Sound Spectra in an Aerated Agitated Tank

T. A. Sutter
Chemical Engineering Department

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

Gas-liquid contacting in agitated tanks is a common multiphase unit operation. Unfortunately, the dispersion process which causes the contact is very complex and fundamental understanding is still under development. The phenomena of impeller flooding, cavity formation behind impeller blades, and distribution of gas from spargers are of interest. The area, however, has been well studied and considerable literature exists concerning these topics. The purpose of most of this literature has been to develop fundamental understanding and design correlations. Questions of whether the design conditions for a particular gas-liquid contacting process are being met in actual plant operations and whether this can be determined on-line are also of interest but are not well studied.

The objective of the present work (Sutter, 1986) was to study the fluid mechanics and acoustical nature of gas dispersion in agitated tanks using hydrophones to record sound spectra and coherence between hydrophones. The regions around the impeller and inside a gas sparger were studied. In the impeller region, sound spectra were obtained as functions of impeller rotational speed, gassing rate, and radial distance from the impeller blade. Coherence studies between two hydrophones positioned at different locations were also performed. For a ladder-type sparger, hydrophones were placed inside the sparge legs and sound spectra and coherence functions were again obtained as functions of impeller rotational speed and gassing rate.

Most studies on gas dispersion usually involve a gas and a low-viscosity liquid (e.g., air and water). However, studies of gas dispersion in high-viscosity liquids have been done (for example, Ranade and Ulbrecht, 1978) although not to the same extent. The following pertains to gas dispersion in low-viscosity liquids. The typical impeller used for gas dispersion in an agitated tank is a flat blade, disk-style impeller such as that shown in Figure 1. The gas inlet is placed below the impeller and a sparger or distributor is used initially to disperse the gas. At the impeller, the gas is forced out to the impeller blades by the disk and enters the low-pressure volumes behind the impeller blades to collect and form gas cavities. The gas is then redispersed from these cavities into the bulk of the tank.

The type of gas cavity formed is mainly a function of the impeller rotational speed, gas flow rate, blade characteristics, and number of blades. Considerable literature (Hsi et al., 1985) is available that describes the nature of the gas cavities, their effect upon power draw of the impeller, and mass transfer. However, a key technical issue is the onset of flooding of the impeller with gas, at which point the impeller no longer has the ability to disperse gas properly. At flooding, the area for transport between the gas and liquid decreases. Another issue is range of operation where the area of the gas dispersion is a maximum. This range is also the optimum range of operation for area-controlled transport processes and is a complex function of gassing rate, impeller rotational speed, blade number, and blade characteristics.

From the present literature, there appears to be an optimum cavity structure, the 3-3 structure shown in Figure 2, for area-controlled transport processes. Warmoeskerken and Smith (1985) have established a flow regime map indicating the occurrence of the 3-3 structure as well as other cavity structures. Vortex-type and clinging cavities occur at low gassing rates and usually give the appearance of good gas dispersion. The bubble size is small, however, and the bubble concentration is low. Large cavities exist at high gassing rates and occur when the impeller is flooded. Again, the area for transport is low. The 3-3 structure resides between these two cavity types and is made up of three large cavities and three clinging-type cavities, which occur at alternating blades for a six-blade impeller. As a result, the operation in the 3-3 structure regime and the detection of such operation on-line are very desirable. Smith and Warmoeskerken (1985) have used a vibrating vane to detect the 3-3 structure. However, with the exception of Hsi et al. (1985), hydrophones have not been used to study gas dispersion in agitated tanks nor for the detection of the 3-3 structure.

Gas sparger

Most hydrodynamic studies of gas dispersion in agitated tanks have focused upon the gas behavior around the impeller.

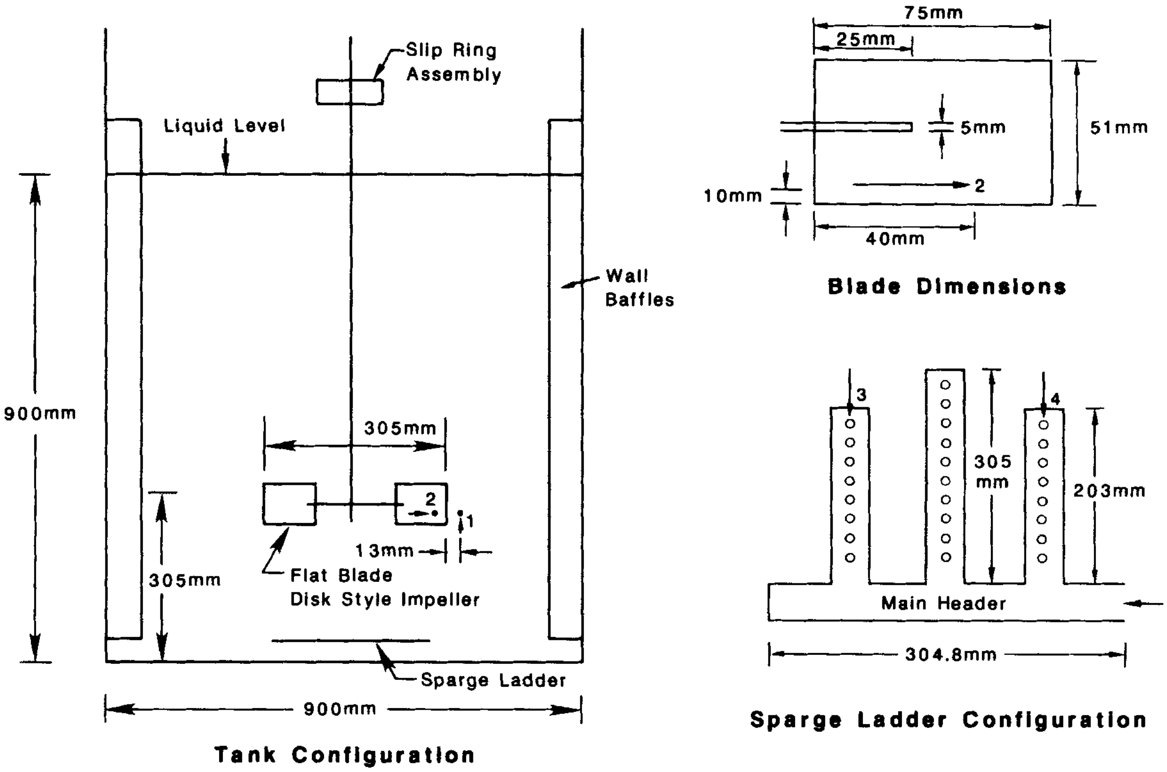

Figure 1. Tank and sparge ladder geometries.

Very few studies have been done on the interaction between the impeller and the gas sparger. However, the sparger geometry is important with regard to operations in the 3-3 structure regime since the symmetry of the pressure fields around the impeller blades permits the 3-3 structure to exist. Any maldistribution of this symmetry due to sparger maldistribution will hinder or prevent the formation of the 3-3 structure. Hsi et al. (1985) did not detect the 3-3 structure for this reason.

Experimental Equipment and Procedure

The mixing tank, shown in Figure 1, was a clear 900 mm dia. cylindrical flat bottom Plexiglas tank that was filled to a height of 900 mm with tap water. Four 91 mm wide vertical baffles were spaced symmetrically inside of the tank. The agitator was a 2 hp Chemineer 2HTD-Z agitator with variable impeller rotational speed to 6 s^{-1}. The impeller was a six flat bladed, disk-style turbine, 304.8mm in dia., which was placed 305 mm from the bottom of the tank. The disk diameter was 200 mm, with a thickness of 5 mm. The blade width was one-sixth of the impeller diameter and the blade length was 75 mm. The gas sparger was a ladder-type sparger that had orifices 3.2 mm in dia. The gas flow rate was measured using two Fischer-Porter model IOA 1755 rotameters, following manufacturer's recommendations.

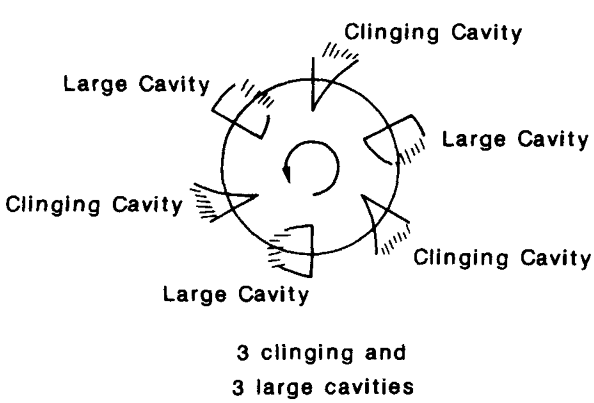

Figure 2. The 3-3 structure.

The hydrophones used for the measurement of the sound pressure were Bruel & Kjaer model 8103 hydrophones with a frequency response from 0.1 to 200 kHz and a receiving sensitivity of -211 dB re $1v/\mu Pa$. An Endevco model 2721A charge amplifier and model 4221A Bruel & Kjaer power supply were used. For the sound spectra, the signal from the charge amplifier was analyzed on a Nicolet 446 single-channel spectrum analyzer, set on peak, sensitivity at 5V, and resolution to 400 lines. To obtain the coherence function, a Hewlett-Packard 3582A dual-channel spectrum analyzer was used. The dual-channel analyzer performed the calculations for the coherence function between the two hydrophones. The frequency ranges for the sound spectra and coherence function were from 0 to 100 and 0 to 500 Hz. The amplitude of the sound covered a 60 dB range. The coherence function had an amplitude span from 0 to 1.

Sound spectra and coherent functions for single and dual hydrophones were recorded covering a range of five impeller rotational speeds and five gassing rates to form a 5×5 matrix of sound spectra. The five gassing rates were 0.0, 8.83, 42.0, 121.7, and 164.5×10^{-4} m^3/s at impeller rotational speeds of 0.0, 0.84, 1.67, 3.34, and 5.0 s^{-1}, respectively. The gassing rates in terms of volume of gas per volume of tank per minute were 0.0, 0.093, 0.44, 1.28, and 1.72 vvm. The positions of the measurements are positions *1* and *2* shown in Figure 1 where the arrows indicate the direction of the hydrophones. The hydrophone at position *1* was stationary; for position *2*, the hydrophone rotated with the impeller inside a low-pressure region, with the sound signal being obtained through a slip ring. In each case, two spectra were taken to insure reproducibility. Coherence functions (Sutter, 1986) were obtained between positions *1* and *2* for the same impeller rotational speeds and gassing rates. For the ladder sparger, the sound spectra and coherence functions were recorded over the same conditions at positions *3* and *4* shown in Figure 1.

Sound Spectra and Coherence in the Impeller Region

Figure 3 displays the sound spectra recorded at position *1* of Figure 1 for the frequency range from 0 to 100 Hz and for a range of 60 dB in sound pressure level on the *y* axis of each spectrum. (Other sound spectra are reported elsewhere [Sutter, 1986].) Spectrum *3(1,1)* shows that the background sound level without gas sparging and a rotating impeller is negligible. Spectra *3(1,2)*, *3(1,3)*, *3(1,4)*, and *3(1,5)* show sound due to entrainment of air from the tank surface. Generally, the spectra show a broad frequency base sound due to random turbulence, specifically shown in spectrum *3(2,5)*, which is roughly independent of gassing rate but increases with impeller rotational speed. Harmonic series *ABCD* and *FGHI* can also be observed occurring at frequencies related to the blade passing frequency of the impeller. These harmonics are formed due to the hydrophone detecting the gas cavity structures being shed by the impeller blades in the region of position *1*. The hydrophone, being a pressure transducer, was measuring the sound (pressure) changes due to these structures as they passed the hydrophone.

The amplitudes of the harmonics produced by the gas cavity structures appear to be roughly independent of impeller rotational speed and gassing rate. At very high gassing rates and low rotational speeds—e.g., in spectra *3(4,2)* and *3(5,2)*—the impeller is flooded and the harmonics series are not present in the spectra.

ABCD Harmonic Series

In spectrum *3(1,2)*, two strong peaks labeled *A* and *B* develop at 5 and 10 Hz, respectively, and make up the first harmonic series, labeled *A*, *B*, *C*, and *D*, in other spectra. The 5 Hz peak (*A*) is the first fundamental, located at the blade passing frequency; the second peak at 10 Hz is the second fundamental. Spectrum *3(1,3)* shows strong peaks *A*, *B*, and *C* at 10, 20 and 30 Hz, respectively, where the 10 Hz peak (*A*) is the first fundamental at the blade passing frequency; the peaks *B* and *C* are the second and third fundamentals. Spectrum *3(1,3)* also has three smaller secondary peaks, labeled *E*, at 13.75, 15.63, and 17.5 Hz; the difference between each successive peak being 1.87 Hz, which is approximately equal to the impeller rotational speed of $1.67 s^{-1}$. Other spectra—e.g., *3(1,4)* and *3(1,5)*—show similar phenomena: the dominant harmonic series, *ABCD*, and the secondary peaks labeled *E*. The *E* peaks, which occur between the fundamentals, are believed to be associated with either alternating unidentified cavity structures or nonlinear interactions between the fundamentals resulting from the vortex-clinging gas cavities.

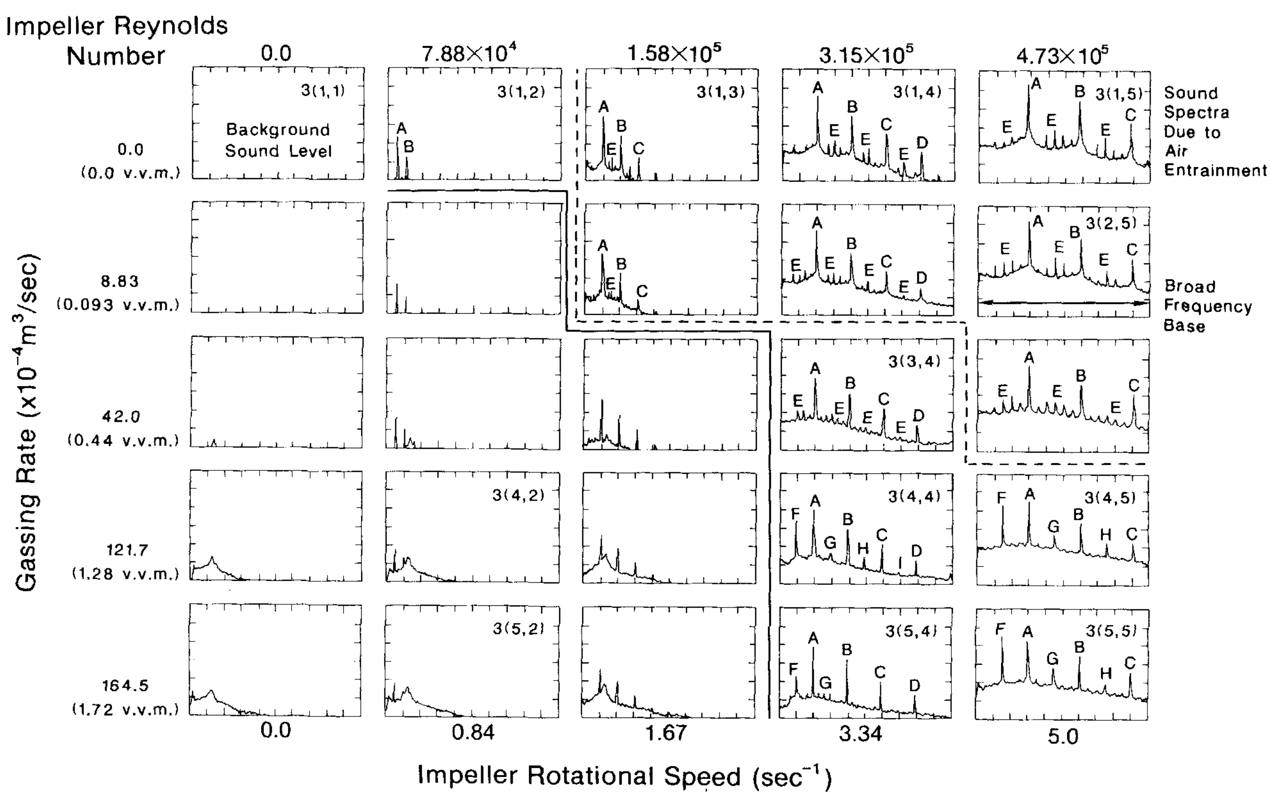

Figure 3. Sound spectra obtained at position 1.
0–100 Hz; ordinate span 60 dB

FGHI Harmonic Series

The second harmonic series, labeled *F*, *G*, *H*, and *I*, has fundamentals at 10, 30, 50, and 70 Hz in spectra *3(4,4)* and *3(5,4)*, and fundamentals at 15, 45, and 75 Hz in spectra *3(4,5)* and *3(5,5)*. The first fundamental of this series occurs at one-half the blade passing frequency with the higher order fundamentals at one-and-a-half and two-and-a-half times the blade passing frequency.

The *FGHI* series, together with the *ABCD* harmonic series, is the harmonic series for the 3-3 structure that can be used for its detection. The 3-3 structure has different gas cavity structures, clinging cavities alternating with large cavities, behind the blades of the impeller. The gas in these structures is shed by the impeller and their sound is detected by the hydrophone. It is the successive changing from one cavity structure to the other as the impeller rotates that produces the harmonic series *ABCD* and *FGHI* in the sound spectra of the hydrophone.

The spectra *3(4,4)*, *3(5,4)*, *3(4,5)*, and *3(5,5)* were taken at rotational speeds and gassing rates that were in the 3-3 flow regime given by Warmoeskerken and Smith (1985). The solid line in Figure 3 is the transition flooding line as given by Nienow et al. (1985) and cited by Smith and Warmoeskerken (1985). The dotted line in the figure is the transition line from the vortex and clinging cavities to the 3-3 structure as given by Warmoeskerken and Smith (1984, 1985). As can be readily seen in Figure 3, the *FGHI* harmonic series in the spectra is not present when the impeller is flooded or when the impeller is operating outside of the flow regime of the 3-3- structure at low gas loadings.

Sound spectra for position *2* on the rotating impeller were obtained to monitor sound inside the gas cavities. The sound spectra were very nondescript except for the zero gassing rate, where spectral peaks occurred due to surface entrainment of air. Overall, the spectra had the same broad frequency base, indicating that again the broadband random turbulence was occurring in the tank. The harmonic series, *ABCD* and *FGHI*, were absence in these spectra, which further indicated that these harmonic series were due to the gas cavity structures, shed by the impeller, periodically impinging upon the hydrophone.

For the sound spectra recorded to study the effect of distance from the impeller upon the spectra, the amplitude of the broad frequency base of the spectra remained constant with distance. However, there was a reduction in amplitude for the harmonic series and for the secondary *E* peaks which was attributed to the gas structures passing less frequently over the hydrophone.

Coherence studies were also performed between positions *1* and *2* to observe any commonality in the nature of the sound over the frequency range of 0 to 500 Hz. However, the coherence spectra showed very little coherence between the sound spectra.

Sound Spectra and Coherence inside the Gas Sparger

To investigate the phenomenon of maldistribution in a gas sparger, hydrophones were placed inside the gas sparger at positions *3* and *4*, as shown in Figure 1. Sound spectra of a hydrophone placed outside a sparge ring have been presented by Hsi et al. (1985). The sound spectra, except for those taken at zero gassing rate, were independent of impeller rotational speed but changed as a function of gassing rate. The spectra had an erratic appearance at low gassing rates, which was attributed to maldistribution of gas issuing from the sparger. No maldistribution was visually observed at higher gassing rates, which was reflected in the smooth appearance of the spectra (Sutter, 1986).

In this study, the gas flow through the orifices was well below sonic conditions and the Reynolds numbers for the flow in the legs indicated that turbulent flow conditions prevailed. The sound spectra for the sparge ladder were independent of the hydrophone location inside the sparger. Coherence studies between positions *3* and *4* inside the sparge ladder showed considerable coherence between spectra for gassing rates of 41.9×10^{-4} m^3/s and higher when the gas flow rate from the sparger was evenly distributed.

Conclusions

Sound spectra of gas dispersion in agitated tanks have been shown to be related to the hydrodynamic conditions of the impeller and gas sparger. In particular, sound spectra were directly related to the 3-3 cavity structure, impeller flooding, and sparger maldistribution.

Acknowledgment

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Literature cited

Hsi, R., M. Tay, D. Bukur, G. Tatterson, and G. Morrison, "Sound Spectra of Gas Dispersion in an Agitated Tank," *Chem. Eng. J.*, **31**, 153 (1985).

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

Ranade, V. R., and J. J. Ulbrecht, "Gas Dispersion in Viscous Inelastic and Viscoelastica Liquids," *Proc. 2nd Eur. Conf. on Mixing*, Cambridge, England, BHRA Fluid Eng. Center, Cranfield, England, F6-6 (1977).

Smith, J. M., and M. M. C. G. Warmoeskerken, "The Dispersion of Gases in Liquids with Turbines," *Proc. 5th Eur. Conf. on Mixing*, Wurzburg, West Germany, BHRA Fluid Eng. Center, Cranfield, England, 115 (1985).

Sutter, T. A., "Assessment of Gas Dispersion in Agitated Tanks Using Hydrophones," M.S. Thesis, Chem. Eng. Dept., Texas A&M Univ. (1986).

Warmoeskerken, M. M. C. G., and J. M. Smith, "The Flooding Transition with Gassed Turbines," *Inst. Chem. Eng. Symp. Ser.*, **89**, 59 (1984).

———, "Flooding of Disc Turbines in Gas-Liquid Dispersions: A New Description of the Phenomenon," *Chem. Eng. Sci.*, **40**, 2063 (1985).

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