of air from the free liquid surface which mixes down into the impeller region.

A vacuum sampling technique, utilizing an evacuated pipet to withdraw samples of liquid-gas mixture, demonstrated that the percentage of air beneath the liquid surface could range as high as 50% by volume. Visual observation, along with a systematic exploration using the sampling apparatus, indicated a behavior previously reported by Taylor and Metzner (3, 5), and shown in Figure 1. This phenomenon was observed with the aid of photographic techniques in a transparent vessel (3).

As Taylor and Metzner observed, a surface or region of high shear exists where fluids flowing in opposite directions meet. This surface does not remain stationary, but appears to be in random oscillatory motion. It is along the upper seam made by this surface that air is introduced into the liquid, and subsequently carried downward into the impeller. The resulting reduction in density and viscosity of the mixture appears to account for the decrease of N_{PO} below its predicted value for this region.

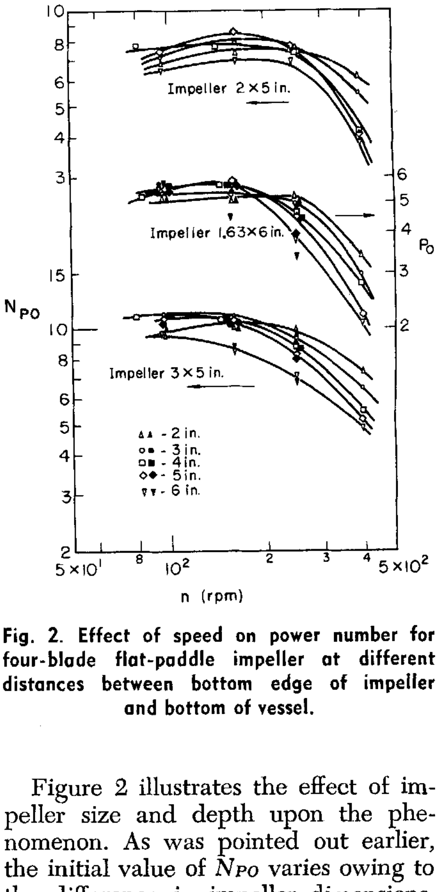

Fig. 2. Effect of speed on power number for four-blade flat-paddle impeller at different distances between bottom edge of impeller and bottom of vessel.

Figure 2 illustrates the effect of impeller size and depth upon the phenomenon. As was pointed out earlier, the initial value of N_{PO} varies owing to the difference in impeller dimensions. The effect of impeller depth is the same for all of the runs; that is, when the impeller is closer to the liquid surface, the decrease in N_{PO} is more pronounced and begins at a lower speed. This appears to be owing to the increase in the upper-surface velocity components as the impeller is brought closer to the top of the liquid.

Theory indicates that the Froude number (n^2L/g) should be used in correlating surface behavior of this type. In order to verify this, several runs were made with carbon tetrachloride. These data indicated clearly that Froude number, rather than Weber or Reynolds number, was the proper correlating parameter. The introduction of L^2W/T^2H, the impeller-to-tank volume ratio, brings the break points of the curves for different impellers to the same value, while Z/H accounts for the described effect of impeller depth. In order to correct the initial power behavior, the modified power number, N_{PW}, was used with an empirical correction factor, s, for impeller depth given by

$$s = [(0.9H/2)/(0.9H\text{-}Z)^{0.5} (Z)^{0.5}] \quad (3)$$

This factor is seen to be nearly symmetrical in Z and H-Z; that is, about the mid-height of the tank. The slight asymmetry is owing to a difference in the effects of the lower and upper liquid boundaries. The results of this general correlation are shown in Figure 3.

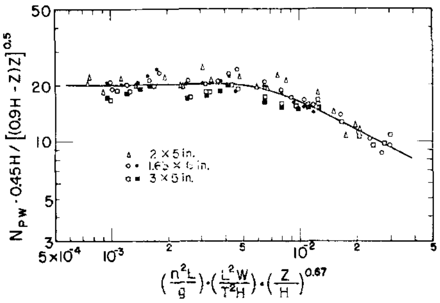

Fig. 3. Correlation of power number for various impeller sizes and positions.

Thus the breakdown of baffling in a baffled tank, marked by a sudden reduction in the power number, may be attributed to regions of high shear which introduce gas from the upper surface into the system. This phenomenon may be predicted to occur at a critical value of the correlating function:

$$N_{Fr} \cdot \frac{L^2W}{T^2H} \cdot (Z/H)\ 2/3 = 5 \times 10^{-3}$$

The use of the modified power number appears to correlate the results quite well for different impeller dimensions, and an additional correction factor, s, shown in Equation (3), will correct satisfactorily for the effect of impeller depth.

In a separate study of bulk mixing of immiscible liquids, Weiss and co-

INFORMATION RETRIEVAL*

Diffusion and reaction in porous glass, Rao, M. Raja, and J. M. Smith, **A.I.Ch.E. Journal, 10,** No. 3, p. 293 (May, 1964).

Key Words: Diffusion-1, Hydrogen-1, Ortho Hydrogen-1, Para Hydrogen-2, Porous Solid-2, Nickel Oxide-4, Vycor-5, Porous Glass-5, Particle Size-6, Catalysis-8, Diffusion-8, Reaction Rate-8, Effectiveness Factor-9, Diffusion Cell-10, Reactor-10.

Abstract: Constant pressure diffusion rates of hydrogen through Vycor porous glass were measured and compared with predicted rates from the random pore and parallel pore models. For the same Vycor samples, containing 2% nickel oxide, kinetic data were obtained for the ortho-para hydrogen reaction at —196°C. These results gave experimental effectiveness factors for comparison with values predicted from theory.

Measurement of mass transfer coefficients in liquid-liquid mixing, Rushton, J. H., S. Nagata, and T. B. Rooney, **A.I.Ch.E. Journal, 10,** No. 3, p. 298 (May, 1964).

Key Words: A. Mass Transfer-8, Solute-5, Organic-5, Dispersed-5, Phase-5, Aqueous-5, Continuous-5, Phase-5, Mixing-10, Tank-10, Conductivity-10, Measurement-10. B. Mass Transfer-7, Coefficient-7, Liquids-5, Viscosities-6, Impeller-6, Speed-6, Size-6.

Abstract: Mass transfer coefficients in a mixing tank were measured for the transfer of a solute dissolved in an aqueous phase to an organic-phase dispersion. Continuous conductivity measurements were used to follow concentration-time changes in batch experiments.

Various pairs of solvents and the speed and size of the impeller were studied as variables. The viscosities of the two phases and the speed of the impeller were found to be controlling variables. The coefficients were high compared with coefficients from other types of equipment.

Transport characteristics of suspensions: part IX. representation of periodic phenomena on a flow-regime diagram for dilute suspension transport, Thomas, David G., **A.I.Ch.E. Journal, 10,** No. 3, p. 303 (May, 1964).

Key Words: Particles-1, Flow-Regime Diagram-2, Liquids-5, Turbulent Flow-5, Horizontal Pipes-5, Settling Rate-6, Particle Diameter-6, Friction Velocity-6, Ripple-7, Dune-7, Heterogeneous-7, Homogeneous-7, Stria-7, Periodic Phenomena-7, Transport-8, Suspension-8, Regime Diagram-9.

Abstract: Four different flow regimes may be identified during transport of dilute suspensions of solid particles through horizontal pipes by liquids in turbulent flow as the velocity is varied. In two of the regimes the bulk of the material is immediately adjacent to the bottom of the channel and is lumped into transverse waves (dunes or islands) with a reproducible periodicity or into longitudinal waves (long stria). The definition of the other two regimes is somewhat more arbitrary but may qualitatively be described as heterogeneous or homogeneous flow. All four of these flow regimes may be represented on a single diagram in which the terminal-settling velocity divided by the friction velocity and the Reynolds number based on particle diameter and friction velocity are coordinates.

Optimization by Pontryagin's maximum principle on the analogue computer, Lee, E. S., **A.I.Ch.E. Journal, 10,** No. 3, p. 309 (May, 1964).

Key Words: Optimization-7, 8, Pontryagin's Maximum Principle-9, 10, Dynamic Programing-9, 10, Analogue Computer-10, Maximum Seeking Methods-9, 10, Random Search-9, 10, Pressure, Temperature Gradient-7, Tubular Chemical Reactor-8, Numerical Solutions-9, Constraints-8, Performance Index-8, Optimizing Control-9, Dimensionality Difficulty-9, Multistage-7, 9, Nonlinear Differential Equations-7, 9, Design-8, Digital Computer-10.

Abstract: A computational method has been developed for obtaining the solution to a class of optimization problems by the combined use of maximum principle and a random search technique on the analogue computer. To illustrate the use of the method the optimum temperature and pressure gradients in a tubular chemical reactor are computed. A comparison between dynamic programing and maximum principle from the standpoint of obtaining numerical solutions is also given.

(Continued on page 424)

*For details on the use of these key words and the A.I.Ch.E. Information Retrieval Program, see **Chem. Eng. Progr.,** 57, No. 5, p. 55 (May, 1961), No. 6, p. 73 (June, 1961); **58,** No. 7, p. 9 (July, 1962).

NOTE: Additional pages of information retrieval abstracts and key words in this issue are available on request.

workers (*8*) have defined an inhomogeneity parameter (κ) that measures the concentration gradient in a vessel and decreases as N_{Fr} increases. Weiss's results suggest that gas introduction would become appreciable at N_{Fr} $(L^2W/T^2H)^{0.5} \sim 0.05$. Since $(L^2W/T^2H)^{0.5}$ in the present experiments is around 0.15, it appears the Taylor's mechanism for gas introduction may provide a generally applicable description of the intermixing of initially stagnant immiscible layers.

Further work in the area of power requirements for liquid-gas agitation is being carried out to explore and explain more fully the quantitative effect of such mixtures on power input to the system.

ACKNOWLEDGMENT

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NOTATION

g = gravitational acceleration
g_c = conversion factor between force and mass
H = tank height
k = experimentally determined constant
L = impeller diameter
n = impeller speed
N_{Fr} = Froude number, n^2L/g
N_{Po} = power number, $Pg_c/n^3L^5\rho$
N_{Pw} = modified power number $Pg_c/n^3L^4W\rho$
N_{Re} = Reynolds number, $L^2n\rho/\mu$
P = power input to the impeller
s = impeller-depth correction factor
T = tank diameter
W = impeller width
Z = distance from center of impeller to tank bottom
μ = fluid viscosity
ρ = fluid density

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