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BRIEF COMMUNICATION

SOME OBSERVATIONS ON FLOW PATTERNS IN TANK-TYPE SYSTEMS

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INTRODUCTION

The design of tank-type gas–liquid systems is complicated by a lack of understanding of the possible flow patterns in the vessel, and a method to adequately account for the liquid and gas circulation in the vessel is needed for a rational design of these systems. For instance, some recent experimental work in surface agitated aeration basins indicates that liquid velocities in the bottom of the tank can increase if the total liquid height in the vessel is increased (Bennett 1981). Such unexpected behavior is attributed to a change in flow patterns in the system. Differences in flow patterns are also responsible for the differences in model behavior for different sized gas–liquid systems.

There are a large variety of gas–sparged systems employed in industrial practice. They vary in geometry, sparger design and in the range of gas flow rates used. Most of the published literature deals with very small laboratory-scale systems, 5–20 liters and gas flow rates that are several orders of magnitude lower than those of practical interest. Some work has been done using industrial-scale gas flow rates in large aeration basins (basin volume = 906 m^3) (Rooney & Mignone 1978 and Rooney & Huibregtse 1978) and in bubble columns (Hills 1974, Miyauchi & Shyu 1970 and Ueyama & Miyauchi 1977). Depending on the conditions of the experiments, researchers have modeled the two-phase region as a cylinder (Ulbrecht & Baykara 1981 and Rietema & Ottengraf 1970), or an expanding plume (Chesters *et al.* 1980 and Hussain & Siegel 1975).

It is necessary to identify the conditions that lead to different flow patterns in gas–liquid systems. These flow patterns and the transitions between them must be understood if systematic design procedures are going to be developed for gas–liquid tank–type systems. The purpose of this communication is to describe some of the flow patterns encountered in tank-type vessels equipped with gas spargers and identify the variables that affect them.

EXPERIMENTAL OBSERVATIONS

When gas is sparged into a liquid, bubbles are formed and a two-phase region above each orifice is established. The density difference between the two-phase region and the liquid surrounding it creates a liquid circulation in the system. Liquid flows upward in the two-phase region and near the top of the vessel it flows radially until it meets the vessel walls or liquid from an adjacent bubbling station. At this point, the liquid flows downward into the vessel. This motion establishes a liquid velocity profile outside of the two-phase region which is a measure of the range of influence of each bubbling station. The shape and behavior of the two-phase region and the liquid velocity profile established adjacent to it depend on the tank and sparger geometry and gas flow rate used. Otero (1983) has studied the two-phase region in an aeration basin or lagoon-type system. These systems are typically 3–6 m in depth and between 15 and 60 m in diameter with bubbling station spacing between 1 and 3 m.

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Figure 1. Typical waste water treatment facility. (Photograph courtesy of Virginia Chemicals.)

Lagoon-type systems have almost no interactions between adjacent two-phase regions and allow one to study the separate circulating units. These systems are mostly used for waste water treatment and a view of the surface of a typical waste treatment system is shown in figure 1. The individual circulating units are clearly shown. Gas flow rates between 0.005 and 0.02 m^3/s per bubbling station are typical for lagoon-type systems.

Otero (1983) studied the two-phase region and the adjacent liquid flow patterns in a tank with dimensions of $12 \times 12 \times 6$ m deep for bubbling station separations of 1.5 and 3 m and gas flow rates between 0.002 and 0.10 m^3/s per station at standard conditions. She found that bubbling station separation is a key parameter in modeling mass transfer. Surface tests showed that the radially flowing liquid turns downward into the vessel when it meets liquid from an adjacent bubbling station.

Figure 2 is an underwater photograph showing two-phase regions in a large aeration basin. Underwater photographic studies indicate that a large gas bubble is formed near the orifice. This bubble breaks up into smaller bubbles about 10–20 cm from the bubbling station. The gas bubble diameter in the system ranges between 0.004 and 0.01 m. However, most bubbles are approximately 0.005 m in diameter which appears to be the equilibrium bubble size for the air/water system. This bubble behavior has been observed by others (Grace *et al.* 1978, Leibson *et al.* 1956, Jones 1971, and Bhavaraju *et al.* 1978).

Otero (1983) has also measured the liquid velocity outside of the two-phase region. Figure 3 shows typical time-averaged liquid velocities, m/s. For large aeration basins or lagoons containing non-viscous liquids one can conclude that the two-phase region is an expanding plume surrounded by liquid flowing toward the plume.

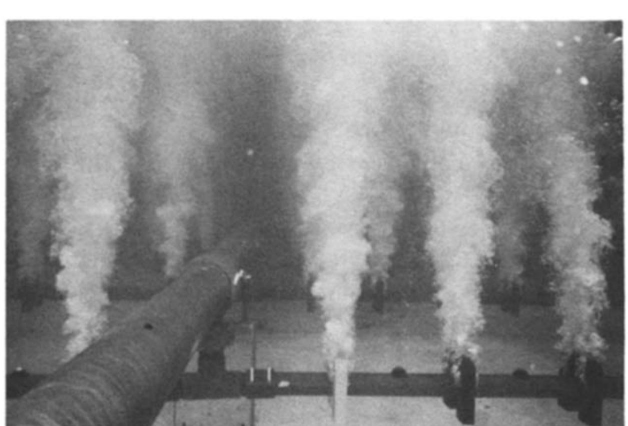

Figure 2. Two-phase regions in large aeration basin.

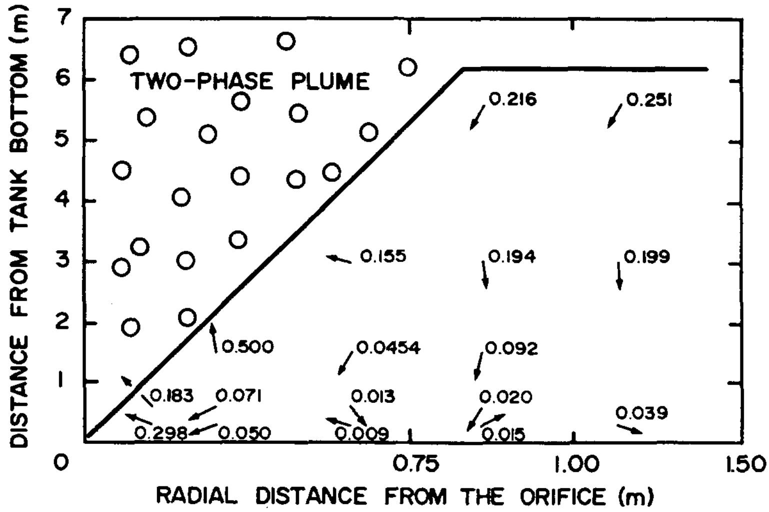

Figure 3.

Otero (1983) also has done work in a small tank with dimensions 1.2 × 2.1 × 1.2 m deep and bubbling station separations of 0.15–0.56 m. The small scale work indicates that the two-phase region behaves in the same manner as it does in the large scale except that there is less expansion of the plume. The basic liquid flow pattern is the same. The liquid flows up the plume and flows radially near the top of the tank until it meets liquid from an adjacent bubbling station where it flows downward into the tank.

For bubbling station separations of the order of the orifice-formed bubble diameter, the two-phase region appears to be as one plume in the center of the tank. The liquid rises in the center of the vessel and flows downward next to the walls. This flow pattern is often encountered in process and laboratory vessels and is depicted in figure 4. A similar pattern is discussed by Freedman & Davidson (1969). We call this the central plume pattern. For a given gas flow rate, increasing the bubbling station separation will allow for separate plumes to form. For a given liquid height, the expansion of the plume appears to be a function of orifice or bubbling station spacing and gas flow rate. As the bubbling station spacing is increased, cylindrical plumes form above each orifice. This flow pattern is depicted in figure 5. For large enough bubbling station separations and high enough gas flows the plumes will expand as shown in the work of Otero (1983) depicted in figure 2.

These flow pattern descriptions appear to be valid for gas flow rates greater than about 5×10^{-4} m^3/s per station. There must be enough energy input into the system to create the stable bubble size (for air–water, about 0.005 m).

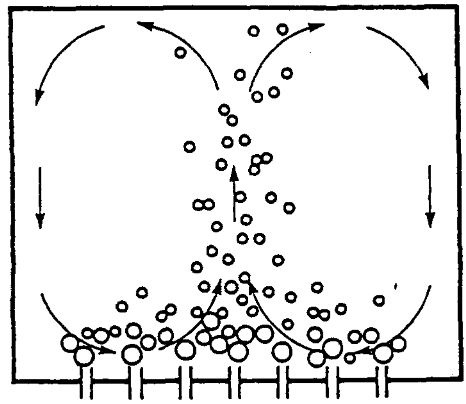

Figure 4.

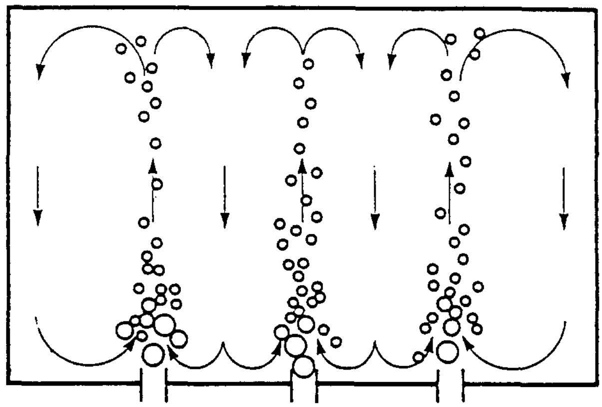

Figure 5.

DEVELOPMENT OF A FLOW PATTERN MAP

Process vessels are generally much smaller in diameter than lagoon-type systems, have heights between 1 and 4 times the diameter and bubbling station spacing between 10 and 50 cm. In an effort to understand and develop design criteria for lagoon-type systems as well as process vessels and laboratory units, the flow pattern map shown in figure 6 has been developed. The data points on the figure indicate the flow pattern observed by the researchers listed.

The central plume flow pattern appears to occur when the orifice spacing is about equal to the initial bubble size. The boundary between the central plume pattern and the two other flow patterns can be established by setting the orifice bubble size d_{b0} equal to the orifice spacing d_s. The orifice bubble sizes are calculated from the following equation:

$$d_{b0} = 0.66\, Q_G^{0.23}\, d_0^{0.12}. \qquad [1]$$

where Q_G is the gas flow rate per bubbling station. This expression was developed by Otero *et al.* (1982) for gas flow rates greater than 5×10^{-4} m^3/s.

An individual plume is defined to exist when the superficial velocity of the liquid flowing down outside of the two-phase region is equal to the superficial velocity inside the two-phase region. A liquid mass balance yields the following expression relating two-phase region

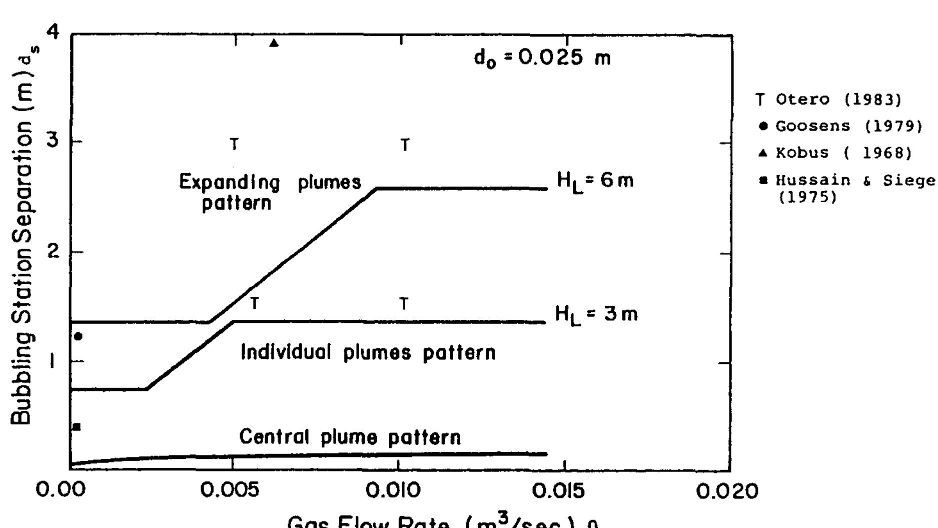

Figure 6.

diameter, d_s, to the diameter of the two-phase region, d_p:

$$d_p = 0.71\, d_s. \tag{2}$$

The angle of the expanding two-phase region, α, has been estimated by Otero (1983):

$$\alpha = 4530\, H_L^{-0.8}\, Q_G^{0.9}. \tag{3}$$

The diameter of the expanding two-phase region at the liquid surface can be easily calculated from geometrical considerations:

$$d_p = d_{b0} + 2H_L \tan(\alpha/2), \tag{4}$$

where d_{b0} can be calculated from [1]. Equation [3] is valid for plume angles, α, between 8° and 16°. These are the maximum and minimum plume angles observed experimentally.

The relationship given by [2], along with [3] and [4] can be used to set the boundary between the individual plumes and the expanding plume region:

$$d_p = 0.71\, d_s = d_{b0} + 2H_L \tan(\alpha/2). \tag{5}$$

Rearrangement yields

$$d_s = 1.41\, d_{b0} + 2.82\, H_L \tan(\alpha/2). \tag{6}$$

Close to the central plume region boundary line, the individual plume will tend to have a cylindrical geometry with flow upwards in the two-phase region and downwards in the annulus. As the boundary designating the expanding plume region is approached, a more cone-like behavior can be expected with more radial flow in the annulus, especially close to the liquid surface. The asymptotes on the boundary between the expanding plumes and the individual plume regions reflect the assumption of the minimum and maximum plume angle observed experimentally.

The gas flow rate, the liquid height and the bubbling station separation determine the shape of the two-phase region. For example, large orifice separations and large liquid heights allow for the expansion of the plume. Liquid height is also important in determining the liquid circulation in the system since the latter increases with increasing liquid height. For low liquid heights, there is some evidence to indicate that bubble break-up does not occur even if the liquid motion is turbulent. For very low liquid heights, such as that encountered on sieve trays (5–10 cm) no bubbles form and the gas "blows through" the liquid layer.

CONCLUSIONS

Flow patterns in tank-type systems are dependent on the gas flow rate, bubbling station separation, liquid height and the geometry of the system. More research is necessary to more clearly define the boundaries between flow patterns depicted in the flow pattern map developed here (figure 6). These flow patterns play a significant role in the determination of liquid velocities in and outside the two-phase region, mixing patterns and the proper power per unit volume input to the system.

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NOMENCLATURE

Variable		Units
d_{b0}	diameter of orifice formed bubble	m
d_0	orifice diameter	m
d_p	diameter of two-phase plume	m
d_s	bubbling station separation	m
H_L	total liquid height	m
Q_G	gas flow rate per bubbling station	m^3/s
α	angle of two-phase region	degrees

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