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# REVIEW PAPER

# EFFECTS OF ALPHA, BETA AND THETA FACTOR UPON THE DESIGN, SPECIFICATION AND OPERATION OF AERATION SYSTEMS

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## INTRODUCTION

Aeration is an essential part of almost all wastewater treatment systems and is usually the major energy-consuming process. With the increasing cost of energy, there has been a resurgence of interest in aeration system design, specification, and operation. This increased interest is evidenced through a number of recent papers discussing general procedures and methods for aerations system evaluation, parameter estimation, and testing. A second factor which has created renewed interest in aeration systems is the lack of uniform, standardized testing and specification procedures.

The U.S. Environmental Protection Agency and the American Society of Civil Engineers have jointly sponsored the development of a manual of practice for aerator testing and specification. A committee of interested manufacturers, consultants, aeration system users, and academics was set up to determine state-of-the-art methods, and to define areas for future research and development. The committee has worked for approximately three years to ascertain state-of-the-art methods and has produced reports describing aspects of aeration system design, specification and testing.

It is the purpose of this review paper to describe the findings of the subcommittee on alpha, beta, and theta factors. No discussion of general procedures will be made, and the reader is directed to recent general reviews and discussions of testing procedures by Bingel (1979), Boon (1980), Boyle (1979), Kayser (1979), Sweeris (1979), and Wheatland & Boon (1979), among others. Undoubtedly, other reports and papers will describe the committee's findings with respect to other areas. It is hoped that this paper will provide a summary and review of all the relevant literature regarding alpha, beta, and theta factors.

## PRELIMINARY REMARKS AND PARAMETER DEFINITIONS

Many factors influence oxygen transfer mechanisms in wastewater treatment processes. Wastewater contaminants, temperature, dissolved oxygen concentration (driving force), type of aeration device, turbulence, and basin geometry all affect oxygen transfer rate. Since these factors make field application of an aeration device unique, it has become standard practice to specify aeration equipment at "standard conditions," and to develop additional techniques for adjusting rates at standard conditions to rates at field conditions.

Standard conditions in the United States are considered to be 20°C, 760 mm Hg barometric pressure, tap water, and zero dissolved oxygen concentration. In Europe, standard conditions are slightly different and 10°C is the standard temperature. Additionally, in the United Kingdom, a surfactant (commercial detergent) is used to change the properties of tap water to more closely approach the properties of wastewater, and to mask the effects of trace contaminants in tap water.

Field oxygen transfer rates are calculated from standard transfer rates through the use of alpha ($\alpha$), beta ($\beta$), and theta ($\theta$) factors. The factors are defined as follows:

$$K_La_{ww} = \alpha\, K_La_{TP} \quad (1)$$

$$C^*_{\infty_{ww}} = \beta\, C^*_{\infty_{TP}} \quad (2)$$

$$K_La(T) = K_La_{20}\, \theta^{T-20} \quad (3)$$

where

$K_La$ = volumetric mass transfer coefficient ($T^{-1}$)
$C^*_\infty$ = saturation dissolved oxygen concentration (mg l$^{-1}$),
ww = subscript indicating wastewater
TP = subscript indicating tap water
$T$ = temperature (°C)
$K_La(T)$ = $K_L$ at temperature $T$
$K_La_{20}$ = $K_L$ at 20°C.

Field oxygen transfer rates (OTR) can be easily calculated from standard oxygen transfer rate, as follows:

$$OTR = \alpha\left(\frac{\beta C^*_{\infty_{TP}} - C_L}{C^*_{\infty_{20}}}\right)\theta^{T-20}\,SOTR \qquad (4)$$

where

$C_L$ = desired value of dissolved oxygen concentration under normal operation

SOTR = oxygen transfer rate at standard conditions

The importance of properly determining the alpha, beta and theta factors cannot be overestimated. For example, a field transfer rate is only 52% of the standard transfer rate when $C_L = 2$, $\alpha = 0.8$, $\beta = 0.9$, $T = 18°$, when $\theta = 1.024$. Drastic over or under-designed aeration systems can result if inaccurate correction factors are used. Figure 1 shows a profile of errors in oxygen transfer rate for incorrect alpha and beta factors.

It is difficult to accurately determine alpha, beta and theta parameters especially alpha factors. It is not unusual for two individuals to measure very different factor values for a given wastewater. In addition, manufacturers and engineers have developed different methods for measurement, which result in differences in design and specification of aeration facilities.

## ALPHA FACTOR

There are several technical problems associated with measuring the alpha factor and Gilbert (1979) has recently discussed these difficulties. The alpha factor varies with many process conditions including wastewater quality, intensity of mixing or turbulence, suspended solids concentration, method of aeration, scale, and other factors. The effect of aeration methods is particularly important with respect to the alpha factor. It is not unusual to observe vastly different factors using two different aeration methods for the same wastewater. It is worthwhile to document this claim from a historical perspective.

One of the first references to the dependence of the alpha factor upon aeration devices was made by Kessener & Ribbius (1935). Kessener and Ribbius noted changes in oxygen transfer rate for two different methods of aeration using tap water and sterilized sewage. They reported concentration versus time data, which can be used to calculate apparent mass transfer coefficients and alpha factors, as shown in Table 1.

It is obvious from the results shown in Table 1 that the alpha factor is quite different for the two aeration systems. Kessener and Ribbius did not attempt to explain the reasons for the large difference in alpha factors, but indicated that such differences should be included in the aerator specifications.

### *Alpha factors for various aeration systems*

The effect of aeration methods on alpha was demonstrated by Holroyd & Parker (1952) using

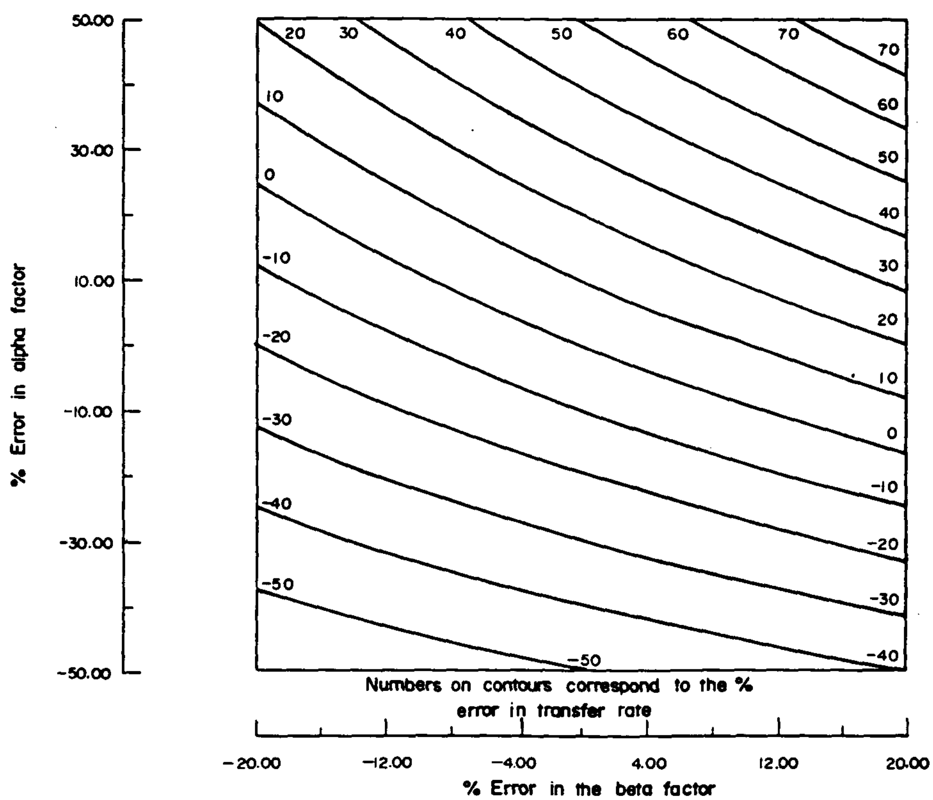


Fig. 1. Errors in oxygen transfer rate as a function of errors in measurement of alpha and beta factors, when alpha = 0.8 and beta = 0.9.

Table 1. Apparent mass transfer coefficients and alpha factors for the data of Kessener & Ribbius*

| Method of aeration (1) | Liquid (2) | $K_L'a$ or $K_La$† ($min^{-1}$) (3) | $\alpha$ or $\alpha'$ (4) |
|---|---|---|---|
| Kessener Brush | Tap water | 0.057 | NA |
| Kessener Brush | Sterilized sewage | 0.047 | 0.82 |
| Compressed Air | Tap water | 0.068 | NA |
| Compressed Air | Sterilized sewage | 0.013 | 0.20 |

* Page 57, Fig. 5, Kessener & Ribbius (1935).
† See notes later on apparent vs "true" $K_La$.

laboratory scale devices. They used a mixture of tap water and several types of surfactants to show that diffused aeration was affected by water contaminants differently than mechanical surface aeration. They found that the alpha factor of a fine bubble diffuser (0.28 cm mean bubble diam.) could be as low as 0.5 in the presence of high surfactant concentrations (20–100 mg $l^{-1}$). The same surfactant concentrations reduced the alpha factor of a 30 cm diameter disc surface aerator to only 0.8. Moreover, the different methods of aeration showed different reductions in the alpha factor with different types of surfactants (i.e. types, and cationic versus anionic).

Baars (1955) has reported the effects of surfactants on fine bubble (approx. 0.25 cm mean diam.). He found that commonly used anionic and non-ionic surfactants at 4 to 10 mg $l^{-1}$ concentration produced an alpha factor reanging from 0.9 to 0.4, respectively. The addition of anti-foaming agents reduced the alpha factor range from 0.8 to 0.35. Baars also tested the Kessener brush aerator under similar conditions, finding that the alpha factor increased, ranging from 1.0 to approx. 2.0 for high surfactant concentrations. The addition of anti-foaming agents tended to reduce the maximum alpha factors. Results similar to Baars and Holroyd and Parker's, for fine bubble diffusers have been reported by a number of investigators, including Lynch & Sawyer (1959), Eckenfelder *et al.* (1956), Downing & Scragg (1958), Burgess & Wood (1959), O'Connor (1963), Aiba & Toda (1963) as well as many others.

The results of Barnhart (1969) shown in Fig. 2, are particularly noteworthy because they show the importance of bubble diameter. Barnhart reports that the addition of surfactants reduces the bubble diameter until the critical micelle concentration is reached. Beyond the critical micelle concentration very little reduction in bubble diameter occurs. Reduction in bubble diameter produces two distinct results: an increase in surface are per unit bubble volume, and a decrease in terminal rise velocity. The decrease in terminal rise velocity results in longer bubble retention time, but reduces surface renewal rate. The total of all mechanisms on alpha (reduction of film transfer coefficient, increase in surface area and retention time, reduction in surface renewal) have been estimated by Barnhart's work for fine bubble diffusers and confirms the findings of field investigators, such as Kessener & Ribbius (1935) who first observed low alpha factors. Barnhart's results are also supported by the work of Motarjemi & Jameson (1979).

The recent increases in energy costs have generated new interest in aeration efficiency and fine bubble aeration systems are being reevaluated. Kiiskinen (1979) has examined the efficiency of seven types of diffusers in clean water, and cites evidence to show that the alpha factors for fine bubble systems range from 0.4 to 0.5. Houck (1980) has presented the results of a survey of 19 plants using fine bubble diffusers, and tabulates process efficiencies, as well as operating experience with fouling and plugging problems, along with mitigating and maintenance techniques. Houck also raises the question of bubble coalescence on fine

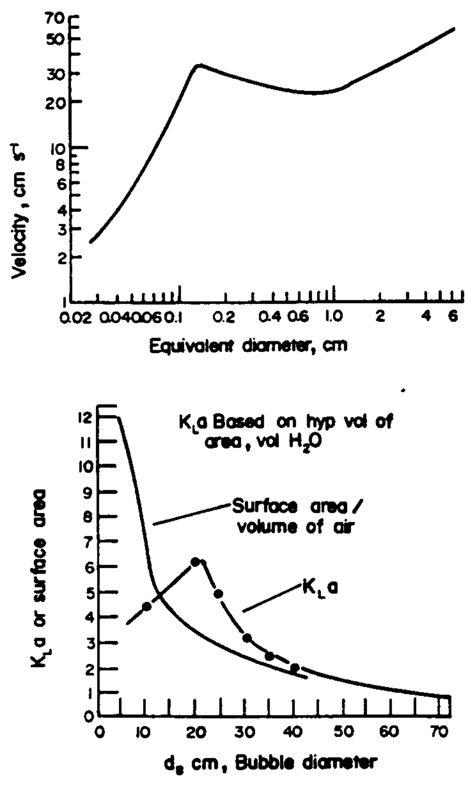


Fig. 2. Effect of bubble size on mass transfer (after Barnhart, 1966).

bubble diffusers due to biological growths on the liquid side of the diffusers. Comparison of process transfer rates reported by Houck. and clean water rates reported elsewhere supports the findings of others with respect to low alpha factors.

The effects of surfactants on alpha have been investigated for various types of surface aerators. Downing *et al.* (1960) investigated alpha factors for the Searle aerator (a modified brush type aerator) and a Simplex Cone aerator (vertically rotating low speed surface aerator with draft tube). The alpha factor was approx. 2.0 for the Searle aerator in the presence of $10\,mg\,l^{-1}$ ABS. For the Simplex Cone aerator, they concluded that an increase in oxygen transfer rate of 10–15% could be expected with surfactant addition, which corresponds to an alpha factor of 1.1–1.15. They also report that anti-foaming agents reduced the alpha factor. Similar results have been reported by Eckenfelder & Ford (1968) and von der Emde (1968).

*Mechanism and effects of surfactants on alpha factors*

The mechanisms of surfactant interference have been investigated by Mancy & Okun (1960), McKeown & Okun (1963), and Mancy & Barlage (1968), among others. Mancy & Barlage (1968) have shown that the effects of surfactants on aeration can be divided into two categories: the effect of the adsorbed surfactant film which increases the resistance to transfer; and changes in hydrodynamic behavior of the air–liquid interface, which results from changes in surface tension produced by the surfactant. Included in this second category are changes in bubble dynamics and shape, and reductions in surface renewal caused by the presence of the adsorbed surfactants. They used three experimental designs in their investigation: a 50 cm bubble column, surface aerator, and a laminar jet orifice. Using the laminar jet aerator, they were able to observe the effects of surfactants on the molecular diffusion coefficient independently of changes in bubble characteristics. They were able to show that the hydrodynamic conditions, which are in large part created by the intensity of mixing, power input, and unique characteristics of each aeration device, will greatly affect oxygen transfer rate. Their results, which have been supported by Mueller (1976) and others, explain why different types of aeration devices are affected differently by surfactants.

The work of Mancy & Barlage (1968) also shows that the rate of surfactant adsorption (a function of the type of surfactant) to the gas–liquid interface will also affect oxygen transfer. Their results give a partial theoretical basis for the observations of many other investigators. This phenomenon can be characterized by dynamic surface tension measurements. The commonly accepted du Nouy ring method for measuring surface tension indicates static surface tension and does not measure dynamic surface tension, and among these are the "ripple" method described by Mancy & Barlage (1968), and rate of bubble formation methods.

*Variance in alpha factor*

The alpha factor also changes substantially with wastewater characteristics. For example, Bass & Shell (1977) report alpha factors fluctuations for 0.5–1.0 for various wastewaters and Eckenfelder (1959) has reported the alpha factor for an industrial wastewater to vary between 0.3 and 0.8. The variance in alpha factor can largely be attributed to the changing characteristics of the raw wastewater with time of day or day of week. To demonstrate this time varying nature of the alpha factor, the results of an investigation by Katz (1967) are reported in Table 2. The data shown in Table 2 represent the results of a 3-month comprehensive study of oxygen transfer rates at the Jones Island Treatment Plant in Milwaukee, Wisconsin. The $K_La$ values shown in the table were measured by off-gass analysis in two-pass aeration tanks approx. 15 ft deep by 45 ft wide by 370 ft long, equipped with fine bubble diffusers. It is not possible to calculate alpha factors, since the clean water or tap water transfer rate is not known; however, a "transfer factor" has been calculated which represents the ratio of the daily measured transfer rate to the mean value of all measured rates. The transfer factor ranges from a minimum of 0.66 to a maximum of 1.39. If the maximum observed transfer rate is approximately equal to the clean water transfer rate, then the range of observed alpha factors can be estimated as 0.47–1.0. The magnitude of this range is conclusive evidence for the need to characterize the variance of the alpha factor due to wastewater characteristics changing with time of day and day of week.

Table 2. Variation in oxygen transfer rate at the Jones Island treatment plant (after Katz, 1967)

| Date | $K_La$ (days$^{-1}$) | Transfer factor* |
|---|---|---|
| 6/18/64 | 59.6 | 0.66 |
| 6/24/64 | 87.8 | 0.97 |
| 6/26/64 | 84.0 | 0.93 |
| 7/08/64 | 125.7 | 1.39 |
| 7/16/64 | 102.4 | 1.13 |
| 7/22/64 | 122.5 | 1.36 |
| 7/24/64 | 97.1 | 1.08 |
| 7/28/64 | 76.3 | 0.85 |
| 7/29/64 | 68.9 | 0.76 |
| 7/30/64 | 91.0 | 1.01 |
| 8/05/64 | 103.2 | 1.13 |
| 8/06/64 | 91.0 | 1.01 |
| 8/12/64 | 70.0 | 0.78 |
| 8/13/64 | 96.4 | 1.07 |
| 8/14/64 | 94.8 | 1.05 |
| 8/20/64 | 78.6 | 0.87 |
| 8/21/64 | 93.2 | 1.03 |
| 8/26/64 | 84.7 | 0.94 |
| 8/27/64 | 98.6 | 1.09 |
| 9/02/64 | 76.3 | 0.85 |
| | Mean = 90.1, Variance = 273 | |

* Transfer factor is the ratio of the observed transfer rate to the mean transfer rate.

Kalinske (1968) and Pfeffer *et al.* (1968) report that the alpha factor also varies with degree of treatment and with location of sampling point in activated sludge aeration basins. Generally, the alpha factor is lowest for the influent wastewater, and increases to maximum for the effluent wastewater, although Marotte (1978) has occasionally observed an opposite trend. Wheatland & Boon (1979) have reported data showing the change in alpha factor with increasing levels of treatment, for fine bubble diffuser aeration systems. They related the alpha factor change to total oxygen consumed during treatment, finding an alpha factor ranging from approx. 0.3–0.4 for 100 mg $O_2$ absorbed to 0.7–0.8 for 300 mg $O_2$ absorbed. Their findings have particular significance for the "plug flow" type aeration systems, where one would expect the greatest spatial variability in alpha factors. Moreover, the use of tapered aeration amplifies this effect, since a simple arithmetic average of alpha factor may not accurately reflect the true average.

Suspended solids concentration has also been reported to affect alpha. Downing (1960) reported on the range of suspended solids from 0 to 3000 mg $l^{-1}$ and found that alpha decreased with increasing solids concentration. Holroyd & Parker (1952) observed no change in alpha with additions of benetonite. It is not clear whether the solids themselves affect alpha, or if the effect is produced by organics associated with the solids. The oxygen uptake rate of biological suspended solids, and the error associated with measuring it, may affect alpha factor determinations.

Turbulence has a very strong affect on alpha factors. Stenstrom & Hwang (1979) have shown that a range of alpha factors can be measured for a specific wastewater (tap water containing synthetic detergent), depending upon the level of turbulence, as indicated by power input per unit volume. For example, in laboratory-scale vessels, (75–750 l.) alpha factors ranging from 0.6 to 1.2 were measured using a surface aerator. The alpha factor increased with increasing turbulence. Similar effects were reported for turbine aerators. Eckenfelder & Ford (1968) have noted similar effects, and proposed intuitive mechanisms to explain this phenomenon.

As indicated previously, the alpha factor is strongly affected by the generic type of aeration device. There is convincing evidence to indicate that alpha factors for fine bubble diffusers are lower than alpha factors for coarse bubble diffusers, and mechanical aerators. Table 3 is a summary of alpha factors reported in the literature by different investigators for different generic devices. The methods of measuring alpha factors, as well as the types of wastewater being tested, are not necessarily consistent for all the data reported in Table 3. This table is included to show the historical evidence of the effects of different aeration

Table 3. Alpha factors observed by different investigators for different aeration devices

| Aeration device | Alpha factor | Comments | Reference |
|---|---|---|---|
| Fine bubble diffuser | 0.4–0.6 | 5–25' tank depths 10–30 SCFM 1000 $ft^{-3}$ (tap water containing detergent) | Lister & Boon (1973) |
| Fine bubble diffuser | 0.4–0.9 | 50 cm Lab Scale Device, containing varying quantities of detergents | Baars (1955) |
| Fine bubble diffuser | 0.3–0.8 | Full scale activated study plant, alpha factor increasing with increasing levels of treatment | Wheatland & Boon (1979) |
| Fine bubble diffuser | 0.4–0.5 | Full scale activated sludge plant, measured using radioactive tracer techniques | Kiiskinen (1979) |
| Brush | 1.0–2.0 | Tap water containing detergents, at high power densities, using full scale devices | Baars (1955) |
| Brush | 0.8 | Calculated from their data (domestic wastewater) | Kessener & Ribbius (1935) |
| Coarse bubble diffuser, sparger | 0.7–0.8 | 10' tank depth, 80–190 SCFM 1000 $ft^{-3}$ 87,000 gal tank | Gilbert (1979) |
| Coarse bubble diffuser, wide band | 0.65–0.75 | 22.5' tank depth 25–92 SCFM 1000 $ft^{-3}$ (tap water with detergent) | Schmit *et al.* (1978) |
| Static aerator | 1.0–1.1 | 10' tank depth 10–180 SCFM 1000 $ft^{-3}$ 87,000 gal tank (tap water with detergent) | Otoski (1978), Otoski *et al.* (1978) |
| Surface aerators | 0.6–1.2 | Alpha factor tends to increase with increasing power (tap water containing detergent and small amounts of activated sludge) | Downing *et al.* (1960) |
| Turbine aerators | 0.6–1.2 | Alpha factor tends to increase with increasing power, 25, 50, 190 gal tanks (tap water containing detergent) | Hwang (1979) |

**The summary of alpha factors reported in this table is intended to illustrate the historical trends observed by previous investigators. The alpha factors reported here should not be used for design purposes, nor should they be used in lieu of testing.**

devices and not to provide a "standard alpha factor" for each device type.

## STATE OF THE ART FOR ALPHA FACTOR TESTING

From the previous discussion and literature review, it can be concluded that alpha factor testing is at best an inexact science. Furthermore, it is the opinion of a number of researchers, including Kayser (1979), and Zlokarnik (1979b), that alpha factors simply cannot be measured reliably on small scale lab devices. Undoubtedly, they are correct with respect to many of the results reported in the literature. The summary reported hereafter draws heavily upon the work of the ASCE oxygen transfer group (see acknowledgements). Also the findings of other workers, including Barnhart (1966), Bass & Shell (1977), Gilbert (1979), Mueller (1976), and Stukenberg *et al.* (1977), are incorporated into this summary.

General conditions for alpha factor testing should resemble the conditions for the proposed full system as closely as possible. Ideally, the alpha factor should only include effects of water or wastewater contaminants; however, in practice, alpha factors include many process-related phenomena, such as the effects of scale-up. A goal of proper alpha factor testing is to eliminate all spurious phenomena in order to make alpha factors dependent only upon wastewater characteristics.

### *Generic types of aeration devices*

It appears that the most profound process-effect on alpha factor resting is the generic type of device used for testing. It should be expected that one type of device, such as a diffuser, will have a different alpha factor than a surface aeration device. This difference, as shown previously, is caused by the different hydrodynamic properties of each aeration device. Alpha testing should be performed with generic devices identical to those proposed for the full scale installation. For diffuser systems, the bubble diameter is the most critical characteristic of the device. For surface aerators, the level of turbulence appears to be the most important characteristic. As shown later, there is no universally accepted indicator of turbulence for aeration systems.

### *Time varying nature*

It has been shown that the alpha factor can vary dramatically over a period of days and weeks, due to the constantly changing characteristics of the influent wastewater. Therefore, one should expect to design aeration systems to accommodate a range of alpha factors, and not a single value.

### *Scale-up*

The scale-up of test equipment seems to dramatically affect the determination of alpha factors. Using small scale laboratory equipment, it is easy to test using high levels of turbulence, or power input per unit volume. In general, these conditions will not be representative of full scale conditions.

The general question of scale-up procedures has been addressed by Ellis & Stanbury (1980), Horvath (1966, 1979), Schmidtke & Horvath (1977), Harremoes (1979), and Zlokarnik (1979b). They have shown that scale-up for certain devices, such as surface aerators, can be performed with acceptable precision and accuracy; however, none have addressed the problem of scale-up with reduced or changing surface tension, or reduced or changing molecular diffusivity of oxygen. Before the effects of scale-up can be eliminated from alpha factor testing, it is necessary to develop scale-up methodologies which incorporate changing surface tension, and reduced or changing molecular diffusivity of oxygen.

Another scale-up problem which must be overcome before diffused aeration devices can be properly scaled, is the influence of changing oxygen transfer mechanisms in a rising bubble plume. There exist three distinct transfer "regions" for diffused aerators. These are the region of bubble formation, where surface renewal and transfer are very high; region of rising bubbles, where reduced transfer rates occur, and the surface region, where the surface "boil" produces transfer. In a small laboratory device, the distribution among the three regions may be quite different than with a full scale device. Several investigators, including Morgan & Bewtra (1960), Aiba *et al.* (1963), Ippen & Carver (1954), and others have demonstrated the effects of depth in oxygen transfer. Their work should be consulted for further details.

Several investigators have proposed the concept of performing alpha factor testing under conditions of "equivalent $K_La$". With the proposed full scale deivce, this procedure has not been shown to be of value, in that very different levels of turbulence of physical characteristics may be necessary to obtain the equivalent $K_L$ a value. For example, in testing with diffused aeration devices at small scale, equivalent $K_La$'s might only be obtained with different relative contributions and transfer from the bubble formation, bubble rise, and surface boil regions of transfer.

### *Sample location*

Ideally, alpha factor testing should be performed using the actual fluids to be aerated. For activated sludge plants, this means that the mixed liquor, containing the biologically active suspended solids, should be used for testing. This may create problems if the treatment plant has not been built, or if it is not possible to accurately measure the oxygen uptake rate of the biological solids. In general, the influent wastewater is a poor substitute for mixed-liquor, and will generally produce lower alpha factors, although occasionally, the opposite effects have been noted.

Special problems exist for "plug flow" type aeration systems, especially those with tapered aeration. Wheatland & Boon (1979) have presented evidence to indicate that alpha factors, for certain specific conditions, may change from as low as 0.3 at the influent end of an aeration tank to as high as 0.8 at the effluent end.

Wastewater samples change quite rapidly after they are removed from a treatment system, and at present, methods to preserve samples for subsequent testing have not been demonstrated.

The trace contaminants in the tap water can also create problems. For example, Naimie & Burns (1977) have presented evidence indicating that the differences in tap water for various American cities may significantly affect oxygen transfer rates and testing. The British have found similar problems, and use a detergent to mask the effects of trace contaminants.

*Experimental procedures*

Experimental procedures and experimental equipment have been discussed and demonstrated by Bass & Shell (1977), Stukenberg *et al.* (1977), and Stenstrom & Hwang (1979). None of these discussions are conclusive. Special attention must be given to experimental procedures, especially such mundane procedures as tank cleaning. It has been demonstrated that the effects of lingering contaminants can drastically affect clean water results. Also, it has been shown that the power consumed by small, lab scale mixers can change with the addition of surfactants to test liquids; therefore, some type of device to measure power consumption as well as mixer RPM is needed.

*Function of alpha factor testing*

Alpha factor testing can be performed for design purposes, or for the purpose of performance testing. Restrictions for performance testing can often be relaxed since only a single value of the alpha factor is needed, representative only of the value at the time of testing. Therefore, the use of the endogenous zone of bacterial growth can be used for performance testing, but not necessarily for design purposes.

*Bubble coalescence*

Bubble coalescence can strongly affect alpha factors. Most wastewater treatment systems operate with coalescing fluid properties; however, with addition of high concentrations of salt, the fluid properties can be changed to non-coalescence. Under these conditions the alpha factors can be many times greater, and Zlokarnik (1979b) has provided an analysis of these effects.

## APPARENT MASS TRANSFER COEFFICIENTS

In measuring mass transfer coefficients using the commonly accepted non-steady state methods, one obtains only an approximation of the true mass transfer coefficient. This approximation occurs due to the gas side oxygen depletion of rising bubbles. For transfer systems with low efficiency, or with surface aeration systems, the difference between the true mass transfer coefficient ($K_L a$), and the apparent transfer coefficient ($K_L a$) is not great and perhaps insignificant. For high transfer efficiency systems, especially deep tank systems, this difference can be large. Downing & Boon (1963), Oldshue (1956), and Baillod (1979a) discuss this phenomena, and how to calculate correction factors to obtain "true" mass transfer coefficients from apparent coefficients.

Gas side oxygen depletion affects alpha factors in a way that is analogous to its effect on transfer coefficients. The magnitude of the effects are usually small, and much less than the experimental error associated with alpha factor testing. However, Baillod & Brown (1980) have developed procedures for correction, and their work should be consulted for further details.

## ALPHA FACTOR TESTING: AN ALTERNATE APPROACH

The previous discussion has shown that it is extremely difficult to determine meaningful alpha factors. An alternate approach has been suggested which should be considered. The British have developed a different set of conditions for specifying aeration equipment. They add $5\ mg\ l^{-1}$ of a synthetic anionic surfactant to test waters in order to simulate the contaminants in wastewater which affect oxygen transfer, and to minimize the effects of trace contaminants in tap water which affect oxygen transfer. Using this test procedure, they contend that more meaningful standard aeration rates are measured, which places less dependence on alpha factor testing. This concept can be advanced by defining $\bar{\alpha}$ (alpha bar) for all types of aeration equipment.

This proposal has several advantages and disadvantages. The primary disadvantage is the length of time required to develop the new standard. Undoubtedly, many years work could be required before all manufacturers could change testing procedures to accommodate surfactants. Additionally, more complex shop testing procedure place an additional burden upon manufacturers, especially small manufacturers. Nevertheless, developing such a standard could result in reduction of design error caused by improper alpha factor testing. This reduction could result because the magnitude of measured alpha factors would be much closer to unity, due to the inclusion of the major effects of surface tension in the manufacturer's specifications, through the alpha bar factor. A new concept of defining the alpha factor could be used, based upon British practice as follows:

$$\bar{\alpha} = \frac{K_L a_{ww}}{K_L a_{TP+S}} \quad (5)$$

where

$K_L a_{ww}$ = mass transfer coefficient in wastewater

$K_L a_{TP+S}$ = mass transfer coefficient in tap water with a surfactant added.

There are problems in defining a proposed standard for "alpha bar." Ideally, the quantity of surfactant used should reduce the tap water surface tension to less than 40 dynes $cm^{-1}$, but potential problems using such a procedure exist. The surface tension and surfactant concentration can change during aeration, which has been reported by Ewing *et al.* (1979), among others. Surface tension measuring equipment is expensive and not easily transported. Also, this approach does not specifically address the problem of alpha factor dependence upon turbulence and mixing intensity.

Many years of successful British practice is a sigficant incentive to develop detergent testing practice in the U.S. Detergent testing procedures are also being evaluated in Germany and other European countries. Development of detergent testing procedures in the United States should receive priority for development.

## BETA FACTOR

The beta factor, $\beta$, has been defined as the ratio of the saturation dissolved oxygen concentration in clean water, or tap water, as follows:

$$\beta = \frac{C^*_{\infty_{ww}}}{C^*_{\infty_{TP}}}. \quad (6)$$

An accurate value of saturation dissolved oxygen concentration is required to accurately estimate the oxygen transfer capability of an aeration device. Unfortunately, the saturation value of dissolved oxygen is affected by a large number of variables and process conditions, including barometric pressure, temperature, suspended solids, dissolved organics, and dissolved solids. Many wastewaters contain sufficiently high dissolved solids to significantly reduce the saturation dissolved oxygen concentration.

The beta factor has been found to vary over a broad range, although variations are generally less than those reported for the alpha factor. Eckenfelder *et al.* (1956) have reported that the beta factor for domestic wastewater is generally about 0.95 and that it can vary over a much broader range for industrial wastewaters. For example, they measured the beta factor for pulp mill wastes using the Winkler test and found it varied from 0.77 to 0.97.

Technical problems exist with measuring beta factors. The most common wet chemical analysis for dissolved oxygen, the Winkler Analysis (as specified by APHA, 1975) is subject to interferences which can make the test ineffective for some types of wastewater. Interferences have been reported by Kalinske *et al.* (1973), and Marotte (1978), among others. Marotte has found that the amount of manganous sulfate added to the sample for analysis changes the measured value of DO concentration. He has hypothesized that organic matter in the wastewater chelates metal ions, such as manganese or cobalt, which reduces their activity in solution and changes results.

It has been proposed that the DO probe be used to determine beta values. This alternative is attractive since the galvanic cell in a DO probe is isolated from the wastewater constituents which interfere with the Winkler test. Unfortunately, the DO probe cannot be used to measure beta factors since the probe responds to the activity of molecular oxygen, and not concentration. This phenomena has been discussed extensively by Carritt and Kanwisher (1959), Mancy and Westgarth (1962), Mancy *et al.* (1962), and McKeown *et al.* (1967).

An alternative method for measuring beta factors, which has been proposed by Bass & Shell (1977), among others, is to use an analytical correction factor, based upon total dissolved solids concentration. Using this technique, a wastewater must be measured for total dissolved solids (TDS) before the beta values can be determined. Once the total dissolved solids are known, and corrections are made for barometric pressure and temperature, the beta factor can be calculated.

A number of popular dissolved oxygen meters have special calibration scales to compensate for salt concentration. Usually, the calibration scales are associated with the temperature correction potentiometer on the DO meter. The need for temperature compensation arises from the dependence of membrane's permeability on temperature. It can be readily observed that a change in membrane permeability also produces a change in cell current. Therefore, a manufacturer can design a DO analyzer which corrects for temperature as well as activity (indicated by salt concentration) using only one control. The mechanism of calibration can be explained from an analysis of electrochemical theory. The steady state current of a galvanic cell oxygen analyzer can be computed as follows:

$$i = nFa \frac{P_m}{b} A \quad (7)$$

where

$i$ = current (amperes)
$n$ = number of electrons transferred in cell reaction
F = Faraday = $9.649 \times 10^4$ ($C\,mol^{-1}$)
$P_m$ = permeability coefficient ($cm^2\,s^{-1}$)
$b$ = membrane thickness (cm)
$a$ = area of electrode ($cm^2$)
A = activity of dissolved oxygen [g mol $(1000\,cm^3)^{-1}$.

The equation can be written in terms of concentration, as follows:

$$i = nFa \frac{P_m}{b} \gamma C \quad (8)$$

where

$\gamma$ = activity coefficient
C = dissolved oxygen concentration.

In a dilute solution, the concentration is nearly equal to the activity, and the activity coefficient has the value of unity. In concentrated salt solutions, the activity coefficient is greater than unity, indicating that the activity of the dissolved oxygen is greater than concentration.

## STATE OF THE ART FOR BETA FACTOR DETERMINATION

The beta factor can be measured using the Winkler test method if it can be demonstrated that no interferences exist. In the event that chemical interferences exist, the beta factor should be calculated from a total dissolved solids measurement. Since the beta factor can vary with wastewater quality, a series of tests must be performed to obtain a range of beta factors. This range must be included in an overall systems design and risk assessment, as indicated for the alpha factor.

## THETA FACTOR

Temperature strongly affects aeration systems in a variety of ways. Perhaps the greatest effect is on saturation dissolved oxygen concentration, which is well documented. The effects of saturation concentration are not included in the theta factor since they can be handled in the field transfer equations.

The theta factor has normally been used to relate mass transfer coefficients as shown in the following equations:

$$K_L a(T) = K_L a(20°)\, \theta_G^{T-20°} \tag{9}$$

or

$$K_L a(T) = K_L a(20°) + \theta_A \cdot (T - 20) \tag{10}$$

where

$K_L a(T)$ = mass transfer coefficient at temperature = $T$
$K_L a(20°)$ = mass transfer coefficient at temperature = 20°C
$\theta_G$ = geometric temperature correction coefficient
$\theta_A$ = arithmetic temperature correction coefficient
$T$ = temperature, degrees Celsius.

The geometric technique, equation (9), is more commonly used. This technique of correcting for the effects of temperature on oxygen transfer is empirical and attempts to lump all possible factors, such as changes in viscosity, surface tension, diffusivity of oxygen, etc. This empirical approach has produced a great variety of correction factors. Some investigators report that the geometric model gives better correction; others report that an arithmetic model is preferred. Table 4 lists a brief summary of the literature showing the range of temperature correction factors reported. Howe (1977) has found a decreasing relationship between temperature, but Brown & Stenstrom (1980) have shown that his conclusions cannot be supported statistically.

The wide diversity of results reported in Table 4 points to the inadequacy of the simple temperature correction technique of equations (9) or (10). Undoubtedly, the range of thetas could be refined if a closer evaluation of the experimental conditions was made; however, a number of the investigations reported in Table 4 were made under very precise experimental conditions and must reflect a correct re-

Table 4. Temperature correction factors

| Temperature correction coefficient (1) | Aeration system (2) | Model type* (3) | Reference (4) |
|---|---|---|---|
| 1.047 | Open channel | G | Streeter *et al.* (1936) |
| 1.024 | Stirred tank | G | Elmore & West (1961) |
| 1.020 | Stirred tank | G | Downing & Truesdale (1955) |
| 1.024 | Stirred tank | G | Downing & Truesdale (1955) |
| 1.016 | Stirred tank | G | Downing & Truesdale (1955) |
| 1.016 | Stirred tank | G | Downing & Truesdale (1955) |
| 1.018 | Channel | G | Streeter (1926) |
| 1.015 | Channel | G | Truesdale & Van Dyke (1958) |
| 1.008 | Channel | G | Truesdale & Van Dyke (1958) |
| 1.0192 | Saran tubes and spargers | | Bewtra *et al.* (1970) |
| 1.020 | Diffused | G | Barnhart *et al.* (1969) |
| 1.02 | — | G | Clark *et al.* (1977) |
| 1.024 | — | G | Metcalf & Eddy (1972) |
| 1.028 | Surface aerators | G | Eckenfelder (1966) |
| 1.02 | Turbine and diffused | G | Eckenfelder (1966) |
| 1.047 | Surface | G | Lakin & Salzman (1977) |
| 0.0284 | — | A | Ward *et al.* (1972) |
| 0.0204 | Stirred tank | A | Downing & Truesdale (1955) |
| 0.015 | — | A | Truesdale & Van Dyke (1958) |

* G = geometric; A = arithmetic.

lation between $K_La$ and temperature. The unavoidable conclusion from the results shown in Table 4 is that presently used temperature correction techniques are inadequate.

Alternate methods for correcting temperature effects have been proposed by Metzger (1968) and Hunter (1979). Metzger has shown that the effect of temperature is related to the value of $K_La$ and has recommended correction factors as a function of $K_La$. This result is an implication of the temperature dependence of $K_La$ upon turbulence as well as oxygen diffusivity. Hunter has used a similar approach in relating the value of $K_La$ to temporal mean velocity gradient, defined as follows:

$$G = \left(\frac{P/V}{\mu}\right)^{1/2} \qquad (11)$$

where

$P$ = power input
$V$ = volume
$\mu$ = absolute viscosity.

This approach accounts for the effects of temperature on liquid viscosity and turbulence.

From a theoretical standpoint, the approach of Metzger (1968) or Hunter (1979) is preferable; however, based upon present knowledge, it is not possible to include such a technique in a design standard. It has been shown that different aeration systems can have different characteristics in the presence of surfactants, and it is plausible that each type of aeration system has a different correction factor, based upon temperature and turbulence. Therefore, more research and development is required before a temperature correction technique based upon turbulence can be used.

From the previous discussion, it can be concluded that no single temperature correction technique can be applied to all methods of aeration. Also, it is apparent that the effect of temperature on $K_La$ results from changes in oxygen diffusivity in addition to other factors such as turbulence.

Figure 3 shows the error which can result from using incorrect theta factors using a geometric correction technique. It is observed that the deviation from unity increases rapidly as the range of temperature correction increases. It is obvious that the single most effective method for minimizing correction error is to avoid testing during extremes of high or low water temperature. For example, using a theta factor of 1.032 instead of 1.024 with 20°C as standard temperature, the oxygen transfer at 30°C rate will be overestimated by over 10%.

### STATE OF THE ART FOR THETA FACTOR DETERMINATION

There is no consensus for a temperature correction factor. The results of a review of the literature indicate that geometric temperature correction factors can range from 1.008 to 1.047, and that some aeration systems have mass transfer coefficients which are linearly related to temperature (as opposed to the geometric relation). Furthermore, it has been shown that the temperature correction factor is dependent upon turbulence.

It appears that a theta factor of 1.024 should be used unless it is known that a different geometric theta factor is more suitable. Consultants and manufacturers who use theta factors other than 1.024 should be prepared to support their position with substantial data. It is also recommended that temperature corrections greater than 10°C be avoided if possible; however, it is recognized that temperature corrections greater than 10°C may sometimes be necessary.

### FUTURE EMPHASIS AND RESEARCH NEEDS

There are many uncertainties which surround the alpha, beta, and theta factors. This review has pointed out many of the uncertainties and should be used to

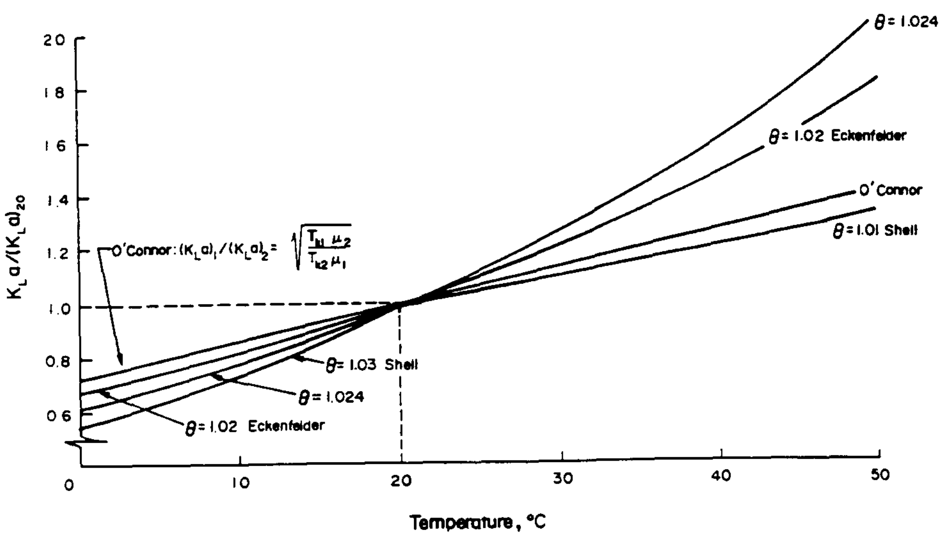


Fig. 3. The effect of theta value on temperature correction (after Gilbert, 1979).

define research needs. Two very high priorities are the needs for better models to explain the effects of turbulence on both the alpha and theta factors. Also, a fundamental analysis of the effects of scale-up to account for changing surface tension and oxygen diffusivity is needed.

It is hoped that manufacturers will assume a position of leadership in the establishment of alpha bar factors ($\bar{\alpha}$) by running shop tests with detergent spiked tap water. A better understanding will undoubtedly result if such information is developed and published.

There are specific research needs which should be addressed. Among these are:

1. Development of bench scale alpha testing equipment which can be scaled up to accurately predict alpha factors for full scale equipment.

2. A comprehensive evaluation of the trace contaminants in tap water, for various locations in the U.S. and elsewhere, should be made. It is necessary to determine the magnitude of the effects of these contaminants on oxygen transfer, and their significance on alpha testing.

3. Portable analytical equipment for measuring such parameters as surface tension, bubble size, and mixer horsepower should be developed. The successful development and use of such equipment will reduce the variability of alpha testing.

4. Detergent testing should be performed to determine its suitability as a standard procedure in the U.S.

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