Effect of Tank to Impeller Diameter Ratio on Flooding Transition for Disc Turbines

G. B. Tatterson, G. L. Morrison
Mechanical Engineering Department
Texas A&M University
College Station, TX 77843

In a review of flooding for the disc style turbine, Warmoeskerken and Smith (1985) developed a basis from which the flooding/nonflooding transition can be determined. The analysis was based upon a balance between the rate of plume pumping, occurring axially, and the rate of impeller pumping, occurring radially. Plume pumping is caused by gas rising to the surface, lifting liquid as a result. At the flooding transition, the two pumping rates were set proportional to each other. From this, a relationship between the gas flow number, Fl or Q_G/ND^3, and the impeller Froude number, Fr_I or N^2D/g, was obtained and given as:

$$Fl = 1.2\, Fr_I \tag{1}$$

This equation establishes the relationship between impeller diameter D, impeller rotational speed N, and gas rating Q, at the flooding transition. Warmoeskerken and Smith cited others, including Zwietering (1963), Mikulcova et al. (1967), and Biesecker (1972), who established similar correlations that followed the relationship:

$$Fl = 0.6\, Fr_I \tag{2}$$

Warmoeskerken and Smith attributed the difference in slopes between the two correlations to differences in geometry, stirrer type, and liquid height.

Biesecker (1972), as cited by Warmoeskerken and Smith, used a power balance between buoyancy effects of the rising bubbles and the stirrer to arrive at his correlation.

In all the correlations given above and in the literature, the effect of the ratio of tank diameter to impeller diameter, T/D, on the flooding transition has not been accounted for except by empirical relationships such as that given by Nienow et al. (1985). A substantial T/D effect is known to exist although no theoretical reason is available that explains the source of the effect. To this end, the following is offered to explain and account for this effect.

The effect of T/D on flooding is important for several reasons. First, to be able to explain the phenomena provides further understanding of the flooding and gas dispersion. Second, scaleup of gas dispersion often is done where geometric similarity is not maintained. In such cases, the ratio of T to D is likely to change, as is the flooding transition.

Theoretical Basis

In the flooded state, the sparged gas flows up and around the impeller. There is little radial discharge from the impeller and the gas flow is not affected greatly by the impeller. The gas flow also generates a vertical liquid plume. In a nonflooded state the impeller disperses the gas radially. At the transition from flooded state to nonflooded state, several events occur:

1. A portion of the liquid plume is stopped
2. There is an initiation of radial liquid pumping from the impeller, Q
3. Gas is dispersed radially.

A power balance for the transition can be written as:

$$P_g = \beta \rho_L Q_G g D + P_C \tag{3}$$

Power input from the impeller to the fluid, P_g, balances:

1. A portion of the power of the rising liquid plume written in terms of a multiple of the quantity $\rho_L Q_G g D$
2. The power increase, P_C, necessary initially to establish a radial liquid circulation, Q

The power contained in the liquid plume is typically written in terms of the gas flow rate, Q_G, because the liquid flow rate in the plume is not usually known.

The portion of the liquid plume that is stopped can be characterized by the length scale of the impeller and/or the sparger diameter. However, it cannot be characterized by the tank diameter since the plume is local to the impeller region and the vertical space above and below the impeller. As a result, the corresponding plume power, $\beta \rho_L Q_G g D$, in Eq. 3 can also be considered independent of tank diameter. After the transition from flooding to a condition of good gas dispersion, the liquid/bubble plume no longer exists.

The second term, P_C, on the righthand side of Eq. 3 has not been included in previous models and will be used to account for the T/D effect on the flooding transition. The power, P_C, is the initial power necessary to establish radial liquid circulation from the impeller and can be obtained from Eq. 4:

$$P_C = \int_0^{t'} \left(\frac{P_g}{V}\right) Q \, dt \qquad (4)$$

where P_g/V is the power per volume that is added to the fluid by the impeller, Q is the volumetric radial pumping rate, and t' is the time over which flooding is stopped and radial circulation is started, i.e., the time required for transition. The term P_C, however, is not the total power to cause circulation throughout the tank.

The actual integration for P_C cannot be performed at the present time; however, P_C can be scaled. The time, t', can be scaled according to the circulation time of the impeller/tank configuration of interest (Greaves and Economides, 1979; Greaves et al., 1983), and Q can be scaled proportional to ND^3 (Holmes et al., 1964). As a result, the integral for P_C can be scaled as:

$$P_C \,\alpha\, [(P_g/P_o) N_P \rho_L N^3 D^2](ND^3)\, t_C \qquad (5)$$

where the circulation time, t_C, (Holmes et al., 1964) is:

$$t_C = \frac{K}{N} \frac{T^2}{D^2}. \qquad (6)$$

Substituting these relations into Eq. 3, using a constant K' to handle all constants involved with P_C, the power balance given in Eq. 3 becomes:

$$\left(\frac{P_g}{P_o}\right) N_P(\rho_L N^3 D^5) = \beta \rho_L Q_G g D + K' \left(\frac{P_g}{P_o}\right) N_P\, (\rho_L N^3 D^2) N D^3 \frac{1}{N} \frac{T^2}{D^2} \qquad (7)$$

where K' is a constant. Upon rearrangement, Eq. 7 becomes:

$$Fl - \left(\frac{P_g N_P}{P_o \beta}\right) Fr_I = K' \left(\frac{P_g N_P}{P_o \beta}\right) Fr_T \left(\frac{T}{D}\right) \qquad (8)$$

where Fr_T is the tank Froude number. This relationship reduces to Eqs. 1 and 2 when P_C is considered zero, i.e., the righthand side of Eq. 8 is set to zero. The quantity $P_g N_P/P_o\beta$ is an important parameter, being the ratio of Fl/Fr_I at P_C equal to zero.

Application

To test Eq. 8, data given by Zwietering (1963) were used. An examination of these data showed that the ratio Fl/Fr_I (i.e., $P_g N_P/P_o\beta$) could vary considerably, between 0.1 at $T/D = 5$ and 0.75 at $T/D = 2.5$. Equation 2, however, indicates the ratio should be approximately 0.6, which is in the range for Zwietering's data. This value will be selected for purposes of discussion.

Figure 1 shows the quantity $Fl - 0.6Fr_I$ plotted vs. $Fr_T(T/D)$, which results in two straight lines having negative constant slopes. Data for T/D of 2.5, 3.0, 3.08, 3.75, and 4.0 fall on line A in the figure and data for $T/D = 5$ fall on line B. Additional figures were also generated for Fl/Fr_I (i.e., $P_g N_P/P_o\beta$) of 0.1, 0.2, 0.4, 0.7, 0.8, 1.0, and 1.2. The results showed the same general relationship as that in Figure 1 except for $P_g N_P/P_o\beta = 0.1$, which showed no correlation.

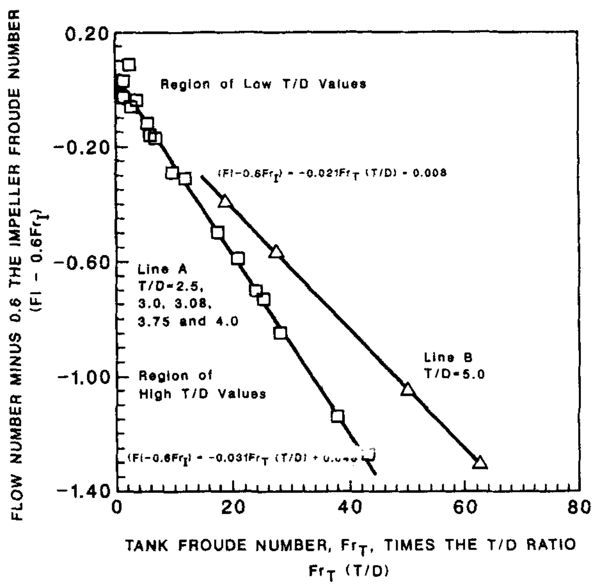

Figure 1. Flow number minus 0.6 impeller Froude number v. a tank Froude number and T/D ratio.

Discussion

The model, as presented using 0.6 for Fl/Fr_I (i.e., $P_g N_P/P_o\beta$), has adequately treated all of Zwietering's data except for $T/D = 5$. However, the noncorrelation of the data at $T/D = 5$ with the rest of the data should not be taken as a failure on the part of the correlation or the theoretical basis of the correlation. Furthermore, it is not certain whether the correlation should group the data taken at $T/D = 5$ with the rest of the data.

An unbaffled condition is approached as the T/D ratio is increased and the fluid mechanics of the fluid near the impeller approaches a solid body rotation. From single-phase power studies, the initial onset of solid body rotation appears to occur in the range $T/D = 4$ to 5. As a result, the physics of the liquid plume at $T/D = 5$ and above are likely to be different from plumes at lower T/D ratios. The power numbers, N_P, at $T/D = 5$ and above are different from values at lower T/D ratios, values of 4 and below (Nishikawa et al., 1979). Changes in the P_g/P_o ratio also occur since the power number changes. Furthermore, the flooding transition for large T/D ratios will also be a function of baffle width, which has not been considered in the present correlation or in any previous work.

An impeller/sparger interaction could also explain the deviation of data taken at $T/D = 5$. At such a high T/D ratio the gas flow from the sparger could entirely cover the impeller if the sparger diameter was not scaled appropriately to match the impeller diameter and the other geometries at the lower T/D ratios.

In any case, in studies of the T/D effect on the flooding transition, the geometry is not fully specified unless the sparger and baffle dimensions are given (Martin, 1946; Nishikawa et al., 1979).

The deviation of data at $T/D = 5$ cannot be attributed to the onset of mixing in the transition regime between laminar and turbulent flow since the data obtained at $T/D = 5$ by Zwietering were taken above an impeller Reynolds number of 10^5.

Scaleup to a T/D ratio of 5 and above is typically not recommended in practice.

Model Latitude

The model as presented, based upon Zwietering's data, does contain a slope of 0.6 (i.e., $P_g N_P / P_o \beta$) between the gas flow number and the impeller Froude number; however, there is a considerable range in slopes that can be incorporated and possibly justified in the modeling. Figure 1 did not change its general appearance as $P_g N_P / P_o \beta$ was changed from 0.2 to 1.2. It is also fortuitous that at $P_g N_P / P_o \beta$ of 0.6, $Fl - 0.6\, Fr_I$ equals approximately zero, which justifies the initial use of 0.6. [For the first five data points occurring at low $Fr_T(T/D)$ values shown in Figure 1, the quantity $Fl - 0.59 Fr_I$ equals zero.] Apparently the data by Zwietering were taken under conditions where $P_g N_P / P_o \beta = 0.6$.

The model, Eq. 8, can be used to predict β, the multiplication factor in Eq. 3, used to model the power contained in the liquid plume. The product of βQ_G is the amount of liquid rising in the plume that is stopped at transition. Using experimental values of $N_P = 5.0$, $P_g/P_o = 0.5$, and $P_g N_P / P_o \beta = 0.6$, β is equal to 4.16. Bubble plumes can easily generate this magnitude of liquid circulation (Warmoeskerken and Smith, 1985; Morrison et al., 1987). Calculations using Zwietering's data indicated that liquid flow in plumes could be 25 times the gas volumetric flow rate Q_G.

Effects of liquid depth, plume flow regime, gas flow rate, sparger geometry, internal baffling, rheological and electrolytic nature of the fluid, and surfactants can, of course, cause variations in β and the slope $P_g N_P / P_o \beta$.

Conclusions

A model has been developed that explains the effect of the T/D ratio on the transition to flooding for disc style turbines based upon a tank Froude number and a T/D length ratio. The model is an extension of previous work by Warmoeskerken and Smith (1985) and Biesecker (1972). The model also explains the source of differences in the relationships between Fl and Fr_I appearing in the literature, and has been applied successfully to the data by Zwietering (1963), which are typical data on the flooding transition.

Complete specification of the system geometry, including baffle and sparger dimensions, as well as the physics of liquid plumes should be reported in studies on flooding transition.

Notation

D = impeller diameter
Fl = gas flow number, Q_G/ND^3
Fr_I = impeller Froude number, N^2D/g
Fr_T = tank Froude number, N^2T/g
g = acceleration of gravity
g_c = gravitational constant
K, K' = constants
N = impeller rotational speed
N_P = ungassed power number, $P_o g_c / \rho N^3 D^5$
Q = pumping rate of the impeller, KND^3
Q_G = gas flow rate
P_C = power increase to initiate circulation
P_o = ungassed power, $N_P \rho N^3 D^5 / g_c$
P_g = gassed power
T = tank diameter
t_C = circulation time, $(K/N)\ (T^2/D^2)$
V = volume, which varies with D^3
ρ_L = liquid density
β = multiplication factor

Literature Cited

Biesecker, B. O., "Begasen von Flussingkeiten mit Ruhrer," *VDI-Forschungsheft*, 554 (1972).

Greaves, M., and C. A. Economides, "Gas-Liquid Mixing Dynamics in a Stirred Vessel," *Proc. 3rd Eur. Conf. on Mixing*, BHRA Fluid Eng., Cranfield, Bedford, England, 357, (1979).

Greaves, M., K. A. H. Kobbacy, and G. C. Millington, "Gassed Power Dynamics of Disc Turbines," *Chem. Eng. Sci.*, **38**, 1909 (1983).

Holmes, D. B., R. M. Voncken, and J. A. Dekker, "Fluid Flow in Turbine-Stirred, Baffled Tanks. I: Circulation Time," *Chem. Eng. Sci.*, **19**, 201 (1964).

Martin, J. J., "Power Consumption of Agitators," *Trans. AIChE*, **42**, 777 (1946).

Mikulcova, E., V. Krudrna, and J. Vlcek, "Conditions for Impeller Flooding," *Sci. Pap.*, Inst. Chem. Tech., Prague, **k1**, 167 (1967).

Morrison, G. L., T. I. Zeineddine, M. Henriksen, and G. B. Tatterson, "An Experimental Analysis of the Mechanics of Reverse Circulation Air Lift Pump," *Ind. Eng. Chem. Process Des. Dev.*, **26** (1986)

Nienow, A. W., M. Konno, M. M. C. G. Warmoeskerken, and J. M. Smith, "On the Flooding/Loading Transition and the Complete Dispersal Condition in Aerated Vessels Agitated by a Rushton Turbine," *Proc. 5th Eur. Conf. on Mixing*, BHRA Fluid Eng., Cranfield, Bedford, England, 143 (1985).

Nishikawa, M., K. Ashiwake, N. Hashimoto, and S. Nagata, "Agitation Power and Mixing in Off-Centering Mixing," *Int. Chem. Eng.*, **19**(1), 153 (1979).

Warmoeskerken, M. M. C. G., and J. M. Smith, "Flooding of Disc Turbines in Gas-Liquid Dispersions: A New Description of the Phenomenon," *Chem. Eng. Sci.*, **40**, 2063 (1985).

Zwietering, Th. N., untitled discussion, *De Ingenieur (Chemische Techniek 6)*, **42**, Ch. 60–61, (Oct. 18, 1963).

Manuscript received Feb. 2, 1987, and revision received June 2, 1987.