FACTORS TO CONSIDER WHEN EVALUATING HORIZONTAL ROTOR AERATOR PERFORMANCE

By

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When evaluating the performance of horizontal rotor mechanical surface aeration equipment in accordance with the ASCE Standard for Measurement of Oxygen Transfer in Clean Water, several factors should be considered with regard to their impact on the reported performance. These include basin geometry and testing volume, source water quality, dissolved oxygen measurement location, and external environmental factors including air temperature and humidity. Each of these factors may influence the reported performance of mechanical surface aeration equipment, specifically horizontal rotor aeration devices, resulting in an inaccurate estimation of the true equipment performance that should be expected in practical applications.
DEDICATION

This work is dedicated to my parents, Gerald and Betty Brown, in appreciation of their support and patience in the long road leading to this day.
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I extend my grateful appreciation to Dr. Dennis D. Truax, my committee chair, adviser, colleague, and friend. His wisdom and guidance throughout my academic and professional career have been invaluable. He is a true professional in all regards.

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Last, but certainly not least, I extend sincere gratitude to my family, friends and colleagues, without whose support in various endeavors, both personal and professional, this work would not have been possible.
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CHAPTER I
INTRODUCTION

In wastewater treatment, aeration is used to provide oxygen to aerobic microorganisms during the stabilization process. Additionally, certain applications use the mixing capabilities of aeration equipment to maintain sufficient agitation within the stabilization reactor to promote the desired level of interaction between the microorganisms and the organic loading to the treatment process.

Aeration equipment may be broadly classified into two groups: diffused-air systems and mechanical surface systems. While both groups are designed to achieve the task of supplying oxygen, the mechanisms employed by each group to achieve the task differ greatly.

The need for a common basis by which to compare the operational performance of various types of aeration equipment led to the development of the Standard for Measurement of Oxygen Transfer in Clean Water, initially adopted by the American Society of Civil Engineers (ASCE) in 1984. This standard presents a general methodology for the unsteady-state evaluation of both diffused-air and mechanical aeration systems. While the standard does
generally acknowledge significant differences in the operational characteristics of diffused-air and mechanical aeration systems, it offers only limited guidance with regard to the impact of certain aspects of the testing protocol on the reported performance of mechanical aeration systems undergoing evaluation in accordance with the published standard. Further, certain procedural requirements set forth in the standard may present a constraint to the natural operational characteristics of certain mechanical surface aeration equipment that impacts the equipment’s reported performance.

An initial investigation has been conducted with the objective of identifying those aspects of the currently adopted performance evaluation protocol with the potential to influence the reported operational performance of mechanical surface aeration equipment. In this investigation, data were collected from operational performance evaluations for an adaptation of the traditional horizontal rotor mechanical surface aeration equipment.

Inconsistencies in the observed results between successive days of testing horizontal rotor aeration equipment and general comparison of data collected in this investigation with limited available data from testing performed by external sources on horizontal rotors and other types of mechanical surface aeration equipment raised questions with regard to the validity of the testing protocol implemented for this investigation. After
evaluating the implemented testing procedure to insure compliance with the ASCE Standard, additional factors that had the potential to influence the reported operational performance were considered. These include basin geometry and testing volume used in the evaluation, specific requirements of the testing protocol such as testing water quality and dissolved oxygen measurement location, as well as external environmental factors including air temperature, pressure, and humidity. Where applicable, data from this and other investigations were used to develop guidelines for consideration with respect to the influence of those additional factors on the reported performance of mechanical surface aeration equipment in general and specifically horizontal rotor aeration equipment.
Aeration, a key component of many wastewater treatment processes, is the process by which oxygen is introduced into a bulk liquid. Aeration may occur through natural means, such as surface diffusion, within a treatment reactor or be promoted through the installation of specialized equipment, such as diffused-air or mechanical systems, within the treatment reactor. Regardless of the mechanism employed, the fundamental concepts of the aeration process remain constant.

Aeration is a mass transfer process where a gaseous constituent is absorbed into a liquid volume. Mass transfer may be generally described by the advection-diffusion equation, which considers transport by moving water as well as dispersion through turbulence and molecular diffusion, and biological, physical, and chemical reaction and interaction of the constituent within the elemental volume (Kiely, 1997). The aeration process in “clean” water is assumed conservative with respect to molecular oxygen at the elemental level. Thus, it is assumed that no biological, physical, or chemical reactions occur to alter the quantity of oxygen transferred. Additionally,
while some mass transfer occurs due to advection and turbulent diffusion at the macro level, mass transfer due to these processes is considered negligible at the elemental level.

![Elemental Control Volume](image)

**Figure 1**

**Elemental Control Volume**

For an elemental volume under quiescent conditions, as illustrated in Figure 1, the dominant transport mechanism is molecular diffusion. Fick’s first law of molecular diffusion states that the transfer of mass in stationary systems may be represented as a function of the concentration gradient, as noted in the following equation (Metcalf & Eddy, Inc., 2003):

\[ r = -D_M \frac{\partial C}{\partial x} \]  

(Eq. 1)
where:

\[ r = \text{Rate of mass transfer per unit area per unit time,}\]
\[ (\text{mass})/(\text{length})^2(\text{time}) \]

\[ D_M = \text{Coefficient of molecular diffusion in the x direction,}\]
\[ (\text{length})^2/(\text{time}) \]

\[ C = \text{Concentration of constituent being transferred,}\]
\[ (\text{mass})/(\text{length})^3, \text{ and} \]

\[ x = \text{distance, (length)} \]

"Two-Film" Theory of Gas Absorption

In 1924, Lewis and Whitman presented the "two-film" theory of molecular gas diffusion under quiescent conditions. This theory notes that the rate of absorption of a gas into a liquid is proportional to the diffusivity through a "film" established on each side of the gas-liquid interface as well as the area of the gas-liquid interface. The "films" represent boundaries at which mixing by convective currents within the bulk volume becomes negligible in comparison to diffusive forces through the interface.
Mass transfer through the gas film, according to the theory, is proportional to the difference in partial pressure of the gas on either side of the gas film. Similarly, mass transfer through the liquid film is proportional to the difference in gas concentration between the liquid at the interface and the bulk liquid outside the liquid film. Under steady-state conditions, the rate of mass transfer through the gas film is equivalent to the rate of mass transfer through the liquid film (Metcalf & Eddy, Inc., 2003). Applying Fick’s first law of molecular diffusion to each film, the following equation holds true:

\[ r = k_G \frac{(P_G - P_I)}{\delta_g} = k_i \frac{(C_I - C_L)}{\delta_l} \]  
(Eq. 2)

where:
\[ k_G = \text{Gas film mass transfer coefficient, } 1/(\text{time}) \]

\[ P_G = \text{Partial pressure of constituent in bulk gas phase, } (\text{mass})/(\text{length})^2 \]

\[ P_I = \text{Partial pressure of constituent at the interface, } (\text{mass})/(\text{length})^2 \]

\[ k_L = \text{Liquid film mass transfer coefficient, } (\text{length})/(\text{time}) \]

\[ C_I = \text{Concentration of constituent at the interface, } (\text{mass})/(\text{length})^3, \text{ and} \]

\[ C_L = \text{Concentration of constituent in the bulk liquid phase, } (\text{mass})/(\text{length})^3 \]

In Equation 2, the driving force for diffusion through each film is the concentration gradient across the film, \((P_G - P_I)\) across the gas film and \((C_I - C_L)\) across the liquid film. Thus, the coefficients \(k_G\) and \(k_L\) are considered as “local” transfer coefficients. Because it is difficult to quantify the local transfer coefficients, it is commonly accepted to apply the overall mass transfer coefficients \(K_G\) and \(K_L\), depending on which film limits the mass transfer process (Metcalf & Eddy, Inc., 2003).

In applying overall mass transfer coefficients, it is important to understand the relationship between the quantity of a constituent in the gas phase and the corresponding quantity in the liquid phase. This relationship is described by Henry’s law, which states that the weight of any gas that will dissolve in a given volume of liquid at a constant temperature is directly
proportional to the pressure exerted by the gas above the liquid (Sawyer et al., 1994). In the case of absorption of a high-solubility, low Henry’s constant gas in a liquid, the limiting factor becomes diffusion of the gas across the gas film, as the liquid will readily absorb the gas molecules passing through the interface.

On the other hand, absorption of a low-solubility, high Henry’s constant gas in a liquid, such as oxygen in water, the rate of absorption is limited by diffusion of the gas across the liquid film. Because the rate of diffusion across the liquid film is significantly less than that across the gas film, the gas-phase concentration at the interface is essentially equivalent to the bulk gas-phase concentration, thereby saturating the interface. Considering this case, the rate of mass transfer may be defined as:

\[ r = K_L (C_S - C_L) = k_g (P_g - P_l) = k_i (C_i - C_L) \]  
\[ \text{(Eq. 3)} \]

where:

- \( K_L \) = Overall liquid mass transfer coefficient, (length)/(time), and
- \( C_S \) = Concentration of constituent at the interface, (mass)/(length)^3

Applying Henry’s law, the following relationships are established:

\[ P_g = H C_S \]  
\[ \text{(Eq. 4)} \]
and

\[ P_l = H C_l \]  \hspace{1cm} (Eq. 5)

where, for both equations:

\[ H = \text{Henry’s Law constant for the constituent, (length)} \]

Thus, the overall driving force for the mass transfer process, assuming diffusion through the liquid film controls the process, may be written as:

\[ (C_s - C_L) = H(C_s - C_I) + (C_I - C_L) \]  \hspace{1cm} (Eq. 6)

From this, the relationship between overall liquid and gas-phase transfer coefficients may be shown as (Metcalf & Eddy, Inc., 2003):

\[ \frac{1}{K_L} = \frac{1}{HK_G} \]  \hspace{1cm} (Eq. 7)

where:

\[ K_G = \text{Overall gas mass transfer coefficient, 1/(time)} \]

Considering the mass transfer process on a unit volume, the following relationship may be developed:

\[ r_v = K_L \frac{A}{V}(C_s - C_I) \]  \hspace{1cm} (Eq. 8)

where:
From this, it may be stated that the overall rate of absorption is:

\[
\frac{dC}{dt} = K_{La} \cdot a \cdot (C_s - C_t)
\]  \hspace{1cm} \text{(Eq. 9)}

where:

\( \frac{dC}{dt} \) = rate of absorption, (mass)/(length)³(time)

\( K_{La} \) = volumetric mass transfer rate coefficient, 1/(time)

\( C_s \) = gas concentration at the liquid interface, (mass)/(length)³

\( C_t \) = gas concentration in the bulk liquid at time \( t \), (mass)/(length)³

From the above equation, it should be noted that, when the concentration differential across the liquid film is maximized (i.e. when \( C_t = 0 \)), the rate of absorption is also maximized. As the solution approaches equilibrium (i.e. when \( C_t \approx C_s \)), the rate of absorption correspondingly decreases to zero.
Natural Aeration Systems

Natural aeration systems rely primarily on surface diffusion to provide the quantity of oxygen necessary to address the needs of the aerobic microorganisms during the stabilization process. As mentioned above, oxygen transfer via surface diffusion is a slow process due to the low solubility of oxygen in water. Thus, natural aeration systems tend to be very land-intensive, requiring stabilization reactors with a surface area of sufficient size to maintain the necessary gas exchange rate with the atmosphere to satisfy the oxygen requirement of the treatment reactor.

In many natural systems, the growth of algae within the reactor provides additional oxygen to supplement the oxygen transferred through surface diffusion. Algae are phototrophic organisms, using sunlight to metabolize nutrients from the wastewater and generating oxygen as a by-product of that conversion. Algae also convert inorganic carbon sources within the wastewater to organic carbon for use by microorganisms during the stabilization process. While algae do provide a supplemental source of oxygen for natural systems, the availability of that source is directly controlled by the availability of light. When access to light is restricted, the photosynthetic processes within the algae decrease proportionally with the restriction, which, in turn, limits the quantity of oxygen generated. In the total absence of available light, algae are unable to synthesize available
nutrients in the water, leading to their death. At this point, the algal colony becomes a detriment to the natural system rather than a benefit as the decaying algae reintroduce the previously metabolized nutrients to the treatment process. This leads to an increased oxygen requirement exerted in the stabilization process.

**Artificial Aeration Systems**

When the natural aeration process is impractical due to inadequate land availability for the organic loading to be stabilized, artificial mechanisms are introduced to the treatment reactor to make certain a sufficient supply of oxygen is available to the aerobic microorganisms in order to achieve the desired performance from the stabilization process. The fundamental operating principle of artificial aeration systems is to increase the surface area of the treatment volume exposed to oxygen, either in pure form or as a constituent of atmospheric air.

While the fundamental principle is similar for all types of artificial aeration mechanisms, the methodologies employed in implementing this principle, and the benefits derived from those methodologies, vary greatly. The two most widely adopted methodologies are diffused-air aeration and mechanical surface aeration.
Diffused-air aeration systems force gaseous air or high-purity oxygen through a sparger, porous plate, or membrane located within the reactor. The diffusing mechanisms are typically installed along the bottom of the basin to maximize contact time between the gas bubble and bulk liquid, thereby maximizing gas transfer into the bulk liquid as the bubbles rise to the reactor surface. In diffused-air aeration, bubble size is a key component of the overall performance. Larger bubble sizes tend to rise more rapidly than bubbles of smaller size. This reduces the contact time between the bubble and bulk liquid, thereby reducing the opportunity for complete diffusion of oxygen through the bubble to occur during its travel through the bulk liquid. In contrast, the smaller bubble sizes rise more slowly through the bulk liquid, maximizing the contact time between the bubble and the bulk liquid. This fact, coupled with the larger specific surface area provided by the smaller bubble diameter for a unit volume of gas, promotes a more complete diffusion of oxygen through the bubble interface into the bulk liquid.

Unlike diffused-air systems, most mechanical surface aeration systems do not directly introduce gaseous air or oxygen into the bulk liquid. Rather, most mechanical systems increase the available surface area within the reactor by discretizing a portion of the bulk liquid into small droplets. These discrete droplets are then introduced into the atmosphere. While exposed to the atmosphere, gas is transferred into the droplets, which are then returned
to and reintegrated with the bulk liquid of the reactor. In a similar manner to diffused-air systems, droplet size is key to the overall observed performance of mechanical aeration systems. Larger droplets have a greater mass, which limits the period of exposure to the atmosphere, thereby reducing the likelihood that the droplet will become oxygen saturated before re-integrating with the bulk volume.

Both mechanisms employed to provide artificial aeration in a wastewater stabilization process have benefits as well as drawbacks when applied to specific applications. Understanding the basic operational characteristics for the principal divisions of artificial aeration and the various subsets within each division, as they relate to the specific treatment process being considered, allows for selection of an optimal aeration system to achieve the desired process goals. Of primary concern is the operational performance of the aeration system in relation to the treatment process.

Aeration Equipment Performance

When discussing performance of aeration equipment for use in a specific application, it is important to consider both the oxygen transfer capabilities of the equipment as well as the distribution, or mixing, capabilities of the equipment. In practice, the predominant focus is the characteristic oxygen transfer rate for the particular style of aeration
equipment under consideration. Inherent in the discussion of oxygen transfer performance is the ability of the aeration equipment to effectively distribute the oxygen-rich liquid to areas of the treatment reactor not directly influenced by the aeration equipment, while at the same time drawing oxygen-limited liquid toward the aeration equipment for oxygenation.

To a certain degree, the distribution or mixing capabilities of the aeration equipment are generally represented in the reported oxygen transfer performance. A higher rate of oxygen transfer is a reasonable indication that the equipment is actively moving liquid with a low concentration gradient (i.e. well-oxygenated) away from itself, while drawing water with a higher concentration gradient into its oxygenation area. However, the mixing capabilities of aeration equipment have a much broader impact on the overall operation of the treatment process than simply distributing oxygenated water throughout the basin. Reactor mixing facilitates the level of treatment achieved by promoting the desired operating hydraulic regime within the treatment process and maintaining the applicable quantity of biomass suspended within the reactor volume. Insufficient or excessive mixing in a treatment process may result in incomplete treatment or the establishment of undesirable conditions within the process.

The ideal environment for evaluating aeration equipment performance for a specific application is in the treatment reactor for the application. Field
performance testing provides a tangible method for evaluation using the specific basin geometric and treatment process conditions of the application under consideration. However, field evaluation of oxygen transfer performance may be impractical in certain applications. These include applications where several types of aeration equipment are being considered for installation as well as applications where the stabilization process selected to achieve the desired treatment goals is not conducive to a valid aeration system performance evaluation. For these and other reasons, a procedure by which aeration equipment performance could be evaluated under a uniform set of conditions and the results of those evaluations extrapolated to provide a reasonable estimate of application-specific aeration performance was developed.

**Measurement of Oxygen Transfer in Clean Water**

In January 1977, the American Society of Civil Engineers (ASCE) established a subcommittee on Oxygen Transfer Standards. This committee was tasked with the development of a consensus standard procedure for the evaluation of aeration devices (ASCE Oxygen Transfer Standards Committee, 1983). Initial efforts of the committee focused on the review and evaluation of existing aeration equipment and the methodologies used to estimate the operating performance of various types of equipment in use. Additionally,
attention was given to the interpretation of equipment evaluations and application of those results to the development of wastewater treatment facilities employing aeration equipment.

The first Standard for Measurement of Oxygen Transfer in Clean Water was adopted by ASCE in 1984. This represented the initial work developed by the Oxygen Transfer Standards committee. After initial adoption, the Standard continued to evolve through application, observation, and evaluation. The most recent update to the Standard was adopted in 1992 and given the designation ANSI/ASCE 2-91. For clarity, the most recent update of the Standard for Measurement of Oxygen Transfer in Clean Water shall be referenced as the ASCE Standard throughout this document.

The methodology described in the ASCE Standard for evaluating aeration equipment performance is based on the removal of oxygen from the volume via chemical reaction through addition of sodium sulfite in the presence of a cobalt catalyst. The aeration device then re-oxygenates the volume to the approximate dissolved oxygen saturation level. Measurements of dissolved oxygen concentration are collected at several locations within the volume throughout the re-oxygenation process. The collected data are then analyzed to determine the apparent volumetric mass transfer coefficient, $K_{La}$. Specific aspects of the testing protocol with the potential to influence
the reported performance of aeration devices are detailed in Chapter IV of this document.

**Horizontal rotor Aerators and ANSI/ASCE 2-91**

Since the most recent review of the standard, the horizontal rotor mechanical surface aerator has gained wider acceptance for installation in wastewater treatment applications other than the oxidation ditch reactor, the traditional treatment process employing horizontal rotor aeration equipment. Several manufacturers have developed a self-contained floating support platform for the horizontal rotor, allowing the horizontal rotor aerator to be installed in treatment basins similar to other types of floating mechanical surface aeration equipment. The flexibility of the floating platform, coupled with the intrinsic operational characteristics of the horizontal rotor, provide a significant advantage in promoting desirable stabilization processes within a treatment basin.

The floating platform horizontal rotor aerator has been in widespread use in the aquaculture field for more than two decades. While wastewater treatment facilities in nearby towns began using horizontal rotor aeration equipment at about the same time, broader acceptance of the horizontal rotor aerator for use in wastewater treatment facilities other than oxidation ditches has developed primarily within the last 10 years. With that broader
acceptance came a more earnest focus on the operational performance that could be expected from the equipment. Testing performed by manufacturers prior to adoption of the initial standard in 1984 yielded aeration efficiencies significantly higher than those of other mechanical surface aerators. This, understandably, led to questions regarding the methodologies employed in achieving the reported results.

In 2000, a new manufacturer developed a floating platform horizontal rotor aerator to be sold in the wastewater treatment market. As a component of development, extensive full-scale testing was conducted to evaluate the operational performance of equipment prototypes and production-level units. The employed testing protocol was based on ANSI/ASCE 2-91, the current Standard for Measurement of Oxygen Transfer in Clean Water. In reviewing the ASCE Standard, it was noted that requirements for certain water quality parameters, equipment power measurement, dissolved oxygen measurement, and data analysis techniques are explicitly detailed. However, only general guidance is offered by the ASCE Standard in other areas of the testing procedure, such as testing volume, source water quality, and environmental conditions. Each of these areas has the potential to impact the reported operational performance of aeration equipment, particularly mechanical surface aeration equipment, to some degree. It is anticipated that such generality is due to the great variation in operational characteristics for the
different types of aeration equipment as well as the variation in conditions
between testing locations.

The testing basin employed for evaluating the performance of the
floating platform horizontal rotor aerators is square in overall geometry,
having a side length of approximately 70 feet. The basin is partially
segmented using cast concrete structures to provide three channels of
approximately equal size, with clear space at each end of the concrete
structures to promote circulation between the channels. The aeration device
to be evaluated is positioned in the central channel and anchored to the wall
of the basin. When operating, the aerator discharges along the center
channel toward the opposite wall of the basin, where the flow is directed
toward the two outer channels. Water then flows along the outer channels,
toward the aeration device. Once reaching the proximity of the aeration
device, the water is drawn toward the device, where it is again discharged,
repeating the circulation cycle. For this discussion, the center channel will be
referred to as the discharge channel while the two outer channels will be
referred to as the return flow channels. Dissolved oxygen measurement
locations were identified in both the discharge and return flow channels for
use in various evaluation scenarios. Figure 3, below, illustrates the testing
basin layout.
Figure 3

Horizontal Rotor Aeration Equipment Evaluation – Testing Basin Configuration
CHAPTER III

TEST BASIN GEOMETRY AND VOLUME

As noted previously, the ideal facilities for evaluating the performance of aeration equipment are the specific wastewater treatment processes utilizing aeration for stabilization. For the vast majority of wastewater treatment applications requiring aeration, such site-specific equipment performance evaluations are not feasible due to logistical issues involved with the evaluation procedure or the intended operating parameters of the treatment process. Adding to this is the additional complexity introduced when evaluation of multiple types of aeration equipment is desired. Therefore, evaluation of aeration equipment performance at non site-specific facilities and adaptation of the resultant observed performance to the site-specific conditions of a wastewater treatment process becomes necessary.

When evaluating aeration equipment at locations other than the specific wastewater treatment facility, it is important to make certain the evaluation yields a consistent, reliable, and reproducible measure of the anticipated performance for the aeration device in a wastewater treatment facility. In developing this evaluation environment, the basin to be employed
for evaluating aeration equipment performance must be considered in terms of both geometric configuration as well as volumetric capacity such that the basin does not influence the measured performance of the aeration equipment.

Geometric Shapes for Testing Basins

It is generally understood that the basin geometry employed for the evaluation of an aeration device may influence the reported performance of that device (Cleasby and Baumann, 1968). However, the magnitude of this influence has not been widely investigated (Rao and Laxmi, 1996). As such, the basins used for evaluation of aeration equipment should closely represent the anticipated operating environment of the aeration equipment in order to maximize the applicability of the reported performance (ASCE Oxygen Transfer Standards Committee, 1983). Because of the great variety of treatment process designs, defining a single basin configuration that would conform to this goal for all aeration devices is difficult (American Society of Civil Engineers, 1993). Rather than defining a single basin configuration for the evaluation of all aeration devices, it would seem reasonable to develop a testing basin geometry optimized for the operational characteristics of the specific aeration equipment under evaluation.
In 1973, Kormanik and Rooney performed a series of evaluations on field-scale vertical-axis, mechanical surface aerators to investigate the influence of tank geometry on the reported performance. Much of the investigation focused on the influence of surface area, though the influence of operating depth was also examined.

The basin used in these evaluations was square in geometry, with a side length of 80 feet, and a maximum depth of 20 feet. This geometry provided a maximum plan-view surface area of 6,400 square feet. Further, the basin could be easily subdivided to allow for evaluations at surface areas of 1,600 square feet, corresponding to a 40-foot square geometry, and 3,200 square feet, corresponding to a rectangular geometry of 80 feet by 40 feet.

The investigation considered two high-speed, vertical-axis aerator designs as well as a low-speed, vertical-axis aerator design. The high-speed, high-trajectory aerator, commonly described as a vertical turbine-type aerator, was evaluated over a range of available horsepower sizes from 3 HP to 75 HP. Additionally, a 50-HP high-speed, low-trajectory aerator and a 75-HP low-speed, bridge-mounted aerator were included in the investigation.

It was decided that evaluating each of the 12 horsepower sizes in each basin configuration was impractical. As such, extensive testing was performed using high-speed, high-trajectory aerators of 15, 30, 50, and 75 HP and the 50-HP high-speed, low-trajectory aerator to develop a detailed
correlation between equipment performance and basin geometry. The remaining equipment was then evaluated for comparison with the noted observations.

From the summarized results of the initial evaluations, the reported performance of each unit size of aeration equipment degrades as the surface area of the testing basin increases (Kormanik and Rooney, 1973). This is as would be expected. Increasing the surface area of the basin provides less lateral constraint to the operational characteristics of the aeration equipment. The reduced lateral constraint also reduces the likelihood of oxygen transfer to the bulk volume that may be caused by “secondary mixing”, or mixing that occurs due to excessive turbulence across the basin surface rather than the direct action of the aeration device. Additionally, the increase in surface area, while maintaining a consistent operating depth, increases in the testing volume involved in the evaluation process. It is possible that this increase in volume resulted in the decrease in reported performance due to limited involvement of the basin volume along the boundaries of the basin. Stated differently, the mixing capability of the aerator being evaluated may not have adequately involved the entire volume of bulk liquid in the aeration process, allowing de-oxygenated water to feed back into the portion of the total volume involved by the aerator, thereby decreasing the reported performance of the equipment. However, there is
insufficient information available to support or defeat the above hypothesis that inadequate mixing of the test volume contributed to the decrease in reported equipment performance.

Of particular interest in the data presented by Kormanik and Rooney (1973), the reported transfer rates for the largest surface area investigated decreased as the unit horsepower size increased. This is not an expected occurrence. Indeed, the larger-horsepower aeration devices should have involved a greater quantity of the total volume in the aeration process. This fact, coupled with the expected greater surface mixing achieved by the larger-horsepower devices, should yield a greater oxygen transfer rate than the smaller-horsepower units evaluated in the same volume. While this observation may be due to an error in data tabulation, it could also be attributed to dissolved oxygen measurement points located within or in close proximity to an anomaly in the flow pattern created by the larger-horsepower aerators within the volume. However, detailed information regarding location of dissolved measurement points with respect to each basin geometry and aeration device undergoing evaluation was not presented.

Kormanik and Rooney (1973) also investigated the relationship between the reported performance of an aeration device and the ratio of power applied by the device to a given basin surface area. Plotting the operating performance for a given aerator horsepower and basin surface area,
it was observed that a correlation can be observed with reasonable certainty. For the complete range of high-speed aerator horsepower sizes evaluated, both high and low-trajectory designs, the reported performance becomes significantly more dependent on the ratio of horsepower applied to a specific surface area as the horsepower size of the aerator is decreased. In contrast, the ratio of horsepower applied to a specific surface area exhibited only a minor influence to the reported performance of the low-speed aerator.

Though basin geometry does have the potential to influence the reported performance of aeration equipment, the information presented by Kormanik and Rooney (1973) raises several questions with regard to the magnitude of influence. Most notably is the lack of consideration given to the change in corresponding bulk liquid volume for a given change in basin surface area. Maintaining a constant volume while changing the basin surface area would allow a more direct approach to the determining the influence of basin surface area on the reported aeration equipment performance. Of course, maintaining a constant volume would require an adjustment in operating depth for the basin when evaluating a specific basin surface area. This adjustment must be considered with care so as not to constrain the vertical operational characteristics of the aeration equipment under evaluation in such a manner that the reported performance is adversely impacted.
In 1996, Rao and Laxmi conducted a series of investigations considering the influence of basin surface geometry on the oxygen transfer characteristics of a bench-scale vertical-axis mechanical aeration device. Unlike the investigation conducted by Kormanik and Rooney (1973), their investigation considered four reactor configurations consisting of three geometric shapes with the intent of identifying an “optimal” geometry. Also, variability within the experimental setup was limited to the geometric shape of the reactor, the focus of the investigation, by maintaining strict relationships between the aeration device and reactor geometric parameters, including surface area and depth. The results of their investigation clearly indicated that the geometric shape of the basin does influence the reported oxygen transfer performance of the aeration device. While Rao and Laxmi (1996) observed an impact on aeration performance resulting from modification of the basin geometry, the scope of their investigation was limited to a single aeration device. Even with this limitation, though, their results allude to a relationship between the aeration device’s operational characteristics, basin geometry, and reported performance.

The operational characteristics of the aeration equipment, including intake and discharge profiles, are typically considered as guides for the placement of aeration equipment within a treatment basin, particularly when multiple devices are required within the basin to provide the necessary level
of treatment for the process. This insures the maximum quantity of the bulk liquid will be involved in the treatment process, thereby maximizing the level of treatment provided within the reactor while minimizing the potential for short-circuiting, wastewater not being actively involved in the treatment process as it moves through the reactor, within the basin. In effect, sub-reactors containing one aerator are created within the overall reactor. Rather than a physical boundary between adjacent sub-reactors, the operational characteristics of the aeration equipment create a less restrictive “hydraulic barrier” to allow interaction between the hydraulic profiles of adjacent units.

To minimize the potential for influence to the reported performance of aeration equipment, it seems reasonable to apply the concepts of equipment arrangement for a specific type of aerator in a wastewater treatment process as a guide for developing the basin geometric constraints needed in the evaluation of equipment performance. Developing a basin geometry corresponding to the natural operational characteristics of a specific type of aeration device for evaluating the performance of that device would provide an evaluation environment that promotes optimal performance, as observed by Rao and Laxmi (1996). As an example of this approach, the basin used to evaluate the performance of a vertical-axis, turbine-type aerator would have a cylindrical geometry to closely approximate the radial discharge profile and
prominent vertical mixing component. An aspirator-type aerator, with its vertical and horizontal discharge components, might be evaluated in either a rectangular, cylindrical, or a racetrack-shaped basin. A horizontal-axis, rotor-type aerator, with its prominent lateral mixing component, could be evaluated in either a racetrack-shaped or a rectangular basin. Though these geometric shapes may not necessarily be representative of the specific basin configurations implemented in wastewater treatment processes that would employ these types of aeration equipment, the proposed geometries do consider the operational characteristics exhibited by the aeration equipment. As noted earlier, however, basin surface area must be considered in concert with operating depth in order to provide a reasonable evaluation of aeration equipment performance.

**Operating Depth for Testing Basins**

In concert with the definition of basin geometry for the evaluation of aeration equipment, the operating depth of the testing basin must also be considered. A basin that is significantly deeper than the acceptable operating depth of the aeration equipment will result in an erroneous reported equipment performance due to the inadequate involvement of the bulk liquid. Similarly, a basin that is significantly shallower than the acceptable operating depth of the aeration equipment will result in an erroneous
reported equipment performance due to the significant dissipation of energy along the bottom of the testing basin.

As an additional aspect of evaluations on mechanical surface aerators performed by Kormanik and Rooney (1973), the influence of operating depth was examined. Operating depth influence evaluations were performed using the high-speed aerators of horsepower sizes ranging from 15 HP to 75 HP at operating depths of 12 feet and 18 feet. From these evaluations, they concluded that operating depth had no impact on the reported operational performance of surface mechanical aeration equipment.

While the evaluations were performed at two depths over a range of equipment horsepower levels, there is insufficient information presented to fully substantiate the statement that aeration equipment operational performance is independent of operating depth. The operating depths used in the investigation are certainly within the normal operating depth range for the equipment used in the evaluation. However, such equipment has also been used in applications with a significantly shallower operating depth than those used in the investigation, where the natural operating characteristics of the equipment are greatly constrained. Though installation in such environments is not typical for this type of equipment, it is difficult to consider that the operational performance of the equipment would not be adversely affected by the vertically constrained operating environment.
Further, the statement that aeration equipment performance is independent of operating depth is based on the operational characteristics of only one broad type of aeration equipment: high-speed, vertical-axis, mechanical surface aerators. The impact of operating depth on alternate types of mechanical aeration equipment, such as the aspirator-type or horizontal rotor-type aerator, did not appear to be considered as a part of the original investigation.

**Operating Depth and Horizontal Rotor Aerator Performance**

Although not specifically investigated during the performance evaluations conducted on horizontal rotor aeration equipment, limited data of sufficient consistency from those evaluations to allow for general comparison of operating depth and equipment performance are available. Specifically, evaluations were conducted to determine the performance of a horizontal rotor aerator at operating depths of 2, 3, and 5 feet. Depths of 2 and 3 feet represent a minimum operating depth for the horizontal rotor aerator while the depth of 5 feet lies within the normal operating depth range for the horizontal rotor aerator.

From these tests, the observed equipment performance was markedly lower at the 2 and 3-foot operating depths in comparison to the observed performance at the 5-foot operating depth. The difference in observed
equipment performance between the evaluated operating depths is likely due to the constraint of the vertical component of the aeration device’s operational characteristic, which causes an excessive dissipation of energy from the discharge profile. While no firm conclusions may be drawn from the available data, it does appear that operating depth may influence the operational performance of the horizontal rotor aerator.

Though the basin geometry and operating depth used in the evaluation of aeration equipment performance should not be disregarded, the myriad of basin configuration options for each type of aerator used in wastewater treatment processes causes difficulty in establishing guidelines to provide evaluations that reasonably approximate the anticipated operating environment in wastewater treatment reactors. Rather than generating guidelines for specific basin geometry and operating depth, a more straightforward approach would be to develop guidelines based on the level of applied mixing energy to define an approximate volume for the performance evaluation. Appropriate basin geometry and operating depth criteria for the type of aeration equipment being evaluated could then be extrapolated for the testing volume.
Test Basin Volume as a Function of Applied Mixing Energy

Recalling the basic principals of wastewater treatment process design, treatment facilities are typically designed to operate in one of three general hydraulic regimes: facultative, partially mixed, or completely mixed. In evaluating the oxygenation performance of aeration equipment, the completely mixed hydraulic environment is most appropriate. However, opinions vary as to the level of applied mixing energy, defined simply as the quantity of energy applied to a volume, necessary to establish and, more importantly, maintain a completely mixed environment. Reynolds and Richards (1996) note the level of mixing energy required to maintain a completely-mixed environment using mechanical aerators ranges between 100 horsepower per million gallons of basin volume (100 HP/Mgal) and 200 HP/Mgal. Crites and Tchobanoglous (1998) place the range between 75 HP/Mgal and 150 HP/Mgal. A third source suggests that a completely mixed environment may be achieved with an applied mixing energy as low as 20 to 30 HP/Mgal (American Society of Civil Engineers and Water Environment Federation, 1988). Additionally, one state regulatory agency noted in their design criteria for municipal wastewater treatment facilities that the applied mixing energy necessary to achieve a completely mixed environment may range from 30 HP/Mgal to 100 HP/Mgal, depending on the type of treatment process implemented (Texas Commission on Environmental Quality, 1997).
Certainly, the difficulty in accurately quantifying completely mixed conditions within a reactor is partially responsible for the vast difference in reported horsepower ranges. Differences in basin geometry and aeration equipment operating characteristics also contribute to the variation in reported horsepower ranges.

As an illustration of this concept, consider three basins to be used in evaluating the oxygen transfer performance of 15-HP aspirator-type, vertical turbine-type, and horizontal rotor-type aerators. Each basin has an operating volume of 100,000 gallons and a geometric configuration suitable for testing one type of aeration device based on the operational characteristics of that device. In each instance, the level of mixing energy applied to the volume is 150 HP/Mgal, sufficient for the volume to be considered a completely mixed hydraulic regime according to all the above references. However, in reaching this conclusion, the unique operating characteristics exhibited by each type of mechanical aeration equipment are largely ignored. As such, the definition of mixing energy in these terms is meaningful only when comparing aeration equipment of a specific type operating under comparable conditions (ASCE Oxygen Transfer Standards Committee, 1983). Further, these values have little, if any, correlation to the actual mixing capability of the specific type of aeration equipment.
Typically, mechanical aeration equipment manufacturers quantify the mixing performance of a specific device as its discharge or pumping rate. Using the documented discharge rate for the aeration device, the intensity of involvement of the bulk liquid may be approximated by the circulation, or turnover, period within the basin, defined as:

\[
\text{Turnover Period} = \frac{\text{Bulk Liquid Volume}}{\text{Aerator Discharge Rate}}
\]  

(Eq. 10)

where:

- **Turnover Period** = Theoretical time for a unit volume of liquid to travel from a designated point in the bulk volume, throughout the bulk volume, and arrive at the same designated point in the bulk volume, (time)
- **Bulk Liquid Volume** = Total volume of liquid under consideration, (length)^3, and
- **Aerator Discharge Rate** = Total flow rate of liquid being directly propelled by the aeration device, (length)^3/time

Recalling that applied mixing energy is the ratio of power applied to a defined volume, the turnover period may also be estimated as a function of the mixing energy applied to a volume according to the following relationship:
Turnover Period = \frac{1}{(\text{Applied Mixing Energy})(\text{Specific Discharge Rate})} \quad \text{(Eq. 11)}

where:

\text{Applied Mixing Energy} = \text{Energy applied to a bulk liquid in order to promote distribution of components within the bulk liquid, power/(length)^3, and}

\text{Specific Discharge Rate} = \text{Flow rate of liquid being directly propelled by the aeration device for each unit of energy supplied, (length)^3/(time \ast power)}

For most applications, a circulation period less than 15 minutes promotes the necessary involvement within the bulk liquid to maintain a completely mixed hydraulic regime within the volume. Continuing the above illustration, Table 1 details the estimated specific discharge rates for typical types of mechanical surface aerators. Using the specific discharge rates and the applied mixing energy for this illustration, 150 HP/Mgal, the approximate turnover period may be estimated according to Equation 3. Table 1 also includes an estimate of the turnover period achieved by each type of aeration device for the conditions of this illustration.
Table 1

Discharge rate and turnover period for various mechanical aerators

<table>
<thead>
<tr>
<th>Aerator Type</th>
<th>Specific Discharge rate, gpm/HP</th>
<th>Turnover Period(^1), min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspirator</td>
<td>300(^2)</td>
<td>22</td>
</tr>
<tr>
<td>Vertical turbine</td>
<td>750(^3)</td>
<td>9</td>
</tr>
<tr>
<td>Horizontal rotor</td>
<td>2,500(^4)</td>
<td>3</td>
</tr>
</tbody>
</table>

Notes:
1. Turnover period based on an applied mixing energy to the volume of 150 HP/Mgal
2. From Product Technical Information for Aeration Industries
   International aerators, Chaska, Minnesota (1983)

Though the mixing energy applied to the volume is identical in all cases, 150 HP/Mgal, the capability of each type of aerator to involve the bulk liquid varies greatly. Therefore, it would appear reasonable to define the level of mixing within the basin as a function of the turnover period of the bulk liquid rather than using the more generic power per volume ratio. Though variation in mixing performance does exist, even between different manufacturers of the same type of mechanical aeration equipment, using the concept of circulation, or turnover, period allows a common basis for comparison of performance. Further, the turnover period provides a reasonable approximation of aeration equipment mixing performance in a specific wastewater treatment process reactor as it relates the mixing capability of the aeration equipment to the volume of the treatment reactor.
While a certain minimal level of mixing is necessary to properly evaluate mechanical aeration equipment performance, care must be taken in establishing the level of mixing within the volume so as not to overly energize the bulk liquid. Applying excessive mixing energy to the volume may lead to a secondary source of oxygen transfer into the bulk liquid resulting from the turbulence created through operation of the aeration equipment. The intensity of turbulence and wave action along the surface are commonly accepted as the principal sources of surface aeration (Rao, 1999). Turbulence is typically described by the Reynolds number and wave action by the Froude number. Thus, it may be inferred that the rate of oxygen transfer is functionally related to both the Reynolds number and Froude number for a given surface aeration device in a given volume. For an observed unit increase in the turbulence and wave action along the surface of a volume, a corresponding increase in oxygen transfer is noted. As the intensity of turbulence and wave action continues to increase within the volume, the corresponding increase in oxygen transfer is markedly more significant. At this moment, the measured oxygen transfer performance of an aeration device becomes a combination of the device’s oxygen transfer performance resulting from the introduction of water droplets into the atmosphere and the oxygen transfer achieved due to the intense turbulence and wave action along the surface of the testing basin.
It is important to understand that, when operating mechanical surface aeration equipment, some amount of turbulence and wave action, commonly described as “secondary aeration”, is generated as a direct result of the operational characteristics of the device. Much of this is located in close proximity to the aeration device and is generated independent of the operating environment for the equipment. As such, the additional oxygen transfer resulting from this turbulence and wave action should be included in an evaluation of the performance characteristics of the device.

On the other hand, significant turbulence and wave action occurring well away from the aeration device should be avoided when conducting evaluations of equipment performance. Such secondary aeration is likely the result of an interaction between the environment used in the evaluation, such as the physical boundaries of the testing basin, and equipment operating characteristics. The interaction creates a mixing condition within the evaluation volume that is not representative of typical applications for the aeration device, resulting in an artificially high estimate of true performance for the equipment.

It is difficult to define the level of mixing necessary to result in the latter form of secondary aeration described above significantly influencing the reported performance of an aeration device as that level is a function of the specific operating characteristics of the aeration device as well as the
specific basin geometric constraints applied during the performance evaluation. Rao (1999) observed that, for a 6-blade vertical axis surface aerator evaluated in a square tank of various side lengths, significant increases in the observed oxygen transfer rate were noticed to correspond with Reynolds numbers between $10^4$ and $10^5$ and Froude numbers around $10^3$.

The above discussion is of particular interest when translating bench-scale or pilot-scale aeration equipment performance evaluations to field application. To reasonably predict the field performance of a mechanical surface aerator using bench-scale models, it is important that the performance of the models approximate the anticipated field characteristics in terms of turbulence and wave action. Maise (1970) notes that, to accurately scale surface aerators, both the model and field unit must be dynamically similar. This dynamic similarity relates not only to the Reynolds and Froude numbers, but also to the similarity in the mechanism of droplet formation between the model and field device.
CHAPTER IV

TESTING PROTOCOL

The ASCE Standard for Measurement of Oxygen Transfer in Clean Water offers a specific protocol with regard to experimental set-up, data collection, and data analysis to provide a uniform methodology capable of yielding reproducible results for a variety of aeration equipment types. However, the differences in operational characteristics between aeration equipment types as well as variability introduced by the testing location must be given due consideration when conducting equipment performance evaluations. Specific aspects of the evaluation procedure requiring consideration include source water quality, location of dissolved oxygen measurement within the testing volume, and data collection and analysis.

Source Water Quality

Section 6.3 of the ASCE Standard addresses quality requirements for the source water used in evaluating aeration equipment performance. Specifically, the ASCE Standard requires that the source water used in evaluating aeration equipment performance be “equivalent in quality to a
potable public water supply”. Further, limits on the level of total dissolved solids (TDS) that may be present in the source water while testing is underway as well as boundaries on the water temperature to be used for equipment evaluation are established. In typical performance evaluations, replicate testing is conducted using an initial volume of source water. With each test, the TDS concentration in the volume increases as sodium sulfite is added to deoxygenate the volume. Several investigators, noted in the development work prepared by the ASCE Oxygen Transfer Standards Committee, report that the absorption rate, $K_{la}$, is impacted at salt concentrations greater than about 1,200 mg/L. To mitigate this impact, it was initially recommended that TDS levels in the testing volume not exceed 1,500 mg/L. The Standard presently limits the TDS level to 2,000 mg/L.

Water temperature is also known to significantly impact the rate of oxygen transfer into the bulk liquid. Additionally, testing at lower temperatures may lead to the introduction of error in the reported performance due to uncertainties of chemical reactions, particularly in the de-oxygenation process (ASCE Oxygen Transfer Standards Committee, 1983). Because of this, the ASCE Standard recommends that performance evaluations be conducted when water temperatures are “between 10°C and 30°C, and as close to 20°C as possible”. Further, the ASCE Standard stipulates that a temperature correction factor, $\theta$, of 1.024 be employed to
adjust results of performance evaluations conducted at water temperatures other than the defined standard temperature, 20°C, to standard conditions.

In addition to TDS concentration and water temperature, other source water quality parameters have the potential to impact the reported performance of aeration equipment. Such parameters include alkalinity, iron, manganese, chlorine residual, pH, total organic carbon (TOC), chemical oxygen demand (COD), cobalt, and surfactants (ASCE Oxygen Transfer Standards Committee, 1983). However, no quantitative relationship identifying the magnitude of impact to the reported equipment performance at a corresponding constituent concentration has been established for the above listed parameters. Thus, no definitive guidelines relating to these parameters have been provided in the ASCE Standard.

To provide some uniformity in source water quality, it was initially suggested that acceptable water for use in clean water equipment performance evaluations be defined as “drinking water quality” (ASCE Oxygen Transfer Standards Committee, 1983). On its face, the proposal seems plausible. After a more thorough review, the differences between drinking water standards in use by many public water suppliers and the difficulty involved in implementation, particularly for full-scale equipment testing, make such a proposal impractical for all but a limited range of facilities.
An alternative methodology for providing a uniform basis for comparison of reported equipment performance is the use of correlation factors to relate the source water quality used for the evaluation to that of a reference water. Correlation factors, such as $\alpha$ and $\beta$, are commonly used to estimate the aeration efficiency that may be expected in a wastewater of a specific characterization based on the reported clean water aeration efficiency of the aeration equipment. The absorption rate correlation factor, $\alpha$, is defined as:

$$\alpha = \frac{(K_L a)_{WW}}{(K_L a)_{RW}} \quad \text{(Eq. 12)}$$

where:

$$(K_L a)_{WW} = \text{Re-aeration rate for wastewater, (time)}^{-1}$$

$$(K_L a)_{RW} = \text{Re-aeration rate for reference water, (time)}^{-1}$$

Similarly, the dissolved oxygen saturation correlation factor, $\beta$, is defined as:

$$\beta = \frac{(C_s)_{WW}}{(C_s)_{RW}} \quad \text{(Eq. 13)}$$

where:

$$(C_s)_{WW} = \text{Dissolved oxygen saturation concentration for wastewater, (mass)/(length)}^3$$
\[(C_{S})_{RW} = \text{Dissolved oxygen saturation concentration for reference water, (mass)/(length)^3}\]

In typical application, \(\alpha\) and \(\beta\) correlation factors are referenced to tap water at the general location of the wastewater treatment facility to remove the physical and chemical composition of the base water as a factor in determining the correlation factors. To apply these factors in adjusting source water quality for clean water evaluations would suggest that the source water supply at the testing location would need to be compared with a reference water of consistent characterization regardless of location. One such reference is distilled water.

It should be noted that these correlation factors are difficult to determine with accuracy. Determination of the \(\alpha\) factor is influenced by many process conditions including variations in water quality, suspended solids concentration, scale, turbulence or mixing intensity, and type of aeration. Determination of the \(\beta\) factor is similarly influenced by both process conditions and external factors, including temperature, barometric pressure, dissolved organics, suspended solids, and dissolved solids. While reported values of \(\beta\) vary widely, the variation in observed results is less pronounced than the observed variation in values of \(\alpha\) (Stenstrom and Gilbert, 1981).
The most significant effect on the determination of $\alpha$ is the type of aeration equipment used in the test. Indeed, wide variations in values of $\alpha$ for a particular wastewater have been reported based upon the type of aeration equipment used. Whereas the critical aspect of diffused-air equipment is the bubble diameter, the critical aspect of mechanical aeration equipment appears to be the mixing intensity or turbulence created on the surface of the basin. Stenstrom and Gilbert (1981) also notes that several investigators reported significant impact to the determination of $\alpha$ due to scale-up effects when translating from laboratory-scale to field-scale diffused-air aeration equipment. While the impact due to scale-up effects was lessened when using mechanical surface aeration equipment, the scale-up effects were not removed entirely. Therefore, it is suggested that determination of $\alpha$ be conducted with equipment representative of that to be installed in the intended application.

As an alternate approach to the empirical determination of $\alpha$ factors, Stenstrom and Gilbert (1981) suggests that consideration be given to the methodology for evaluating aeration equipment performance used by the British. In their methodology, 5 mg/L of synthetic anionic surfactant is added to the testing volume to simulate the contaminants in wastewater that impact oxygen transfer and to minimize the influence of trace contaminants in tap water that might impact the reported oxygen transfer. Such an
approach would provide an estimation of the “dirty water” efficiency for the aeration equipment undergoing evaluation regardless of the source water quality. While this approach would certainly simplify application of aeration equipment performance to wastewater treatment processes, adaptation of the current performance evaluation protocol or establishment of a new evaluation protocol based on surfactant addition would require significant amounts of time to develop. Additionally, implementation would require adoption by the equipment manufacturers and could represent a significant burden to those manufacturers (Stenstrom and Gilbert, 1981).

The commonly accepted procedure for determination of $\beta$, the iodometric or Winkler analysis, is subject to interference from constituents within the source water, particularly oxidizing or reducing agents (American Public Health Association, 1998). While it would appear that $\beta$ could be determined using a membrane probe for measurement of dissolved oxygen concentration, several investigators have noted that the membrane probe directly measures the activity of molecular oxygen within the liquid, not the concentration (Stenstrom and Gilbert, 1981). Because the membrane probe employs a galvanic cell to measure the activity of molecular oxygen, which is then converted to a corresponding concentration, it is subject to interference relative to the salinity of the source water. In dilute solutions, the activity of molecular oxygen in solution is approximately unity, so the dissolved oxygen
activity measured by the membrane probe is equal to the concentration. However, in solutions with large salinity, the activity of molecular oxygen in solution is greater than unity, causing the dissolved oxygen activity measured by the membrane probe, without a mechanism to correct for salinity in the source water, to be greater than the true dissolved oxygen concentration in the source water (ASCE Oxygen Transfer Standards Committee, 1983). When the Winkler analysis is deemed invalid due to interference, the value of $\beta$ may be determined as the ratio of the source water’s calculated surface saturation concentration to the calculated surface saturation concentration of the reference water, where both concentration values have been adjusted for temperature, pressure, and total dissolved solids (TDS) concentration (American Society of Civil Engineers, 1993).

**Location of Dissolved Oxygen Measurement Points**

ANSI/ASCE 2-91 provides two methods for measurement of dissolved oxygen concentration in the testing volume: samples pumped to BOD bottles for evaluation by the Winkler method or membrane probe or in-situ measurement by membrane probe. With the significant advancements in instrumentation that have occurred in the past decade, the in-situ measurement of dissolved oxygen concentration using membrane probes has become more commonplace.
Regarding the location of measurement points within the testing volume, the *ASCE Standard* requires that:

“A minimum of four determination points shall be used. One should be at a shallow depth, one should be at a deep location, and one should be at middepth. The points should be at least two feet (0.6 m) from the walls, floor, and surface, and no closer to the surface than 10% of the minimum tank dimension.”

From this statement, one could reason that the absolute minimum depth for conducting an evaluation of oxygen transfer performance is four feet. At this testing depth, all measurement points would be at the same depth within the volume. To provide some level of vertical separation between the measurement locations, a more practical minimum would be between 5 and 6 feet. In practice, this depth constraint is of little concern when evaluating both diffused-air and most mechanical surface aeration equipment due to the operational characteristics of the equipment. Specifically, these units provide a significant vertical component to their area of influence during operation. Figures 4 and 5 illustrate the suggested measurement point locations for mechanical surface aeration equipment (*ASCE Oxygen Transfer Standards Committee, 1983*).
Figure 4

Dissolved Oxygen Measurement Locations – Vertical-Axis Surface Aerator

Figure 5

Dissolved Oxygen Measurement Locations – Vertical-Axis Surface Aerator with Draft Tube
However, the horizontal rotor mechanical surface aerator provides a limited depth of influence, predominantly involving the surface of the basin in its operation. Because of this operational characteristic, evaluating the operational performance of a horizontal rotor aerator in a basin with a depth comparable to that used for diffused-air or other mechanical surface aerator evaluations would likely result in an under-reporting of its overall performance. Further, constraining the surface geometry to provide a greater depth of influence may increase the surface mixing to a level where oxygen transfer due to secondary aeration becomes significant, a condition that would yield an artificially high reported operating performance.

It would, therefore, appear reasonable to adjust the constraints on dissolved oxygen measurement points when evaluating mechanical surface aeration equipment with a significant surface influence operational characteristic. However, adjustment of the boundary constraints must consider the basis behind the establishment of the constraints and the level of influence that may be expected due to any adjustment. In the developmental work leading to the initial oxygen transfer Standard, the two-foot minimum separation between oxygen measurement points and the walls and floors of the testing basin is provided as a suggestion without justification (ASCE Oxygen Transfer Standards Committee, 1983).
While no specific justification is presented, an understanding of various aeration devices offers a reasonable basis for the suggestion. Diffused-air aeration devices are typically installed along the floor of the reactor. The diffuser bodies are typically positioned on top of air distribution headers which, depending on configuration, places the diffuser bodies between 6 and 12 inches above the reactor floor. An additional level of separation between the diffuser body and measurement point mitigates the potential for fouling of the measurement probe or sample line by air bubbles as they emerge from the diffuser body.

Regarding the minimum separation between measurement point and testing basin walls, two factors must be considered. First is the “skin effect”, the frictional resistance exhibited as water moves along the boundary surface. Additionally, the boundaries present areas of energy dissipation and momentum change. Placement of a measurement point in close proximity to the boundaries could result in under-estimation in the reported performance.

Maintaining a sufficient separation between the basin water surface and dissolved oxygen measurement point must also be considered. The turbulence created at the surface, particularly when evaluating mechanical surface aeration equipment, is often sufficient to cause significant instability in observed oxygen concentrations. Additionally, this turbulence does lead to some level of secondary aeration, oxygen transfer not directly attributable to
the action of the aeration equipment, which would contribute to the aforementioned observed instability as well as lead to an artificially high estimation of equipment performance.

Another consideration for maintaining a sufficient separation between the basin water surface and dissolved oxygen measurement point is the oxygen transferred into the testing basin through surface diffusion. While surface diffusion does occur, recall that the limiting factor in the absorption of oxygen into the bulk liquid is the rate of diffusion across the liquid film, which is a very slow process. Thus, the rate of oxygen transfer into the basin due strictly to diffusion across the gas-liquid interface would be negligible in comparison to the rate of oxygen transfer into the bulk liquid due to the operational characteristics of the aeration equipment under evaluation.

An experiment was conducted to investigate the impact of adjusting the location of dissolved oxygen measurement points used to evaluate the operational performance of horizontal rotor mechanical surface aerators. This test considered only adjusting the vertical constraints, separation between the water surface and measurement point as well as separation between the basin floor and measurement point. To that end, five measurement points dispersed between three stations within the testing basin were used. The operating water depth in the testing basin for this
evaluation was set at 4.5 feet. Figure 6 illustrates the experimental configuration for this evaluation.

Figure 6
Dissolved Oxygen Measurement Location Evaluation – Experimental Setup

Stations 1 and 2 were positioned in the discharge stream of the aeration device while Station 3 was located in the return flow for the equipment. Station 1 was located approximately 34 feet downstream of the rotor centerline and 4 feet left of the discharge centerline. Station 2 was located approximately 20 feet downstream of the rotor centerline and approximately
in-line with the discharge centerline for the device. Figure 7, below, provides a clearer illustration of the positioning of Stations 1 and 2.

Figure 7

Dissolved Oxygen Measurement Location Evaluation – Stations 1 and 2

In developing the measurement location layout shown in the above figures, data from dissolved oxygen measurement points positioned at the various locations throughout the testing volume illustrated in Figure 3
during preliminary equipment performance evaluations were analyzed to define a series of locations for this evaluation that were representative of the volume. It was noted that results for comparable locations in both the discharge and return portions of the equipment flow profile through the basin yielded consistent estimates of equipment performance. Based on this finding, it was concluded that reliable estimates of equipment performance could be obtained by locating measurement points in the discharge channel and either of the two return flow channels within the testing basin.

During this evaluation, data were collected and analyzed to determine the rate of oxygen transfer, $K_{La}$, measured at each location. Pertinent information from the evaluation are detailed in Table 2 and illustrated in Figure 8.

Table 2
Results of Measurement Location Evaluation

<table>
<thead>
<tr>
<th>Measurement Location</th>
<th>Depth, ft.</th>
<th>$K_{La}$ @ 20°C, min$^{-1}$</th>
<th>Std. Deviation</th>
<th>% Std. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.50</td>
<td>0.0468</td>
<td>0.000996</td>
<td>2.41</td>
</tr>
<tr>
<td>2</td>
<td>1.50</td>
<td>0.0446</td>
<td>0.000746</td>
<td>1.89</td>
</tr>
<tr>
<td>3</td>
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<td>0.0515</td>
<td>0.00485</td>
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<td>0.0462</td>
<td>0.00117</td>
<td>2.87</td>
</tr>
<tr>
<td>5</td>
<td>1.50</td>
<td>0.0476</td>
<td>0.000311</td>
<td>0.738</td>
</tr>
</tbody>
</table>
Results of Measurement Location Evaluation

It is noted from the above plot that, for the two stations configured to collect data at measurement depths of 1.5 feet and 3.5 feet below the water surface, the resultant re-aeration rates are consistent between the measurement points at each depth. Additionally, the re-aeration rates determined for the two depths are comparable. Further, considering all measurement points in this evaluation, the re-aeration rates are reasonably consistent between all locations, as indicated by observing the general trend of the plotted results.
Although the re-aeration rate for data collected at Point 3 varies from the mean for this evaluation by about 9%, the value is considered to be consistent with the remaining measurement points due to the relatively large standard deviation observed in the regression of collected data for Point 3. The large standard deviation is likely due to location of the measurement point in somewhat close proximity to the discharge of the aeration equipment, as shown in Figure 7.

The consistency of the re-aeration rates from this evaluation suggests that the dissolved oxygen concentration measurements were not adversely affected due to their positioning in closer proximity to the physical boundaries than permitted by the ASCE Standard. This position is supported by the relatively small standard deviation observed in the measurements at Points 1, 2, 4, and 5, indicating no significant influence from an external source occurring during the evaluation.

Subsequent evaluations of horizontal rotor mechanical surface aeration equipment performance utilizing measurement points at the depths shown in Table 2 yielded results of similar consistency. Therefore, it would appear reasonable to consider minor adjustment of the boundary constraints for measurement point location when evaluating the performance of horizontal rotor aerators according to the protocol set forth in ANSI/ASCE 2-91. Consideration of such adjustment should include a review of collected
data illustrating the impact of the proposed adjustment on the reported operational performance of the aeration equipment being evaluated.

**Data Collection and Analysis**

Evaluation of aeration equipment performance involves the measurement and recording of dissolved oxygen concentrations and the corresponding point in time during the evaluation when that concentration was observed. The collected data are then analyzed to determine the rate of absorption or overall mass transfer coefficient, $KLa$, into the bulk volume achieved by the aeration equipment. While the analysis may be performed graphically, the characteristic plot of the collected data is curvilinear, making graphical determination difficult without some mathematical manipulation of the data. For data exhibiting such characteristics, determination of the parametric values using a numerical model to approximate the characteristic curve generated from the collected data is the preferred analysis technique.

The basic model used to describe the data collected during an unsteady-state, clean water oxygen transfer performance of both surface and submerged aeration devices is represented in differential form as:

$$\frac{dC}{dt} = K_La^* \left(C^*_w - C\right)$$

(Eq. 14)
where:

\[
\frac{dC}{dt} = \text{Rate of oxygen transfer, (mass)/((length)^3 (time))}
\]

\[
K_La = \text{overall mass transfer coefficient, (time)^{-1}}
\]

\[
C_\infty^* = \text{Equilibrium dissolved oxygen concentration, (mass)/(length)^3, and}
\]

\[
C = \text{Dissolved oxygen concentration at time, t, (mass)/(length)^3}
\]

Integrating Equation 14, and establishing the dissolved oxygen concentration at the initial time, \(t_0\), as \(C_0\), yields two additional forms of the basic model: the logarithmic form, illustrated in Equation 15, and the exponential form, illustrated in Equation 16.

\[
\ln\left(\frac{C_\infty^* - C}{C_\infty^* - C_0}\right) = -K_La^*(t - t_0) \quad \text{(Eq. 15)}
\]

\[
C = C_\infty^* - (C_\infty^* - C_0)e^{-K_La^*(t-t_0)} \quad \text{(Eq. 16)}
\]

where, for both equations above:

\[
C = \text{Dissolved oxygen concentration, (mass)/(length)^3}
\]

\[
C_\infty^* = \text{Equilibrium dissolved oxygen concentration, (mass)/(length)^3}
\]

\[
C_0 = \text{Dissolved oxygen concentration at time zero, (mass)/(length)^3}
\]

\[
K_La = \text{overall mass transfer coefficient, (time)^{-1}, and}
\]
While each of the above equations will produce a resultant oxygen transfer rate for a given set of data, the resultant oxygen transfer rates generated using a particular form of the model may differ significantly from that generated using another form of the same model. Further, no specific form of the model has yielded consistently reliable results for all data sets analyzed. As such, it is important to carefully consider the model form used when analyzing a specific data set as well as the behavior of the data set itself.

Analysis of a data set using the differential form of the model, Equation 14, would appear the most straightforward approach for determining the rate of oxygen transfer achieved by the aeration device undergoing evaluation. Indeed, this form is linear in $KLa$ and does not require the specification of a value for $C_\infty^*$ in order to perform the least-squares analysis (Brown and Baillod, 1982). However, inconsistencies during the experiment leading to “noise” in the data are magnified when using this form. The scatter produced is noticeable even when the data set contains little noise. When the data set contains significant inconsistencies, or is generally not well behaved, the scatter produced when using this form increases greatly. In contrast, use of a method based on the integrated form of this equation tends to reduce the influence of errors within the collected
data on the resultant estimates. Because of the magnification of error present within a data set and the lack of precision in estimating the overall mass transfer coefficient compared to other analytical methods, use of the differential form of the model for estimation of aeration equipment performance is generally not recommended (Brown and Baillod, 1982).

Analysis of the data set using the logarithmic form of the model, Equation 15, is commonly referred to as the log-deficit approach. As with the differential form, this approach is linear with respect to the overall mass transfer coefficient, allowing linear least squares techniques to be employed in parameter estimation. Unlike the differential form, this approach requires that the value of $C_\infty^*$ be provided to perform the least squares analysis. The value of $C_\infty^*$ used in the log-deficit approach may be based on field measurement, published value, or simple assumption (Brown and Baillod, 1982). However, selection of the “correct” value for $C_\infty^*$ is, perhaps, not as straightforward as simply referencing published tables of such values (Boyle et. al., 1974). Common practice has typically been to select an appropriate value from a published table and apply adjustments for temperature, pressure, and salinity. Care must be used when employing this technique as deviations between published tables have been observed, particularly within the acceptable temperature range for aeration equipment performance evaluations, $10^\circ$C to $30^\circ$C (Boyle et. al., 1974).
It is worth noting that selection of a particular value for $C_\infty^*$ will influence the resultant value for $K_{La}$ determined by the log-deficit approach. This bias is discussed by Boyle et. al. (1974), who observed that an increase in the selected value for $C_\infty^*$ corresponded to a decrease in the resultant value of $K_{La}$ for a specific data set analyzed by the log-deficit approach. Additionally, this approach typically requires truncation of data along the upper portion of the curve, near the saturation concentration, to avoid the possibility of negative deficits.

In the exponential method of data analysis, the exponential form of the model, Equation 16, is evaluated using non-linear regression techniques to simultaneously estimate the overall mass transfer coefficient, equilibrium dissolved oxygen concentration and initial dissolved oxygen concentration based simply on the data collected during an aeration equipment evaluation. The non-linear regression technique is similar to that used in the analysis of BOD data to estimate the exertion rate, $k$, and the ultimate biochemical oxygen demand, $L$. The most obvious advantage to this method is the limited opportunity for bias to be introduced in the analysis. This method employs the collected concentration data directly in the estimation of the parameters rather than first subjecting the data to mathematical manipulation or transformation. Further, analysis using this method does not require the truncation of data, necessary in the other methods presented, in order to
provide parameter estimates the resultant parameters. As a result, the
parameters tend to be estimated with greater precision than is afforded by
the other methods discussed.

The most notable drawback to the exponential method is that the non-
linear regression technique is an iterative process. Therefore, efficient
parameter estimation using this technique necessitates the use of a
computational aid to perform the repetitive calculations.

Although the exponential method is the preferred means of resultant
parameter estimation according to the ASCE Standard, no one method is
able to provide consistent, accurate parameter estimations for all data sets.
This is due to the structure of the error present in the data itself and the
impact of the analytical method employed on that error. If the data
contained error that was equally distributed among all observations, then the
non-linear technique, which weights all the data equally, would seem
appropriate. On the other hand, if the error associated with lower dissolved
oxygen concentrations were greater than the error associated with higher
dissolved oxygen concentrations, then some form of weighted regression
analysis, such as the log-deficit approach or one of its variations, would
provide a more accurate estimate of the parameters (Boyle et. al., 1974).

Both the exponential method and the “best fit” log-deficit method, a
variation of the log-deficit method presented above, included in the ASCE
Standard, require data to be collected over an extended period of time to provide accurate estimation of the saturation dissolved oxygen concentration in the test volume. When using the exponential method, the ASCE Standard requires data to be collected until all measurement points reach a dissolved oxygen concentration of 98% of the steady state concentration, corresponding to a time of approximately $4/K_{La}$. When using the “best fit” log-deficit method, the ASCE Standard requires collection of data until all measurement points reach a dissolved oxygen concentration of 99.7% of the steady state concentration, corresponding to a time of approximately $6/K_{La}$.

In addition to this maximum time, the time corresponding to a dissolved concentration equal to 67% of the steady state concentration, approximately $1/K_{La}$, and time zero are important as they represent the points where the sensitivities for the remaining parameter estimates are maximized.

A minimum of 10 to 15 data points should be collected in order to provide good precision in parameter estimation (Brown and Baillod, 1982). While a greater number of measurements may be recorded, significant improvement in the precision of parameter estimation was not observed when more than 20 data points were analyzed. About 67% of the data points should be collected during the time period between zero and the time to reach a dissolved oxygen concentration in the volume equivalent to about 86% of the steady state concentration, approximately $2/K_{La}$. The balance of the data
points should be collected in the time period between $2/K_{\text{La}}$ and $4/K_{\text{La}}$ or $6/K_{\text{La}}$, depending on the analysis method selected. When more than 20 data points will be collected during an aeration equipment performance evaluation, the *ASCE Standard* allows the data to be evenly distributed at approximately equivalent time intervals between the initial and final observed concentration. However, if this procedure is used, care must be taken to insure that the time interval is sufficiently small to accurately reflect the increase in dissolved oxygen concentration for equipment exhibiting a rapid rate of oxygen transfer.

As mentioned above, the critical time points in the evaluation process occur at times of zero, $1/K_{\text{La}}$, and $4/K_{\text{La}}$ or $6/K_{\text{La}}$. Of these points, the two parameters of greatest interest, $K_{\text{La}}$ and $C_\infty^*$, correspond to the latter two. The exact moment of time zero is difficult to identify while performing an evaluation. Additionally, lingering effects of the de-oxygenation process due to unequal distribution of chemicals tend to be exhibited in noticeable “noise” in initial collected data. This leads to consideration of data truncation to mitigate the impact of the “noise” on parameter estimation.

When considering truncation of data near the beginning of the evaluation, it is important to keep in mind the critical time points of the process needed for precise parameter estimation. Truncating data in close proximity to the critical time points would impact the precision of parameter
estimation. The Standard allows for truncation of data up to 20% of the steady state dissolved oxygen concentration where the plotted data exhibit the lingering effects of the de-oxygenation chemicals. Where these effects are observed at concentrations greater than 20% of the steady state dissolved oxygen concentration, the ASCE Standard permits truncation “up to a concentration equal to 1.5 times the concentration at the inflection point”, but not greater than 30% of the steady state concentration.
CHAPTER V

EXTERNAL ENVIRONMENTAL FACTORS

When evaluating the performance of aeration devices, much of the focus is centered on the transfer mechanisms achieved by the device itself. Little attention is paid to factors outside the direct operation of the aeration device, such as the environmental conditions at the site where the evaluation is being conducted, which may have the potential to impact the reported performance of the aeration device.

In the case of diffused-air devices using atmospheric air as its source of oxygen, these external factors may be of little concern. The infrastructure used in diffused-air systems do provide some modification of the air supply in the sense that the temperature, pressure, and moisture content are changed as the air moves from the inlet of the blower to the diffuser. Depending on the arrangement of that infrastructure, particularly the placement of supply piping, it is possible that the air passing through the diffuser would be reasonably consistent in temperature, pressure, and moisture content somewhat independent of the general atmospheric conditions at the facility.

On the other hand, mechanical surface aeration equipment offers no intermediate mechanism in its operation to provide adjustment to the
atmospheric air used in the aeration process. Rather, the liquid from the volume to be aerated is introduced directly to the atmosphere for oxygen absorption. Because of this, it would appear that the potential for atmospheric conditions to influence the performance of mechanical surface aeration equipment is greater than for diffused-air devices.

The Standard does not specifically consider atmospheric conditions, other than barometric pressure, in the evaluation of aeration devices. In fact, little information has been put forth regarding the influence of atmospheric conditions on the aeration process in general. Of the available information, investigations have typically focused on the influence of atmospheric phenomena with regard to the natural re-aeration process occurring in streams and estuaries. Extrapolating the findings of these investigations to the evaluation of mechanical surface aeration equipment would require consideration of the operating characteristics of the equipment and, arguably, would be of questionable value. However, considering the particular concepts presented, as they relate to the operation of mechanical surface aeration devices, may yield some level of insight into the influence of atmospheric conditions on the reported performance of mechanical surface aeration equipment.

There are three specific atmospheric conditions of interest in terms of their influence on reported equipment performance: air temperature,
barometric pressure, and moisture content. In addition to the potential influence exerted by each condition independently, it is also important to consider the potential influence resulting from interaction of the conditions.

The following tables summarize the meteorological conditions, water quality, and analytical results for equipment performance testing conducted on a horizontal rotor mechanical surface aerator over two successive days. While not collected with the specific intent of investigating the influence of atmospheric conditions on reported equipment performance, the data do provide a reasonable, if somewhat limited, basis for such a review as several factors that would otherwise be unconstrained are constrained for the summarized analysis. Specifically, a single aeration device was used for all tests during the evaluation period. Further, all requirements with regard to aeration device start-up and operation, dissolved oxygen measurement instrument placement and calibration, de-oxygenation protocol, and data collection and analysis were consistently applied for each testing session during the evaluation period.
Table 3

Reported Meteorological Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 3</td>
</tr>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td>Start</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>12</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Dew Point, °C</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Barometric Pressure, in. Hg.</td>
<td>30.07</td>
<td>30.07</td>
<td>30.02</td>
</tr>
</tbody>
</table>

Note: Meteorological observations recorded from Automated Weather Observation Station located at Golden Triangle Regional Airport, Columbus, Mississippi

Table 4

Testing Volume Water Quality

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 3</td>
</tr>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td>Start</td>
</tr>
<tr>
<td>pH, std. Units</td>
<td>8.46</td>
<td>8.33</td>
<td>8.33</td>
</tr>
<tr>
<td>Total Dissolved Solids, mg/L</td>
<td>302</td>
<td>448</td>
<td>448</td>
</tr>
<tr>
<td>Conductivity, µS/cm</td>
<td>353</td>
<td>550</td>
<td>550</td>
</tr>
</tbody>
</table>
### Table 5

Horizontal Rotor Aeration Equipment Evaluation Results Summary

<table>
<thead>
<tr>
<th>Meas. Loc.</th>
<th>Avg. Water Temp., °C</th>
<th>Cs, mg/L</th>
<th>C₀, mg/L</th>
<th>K&lt;sub&gt;La&lt;/sub&gt;, min&lt;sup&gt;-1&lt;/sup&gt;</th>
<th>Cs, mg/L</th>
<th>C₀, mg/L</th>
<th>K&lt;sub&gt;La&lt;/sub&gt;, min&lt;sup&gt;-1&lt;/sup&gt;</th>
<th>Percent Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non-Linear Regression Parameter Estimates</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avg.</td>
<td>14.46</td>
<td>10.10</td>
<td>-0.11</td>
<td>0.0408</td>
<td>0.0739</td>
<td>0.0837</td>
<td>0.000915</td>
<td>0.73</td>
</tr>
<tr>
<td><strong>Day 1, Test 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.50</td>
<td>9.83</td>
<td>0.22</td>
<td>0.0426</td>
<td>0.0412</td>
<td>0.0511</td>
<td>0.000619</td>
<td>0.42</td>
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<td>0.76</td>
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<td>0.1060</td>
<td>0.0493</td>
<td>0.000969</td>
<td>1.00</td>
</tr>
<tr>
<td>3</td>
<td>14.45</td>
<td>10.06</td>
<td>-0.79</td>
<td>0.0404</td>
<td>0.1500</td>
<td>0.2150</td>
<td>0.001970</td>
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</tr>
<tr>
<td>4</td>
<td>14.45</td>
<td>9.85</td>
<td>-0.27</td>
<td>0.0411</td>
<td>0.0396</td>
<td>0.0544</td>
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</tr>
<tr>
<td>5</td>
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<td>-0.49</td>
<td>0.0411</td>
<td>0.0327</td>
<td>0.0487</td>
<td>0.000450</td>
<td>0.32</td>
</tr>
<tr>
<td><strong>Day 2, Test 1</strong></td>
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<tr>
<td>1</td>
<td>14.00</td>
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<td>2</td>
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</tr>
<tr>
<td>4</td>
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<td>13.01</td>
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</tr>
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<td>0.0465</td>
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<td>0.0755</td>
<td>0.000665</td>
<td>0.49</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>14.25</td>
<td>11.21</td>
<td>0.63</td>
<td>0.0392</td>
<td>0.0941</td>
<td>0.0527</td>
<td>0.000850</td>
<td>0.84</td>
</tr>
<tr>
<td>2</td>
<td>14.15</td>
<td>11.54</td>
<td>-1.05</td>
<td>0.0413</td>
<td>0.3290</td>
<td>0.3180</td>
<td>0.003120</td>
<td>2.85</td>
</tr>
<tr>
<td>4</td>
<td>14.15</td>
<td>11.41</td>
<td>-0.40</td>
<td>0.0426</td>
<td>0.1090</td>
<td>0.0797</td>
<td>0.001050</td>
<td>0.95</td>
</tr>
<tr>
<td>5</td>
<td>14.25</td>
<td>11.14</td>
<td>-0.77</td>
<td>0.0444</td>
<td>0.0736</td>
<td>0.0646</td>
<td>0.000782</td>
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</tr>
<tr>
<td><strong>Day 2, Test 3</strong></td>
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<td></td>
<td></td>
</tr>
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<td>1</td>
<td>14.45</td>
<td>11.17</td>
<td>0.78</td>
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<td>0.1270</td>
<td>0.0738</td>
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<td>14.40</td>
<td>10.82</td>
<td>-2.46</td>
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<td>0.4000</td>
<td>0.003660</td>
<td>2.54</td>
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<tr>
<td>4</td>
<td>14.40</td>
<td>11.22</td>
<td>0.01</td>
<td>0.0436</td>
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<td>0.71</td>
</tr>
<tr>
<td>5</td>
<td>14.50</td>
<td>11.14</td>
<td>-0.14</td>
<td>0.0430</td>
<td>0.0499</td>
<td>0.0371</td>
<td>0.000511</td>
<td>0.45</td>
</tr>
<tr>
<td><strong>Avg.</strong></td>
<td><strong>14.44</strong></td>
<td><strong>11.09</strong></td>
<td><strong>-0.45</strong></td>
<td><strong>0.0444</strong></td>
<td><strong>0.1330</strong></td>
<td><strong>0.1420</strong></td>
<td><strong>0.001550</strong></td>
<td><strong>1.21</strong></td>
</tr>
</tbody>
</table>
While the anomalies present in the above analysis summary may be caused by any of several factors described in the *ASCE Standard*, acting independently or in concert, meteorological conditions at the test site should not be excluded from consideration as a possible source of the observed data inconsistency. For the evaluations summarized above, the visual meteorological conditions for the first day of testing may be described as overcast with noticeable moisture present near ground level for much of the day. On the second day of testing, it was observed to be sunny, with little moisture present in the air near ground level. These descriptions are supported somewhat by the recorded observations presented in Table 3. It should be noted that the reporting station used to collect meteorological data is located a significant distance from the test site, which could lead to inconsistencies between data reported by the monitoring station and visual observations at the test site. However, at the time these equipment evaluations were being performed, the monitoring station represented the most reliable, accurate, and readily accessible source of meteorological data.

**Influence of Air Temperature**

The relationship between water temperature and dissolved oxygen concentration is well known. A similar relationship exists between gas
temperature and molecular oxygen concentration. For the temperature differentials between the atmosphere and bulk liquid typically observed in aeration processes, a sufficient surplus of molecular oxygen would remain at the gas-liquid interface and the absorption process would continue to be limited by the rate of diffusion through the liquid film, a function of the temperature of the bulk liquid. Thus, it would appear that the air temperature would have little influence in the reported equipment performance. However, oxygen absorption is not the only aspect of the mechanical surface aeration process that may be influenced by air temperature.

Consideration should also be given to the influence due to heat exchange between the bulk liquid and bulk gas. In the majority of cases, a temperature differential exists between the liquid and the atmosphere above the liquid. As a portion of the bulk liquid is discretized and introduced into the atmosphere by the operation of a mechanical surface aerator, it is reasonable to anticipate that some level of thermal exchange would occur as the water droplets travel through the atmosphere above the bulk liquid. The level of exchange depends on the thermal differential between the water droplet and the atmosphere as well as the exposure time of the water droplet to the atmosphere. Such a change in the temperature of the water droplet would certainly impact the oxygen absorption process occurring for each
water droplet as well as the concentration of dissolved oxygen required to saturate the discretized volume. Figure 9, below, illustrates the relationship between observed equipment performance and air temperature recorded during the evaluations for the subject data of this discussion.

Figure 9

$K_{La}$ versus Recorded Air Temperature — Horizontal Rotor Aeration Equipment

$K_{La} = 0.0005T_{air} + 0.0345$
While it is reasonable to anticipate that the air temperature is influencing the reported performance of mechanical surface aeration equipment, the magnitude of that influence is not readily apparent. Reviewing the data presented in Tables 3 and 5, the recorded air and water
temperatures for the first day of testing show a temperature differential of approximately 2.5 degrees Celsius, with the air temperature lower than the bulk liquid temperature. For the second day, a similar comparison indicates a temperature differential ranging from approximately zero at the start of the first testing session to about 2.6 degrees Celsius during the third testing session, with the air temperature being higher than the bulk liquid temperature in all sessions. Considering this information, it would appear that the performance reported on the first day of testing would be greater than the performance reported on the second day of testing as the temperature of the water droplets would be lowered as they passed through the cooler temperature of the atmosphere, increasing the saturation dissolved oxygen capacity of the droplet. However, comparison of the first day’s estimated performance to the estimated performance of the second day, as illustrated in Figure 10, indicates this not to be the case.

An additional point of interest in the presented data is the progressive increase in temperature differential during the second day of testing. While this is an expected occurrence, as the density of water is greater than that of the atmosphere, it may be argued that some level of increase in bulk liquid temperature is a result of the operational characteristics of the mechanical aeration device. This would seem to indicate that some thermal exchange is occurring between the water droplets and atmosphere above the bulk liquid.
As the fraction of the bulk liquid exposed to the atmosphere and, thereby, available for thermal exchange with the atmosphere is very small when compared with the total operating volume of the basin, the magnitude of temperature increase within the bulk liquid as a result of thermal exchange would likely be minimal. However, the impact to the reported performance, based on the limited data set presented, is not clear.

**Influence of Barometric Pressure**

The barometric pressure observed during an aeration equipment evaluation also has the potential to influence the device’s reported performance. At pressures greater than standard atmospheric pressure, 760 mm of mercury, the concentration of dissolved oxygen required to saturate a unit volume is greater than the concentration required at standard atmospheric pressure. Because of this, and the fact that the reported equipment performance is a function of saturation dissolved oxygen concentration, the *ASCE Standard* requires that barometric pressure at the evaluation site be recorded during the performance evaluation. The site barometric pressure is used to determine the pressure correction factor, $\Omega$, needed to adjust the steady state dissolved oxygen concentration estimated through data analysis to standard conditions. It is important to note that the
barometric pressure is the only atmospheric condition required by the evaluation procedure defined in the *ASCE Standard*.

![KLa vs. Barometric Pressure](image)

Figure 11

*KLa* versus Barometric Pressure – Horizontal Rotor Aeration Equipment

It is interesting to note the trend of the data presented in the above figure. The data illustrated above contradict the accepted relationship
between dissolved oxygen and barometric pressure. As noted above, the concentration of dissolved oxygen required to saturate a given volume increases with increasing pressure applied to that volume. Therefore, it stands to reason that the rate of oxygen transfer would be similarly affected. However, Figure 11 suggests this is not the case. As mentioned previously, it is difficult to reach any firm conclusion based on the presented data due to the size of the data set and the lack of constraint with regard to other atmospheric parameters. Indeed, the data presented in Figure 11 are likely being influenced to such a degree by one or more parameters that the relationship between equipment performance and barometric pressure appears in the manner shown.

**Influence of Atmospheric Water Vapor**

The presence of water vapor in the atmosphere during the evaluation of mechanical surface aeration devices bears consideration with regard to its influence on the reported performance of mechanical surface aeration equipment. The standard atmosphere, under most conditions, contains some quantity of water vapor, or water in gaseous form. As with other gaseous components of the atmosphere, such as nitrogen and oxygen, the water vapor exists at some pressure, which is a proportional component of the total atmospheric pressure. As the quantity of water vapor in the atmosphere
increases, its pressure also increases. Because the total atmospheric pressure may not increase at the same rate, the increase in water vapor pressure correspondingly decreases the pressures of other gaseous components.

The quantity of water vapor present in the atmosphere is most commonly expressed in terms of relative humidity, $\phi$. Relative humidity is defined as the ratio of water vapor pressure at a given air temperature and pressure to the saturation water vapor pressure for the same air temperature and pressure. The relative humidity for a volume of atmosphere may be determined using the following equation (Rogers and Mayhew, 1967):

$$\phi = \frac{p_S}{p_G} \times 100\%$$  \hspace{1cm} (Eq. 17)

where:

- $\phi$ = Relative humidity
- $p_S$ = Partial pressure of water vapor, (mass)/(length)$^2$, and
- $p_G$ = Saturation partial pressure of water vapor, (mass)/(length)$^2$

The actual vapor pressure, $p_S$, may be calculated as a function of temperature according to the following simplified relationship (Brice, 2005):
\[ p_s = 6.11 \times 10^{\frac{7.5T_D}{237.7+T_D}} \]  
\text{(Eq. 18)}

where:

\[ p_s = \text{Partial pressure of water vapor, (mass)/(length)², and} \]

\[ T_D = \text{Dew point, °C} \]

Similarly, the saturation vapor pressure, \( p_G \), may be calculated according to the following simplified relationship (Brice, 2005):

\[ p_G = 6.11 \times 10^{\frac{7.5T}{237.7+T}} \]  
\text{(Eq. 19)}

where:

\[ p_G = \text{Saturation partial pressure of water vapor, (mass)/(length)², and} \]

\[ T = \text{Air temperature, °C} \]

Using the above equations, the relative humidity may be estimated using the air temperature and dew point recorded for the evaluations noted previously. The following table summarizes the relative humidity for each evaluation.
Table 6
Relative Humidity During Equipment Evaluation

<table>
<thead>
<tr>
<th>Day 1</th>
<th></th>
<th>Day 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Test 1</td>
<td></td>
<td>Test 1</td>
<td></td>
</tr>
<tr>
<td>Start</td>
<td>12</td>
<td>Start</td>
<td>14</td>
</tr>
<tr>
<td>End</td>
<td>12</td>
<td>End</td>
<td>16</td>
</tr>
<tr>
<td>Test 2</td>
<td></td>
<td>Test 3</td>
<td></td>
</tr>
<tr>
<td>Start</td>
<td>16</td>
<td>Start</td>
<td>17</td>
</tr>
<tr>
<td>End</td>
<td>17</td>
<td>End</td>
<td>17</td>
</tr>
<tr>
<td>Test 3</td>
<td></td>
<td>Test 3</td>
<td></td>
</tr>
<tr>
<td>Start</td>
<td>17</td>
<td>Start</td>
<td>17</td>
</tr>
<tr>
<td>End</td>
<td>17</td>
<td>End</td>
<td>17</td>
</tr>
</tbody>
</table>

| Temperature, °C | 12 | 14 | 16 | 17 |
| Dew Point, °C   | 6 | 6 | 6 | 7 |
| Relative Humidity, % | 67 | 59 | 55 | 52 |

The relative humidity values tabulated above correspond well to the visual meteorological observations observed at the testing site. Figure 12 illustrates the correlation between relative humidity and observed equipment performance for the subject evaluations of this discussion.
In discussing the influence of rainfall on the natural re-aeration process of streams, Pareek (1978) hypothesized that increases in relative humidity may result in a decreased rate of absorption due to a reduction of the oxygen tension in the atmosphere. As noted earlier, an increase in the water vapor pressure, signified by an increase in the relative humidity,
results in a corresponding decrease in the pressure of other gaseous components of the atmosphere. Since the concentration of a gas is a function of its partial pressure, a decrease in the partial pressure of gaseous components, such as oxygen, in the atmosphere translates to a decrease in the concentration of that component in the atmosphere. Additionally, the density of the atmosphere decreases with increasing humidity levels, as the molecular weight of water is less than the molecular weight of other gaseous components. Considering the calculated values of relative humidity for each testing session in relation to the estimated performance recorded for the testing session, as illustrated in Figure 10, it appears that the level of water vapor present in the atmosphere might have some influence in the reported equipment performance.

While the relative humidity provides a convenient means for general comparison, the absolute, or specific, humidity quantifies the actual water vapor present in the atmosphere, allowing for determination of any influence on the reported performance of aeration equipment due strictly to the amount of water vapor present at the time of equipment evaluation. To determine the absolute humidity present for given environmental conditions, the water vapor is treated as an ideal gas. From this, the ideal gas law may be applied to both the water vapor and air, yielding the following relationship (Rogers and Mayhew, 1967):
\[ \omega = \frac{R_A p_S}{R_S p_A} \]  
(Eq. 20)

where:

\[ \omega = \text{Absolute humidity, mass of water vapor/mass of dry air} \]
\[ R_A = \text{Ideal gas constant for dry air, 0.2871 kJ/kg*K} \]
\[ p_S = \text{Partial pressure of water vapor, mass/(length)}^2 \]
\[ R_S = \text{Ideal gas constant for water vapor, 0.4619 kJ/kg*K} \]
\[ p_A = \text{Partial pressure of dry air, mass/(length)}^2 \]

The partial pressure of dry air, \( p_A \), may be determined by subtracting the partial pressure of water vapor, \( p_S \), from the total barometric pressure, \( P_B \), recorded during the evaluation. Thus, Equation 20 may be reduced to:

\[ \omega = 0.622 \frac{p_S}{P_B - p_S} \]  
(Eq. 21)

where:

\[ P_B = \text{Barometric Pressure, mass/(length)}^2 \]

Table 7 notes the absolute humidity corresponding to each recording of barometric pressure for the subject evaluations of this discussion.
Table 7

Absolute Humidity During Equipment Evaluation

<table>
<thead>
<tr>
<th></th>
<th>Day 1</th>
<th>Day 2</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Test 1</td>
<td>Test 1</td>
<td>Test 2</td>
<td>Test 2</td>
<td>Test 3</td>
<td>Test 3</td>
</tr>
<tr>
<td></td>
<td>Start</td>
<td>End</td>
<td>Start</td>
<td>End</td>
<td>Start</td>
<td>End</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>12</td>
<td>12</td>
<td>14</td>
<td>16</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>Dew Point, °C</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Barometric Pressure, in. Hg</td>
<td>30.07</td>
<td>30.07</td>
<td>30.02</td>
<td>30.00</td>
<td>30.00</td>
<td>29.96</td>
</tr>
<tr>
<td>Absolute Humidity, (kg)_vapor/(kg)_dry air</td>
<td>0.0057</td>
<td>0.0057</td>
<td>0.0057</td>
<td>0.0062</td>
<td>0.0062</td>
<td>0.0062</td>
</tr>
</tbody>
</table>

Figure 13 illustrates the correlation between absolute humidity and observed equipment performance for the subject evaluations of this discussion.
In contrast to the indications presented in Figure 12, which compares reported equipment performance to the observed relative humidity, the data presented in Figure 11 appears to suggest that the reported equipment performance increases with corresponding increases in water vapor within the atmosphere. This would indicate that the equipment performance might
not necessarily depend on the quantity of water vapor present in the atmosphere, but on the degree of saturation in the atmosphere with respect to water vapor.

No estimate of the level of influence on equipment performance resulting from the presence of water vapor in the atmosphere may be obtained from the above data, as it is not sufficiently large and is not adequately constrained with regard to other atmospheric parameters. However, it may be generally stated that, as the degree of saturation of water vapor in the atmosphere increases, the observed performance of mechanical surface aeration devices decreases by some amount.

The observed influence of atmospheric conditions on the operational performance of mechanical surface aeration equipment is important for several reasons. Most notably, it highlights a potential source of error when reporting the operational performance of mechanical surface aeration equipment. While this error may be of lesser magnitude than other experimental or analytical sources, it should not be discounted.

The influence of atmospheric conditions also hinders the reproducibility and, ultimately, the reliability of reported performance. With such an importance placed on the reported oxygen transfer performance of mechanical surface aeration equipment by project engineers when designing
wastewater treatment facilities, the need for reliable and reproducible equipment performance data from manufacturers is required.
CHAPTER VI

RECOMMENDATIONS AND CONCLUSION

Though both diffused-air and mechanical surface equipment introduce oxygen into the bulk liquid, the mechanisms implemented by each equipment type to achieve this goal are vastly different. The Standard for Measurement of Oxygen Transfer in Clean Water, adopted by the American Society of Civil Engineers in 1991, was developed as a consensus standard, defining a uniform procedure for the evaluation of both diffused-air and mechanical surface aeration equipment. The ASCE Standard offers specific guidance for certain aspects of the evaluation process such as de-oxygenation methodology, data collection, power or gas flow measurement, and data analysis. However, aspects of the evaluation process, such as basin geometry, mixing requirements, source water quality, and the influence of external environmental factors, are not offered similar guidance in the ASCE Standard.

While evaluating the performance of horizontal rotor mechanical surface aerators, several inconsistencies were noted in the reported performance that could not be directly linked to any physical change in the
equipment or procedural oversight in the evaluation process. These inconsistencies led to a review of the evaluation procedure employed to measure the performance of horizontal rotor aeration devices against the ASCE Standard with the objective of identifying those areas of the procedure that might contribute to the observed inconsistencies. Several specific areas that have the potential to influence the reported performance were identified and explored in detail, using data collected from performance evaluations conducted on a modification of the typical horizontal rotor aerator design. These include the basin geometry and volume employed in the evaluation process; aspects of the testing protocol including source water quality, location of dissolved oxygen measurement, and data collection and analysis; and external environmental conditions at the time of the evaluation.

Several investigators have noted that basin geometry and volume used in the evaluation of mechanical surface aeration devices does impact the reported performance of those devices. These observations were confirmed to some degree through review of data collected while evaluating the performance of a modified configuration of the typical horizontal rotor aeration device. Because of these findings, it is recommended that the topics relating basin geometry and volume to equipment performance listed below be evaluated further.
• Development of guidelines for defining the basin geometry to be used for clean water aeration equipment performance evaluations as representative of the intended field application and favorable to the operational characteristics of the aeration device being evaluated

• Development of guidelines for specifying the volume to be used for clean water aeration equipment performance testing based on the generally accepted mixing requirements (power per unit volume) for completely mixed hydraulic regimes, and

• Development of guidelines for specifying the volume to be used for clean water aeration equipment performance testing based on the circulation, or turnover, period, defined as the theoretical time required for a unit volume of liquid to circulate completely through the testing volume

These recommendations would serve to provide results of equipment performance evaluations that are representative of the practical operating conditions experienced by the equipment in field applications. They may be applied to the evaluation of both pilot-scale and field-scale equipment, although the latter of these recommendations would likely be more applicable to field-scale equipment because of the need for a reasonably accurate estimate of discharge rate from the aeration device.
Similarly, source water quality and location of dissolved oxygen measurement points within the testing volume also have the potential to influence the reported performance of aeration equipment. Accurate quantification of influence on reported horizontal rotor aeration device performance due to source water quality was difficult to obtain, yet it is believed that constituents within the source water used for evaluation may influence the reported equipment performance. Additionally, identification of valid dissolved oxygen measurement points for use in equipment evaluation requires that the interaction of the equipment operational characteristics and basin geometry and volume be considered in order to accurately represent the equipment’s performance. To consider these factors, the recommendations noted below should be evaluated further.

- Development of guidelines for a single standard source water quality to be used for clean water testing of aeration equipment performance
- Investigation of the feasibility to implement the British methodology for aeration equipment performance testing as a mechanism to address differences in source water quality, and
- Development of guidelines for location of dissolved oxygen measurement points that consider the operational characteristics of the aeration equipment being evaluated, specifically when the guidelines currently implemented in the ASCE Standard would not
present an accurate representation of the operational characteristics of the aeration equipment undergoing evaluation.

Source water quality varies greatly from location to location, depending on the nature of the source water and the processes implemented to achieve a potable product. This fact, coupled with the difficulty in obtaining accurate estimates for the characterization parameters $\alpha$ and $\beta$, emphasize the need for a single standard for source water quality to mitigate the potential influence to the reported performance of aeration devices as a result of constituents present in the source water.

Finally, the influence of external environmental factors on the reported performance of mechanical surface aeration devices is, perhaps, the least understood of all potential sources of influence. Testing conducted on a production horizontal rotor aerator over two successive days showed some level of influence is possible, however isolation of the specific conditions responsible for the observed influence are not possible due to the limited size of the data pool and the lack of adequate constraint on the various parameters during the testing. Thus, additional study is recommended on the following topics:

- Investigating the magnitude of influence on the reported performance due to the air temperature of the atmosphere above the bulk liquid.
• Investigating the magnitude of influence on the reported performance due to the presence of water vapor in the atmosphere above the bulk liquid, both in terms of quantity and degree of saturation, and

• Developing guidelines for evaluation of mechanical surface aeration equipment that consider the influence of atmospheric conditions on the reported performance

Both air temperature and water vapor, or humidity, are not directly considered within the *ASCE Standard*. Yet, these parameters appear to exhibit at least some effect on the reported performance of mechanical surface aeration equipment due to the operational characteristics of mechanical aeration devices. At a minimum, the site environmental conditions should be reported with the corresponding equipment performance. If no comprehensive means of correcting the observed equipment performance to account for all external environmental factors were able to be implemented, an operating range of atmospheric conditions suitable for conducting aeration equipment evaluations could be developed in a manner similar to the range of water temperatures currently specified in the *ASCE Standard*.

From these findings, it may be concluded that the objective of this initial investigation has been achieved. While no specific recommendations are generated from this investigation, several areas have been identified as
possible sources of error in achieving a consistent, reliable, and reproducible estimate of performance for both horizontal rotor aeration equipment and mechanical surface aeration equipment in general.

The ASCE Standard is a sound basis for the evaluation of aeration equipment performance. As a consensus standard covering the evaluation of diffused-air and mechanical surface devices, it is simply not practical to address all possible operating conditions for all types of equipment since doing so would likely result in an overly complex or, possibly, incomprehensible evaluation protocol. Thus, it is important to understand not only the procedural requirements of the ASCE Standard, but also the individual operational characteristics of the specific aeration device undergoing evaluation as well as the interaction of that device with the evaluation environment when quantifying equipment performance. Only by considering all possible influences with regard to estimation of aeration equipment operational performance will the goal of providing consistent, reliable, and, above all, reproducible performance estimates be achieved.
REFERENCES


