Dissolved Gas Infusion

WHITE PAPER

Validation Testing of the Fuel Tech, Inc. Dissolved Gas Infusion DGI® Technology

JULY 2022

Oxygen Transfer Efficiency in Clean Water

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EXECUTIVE SUMMARY

The Fuel Tech DGI® system has undergone rigorous testing to assess the transfer efficiency of oxygen dissolved within the DGI process to a receiving water tank. This report describes the testing protocol, results and uncertainty analysis that validate the oxygen transfer performance of the DGI system in clean water. Aeration and oxygenation technologies are validated for oxygen transfer efficiency to the treatment reservoir via standardized testing, typically the "Measurement of Oxygen Transfer In Clean Water" standard published by American Society of Civil Engineers (ASCE) and its Environmental & Waters Resources Institute (EWRI). This standard is suitable for testing oxygen transfer efficiency of aeration and oxygenation technologies that rely on gas transfer from bubbles to the receiving water.

The DGI system pre-dissolves oxygen for delivery into the receiving water directly and so 100% oxygen transfer efficiency would be expected as its oxygen-laden effluent is mixed into a receiving body of water. However, due to the high rate of dissolved oxygen introduction and the depressurization of the DGI effluent upon injection into the receiving water, bubble generation can be a secondary outcome. It was thus both necessary and desirable to validate that any bubbles so formed are reabsorbed in the receiving water and not lost to the water's surface. A modified version of the ASCE/EWRI method was conceived to test the DGI system and endorsed by two industry experts to validate the technology's oxygen transfer efficiency.

The results prove that any oxygen bubbling out of solution during injection by the DGI system is not lost, but is instead reabsorbed by the receiving water volume before loss to the surface exposed to the atmosphere can occur. Within the accuracy of instrumentation used for the testing, essentially 100% of the injected oxygen remains available.

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INTRODUCTION

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INTRODUCTION

Aeration of natural waters and wastewaters is essential to the biological and chemical processes that convert contaminants to safe by-products and sustain the environment. Aeration refers to the introduction of air, primarily a mixture of approximately 79% nitrogen and 21% oxygen, into the body of water. However, as the end goal of aeration is to increase the dissolved oxygen in the water to make it available for biological and chemical processes, the nitrogen concentration in the air is a significant limit to the rate at which aeration can provide dissolved oxygen.

Other limits to the rate at which aeration can provide dissolved oxygen are introduced when the aeration technology relies on in situ air bubbles for transferring oxygen to the water. The rate of oxygen transfer from the gas bubbles into dissolved oxygen molecules in the water is dependent on the total surface area of the bubbles in contact with the water and the residence time of the bubbles in the water. The residence time in turn depends on the rise rate of the bubbles, as once they rise to the water's surface their oxygen is lost.

The DGI® Dissolved Gas Infusion system was developed to significantly increase the rate at which dissolved oxygen can be introduced into a water treatment process. The system uses a combination of technologies and scientific principles to accomplish its performance. First, the DGI system uses a slip stream of the water to be treated and pre-dissolves high purity oxygen into the slip stream. By using high purity oxygen, the DGI system eliminates the inefficiency of co-dissolving nitrogen with the oxygen. As such, the DGI system is referred to as an oxygenation technology as opposed to an aeration technology.

Next, the DGI system uses the scientific principle of Henry's Law to achieve higher concentrations of dissolved oxygen in the slip stream. Henry's Law states that the amount of gas that can be dissolved in a liquid is proportional to the pressure of that gas at the transfer surface.

The DGI system pressurizes both the high purity oxygen and the slip stream as necessary to achieve the oxygenation goals of the application, up to 300 psi.

Finally, the DGI system includes unique technology for injecting the pressurized and oxygenated slip stream back into the receiving body of water. As the receiving body of water is at a lower pressure, the DGI effluent must be introduced in a way that either rapidly distributes the oxygenated water to minimize dissolved oxygen coming out of solution or that produces bubbles of sufficiently small size to minimize oxygen loss via rise rate to the water surface. The DGI injection system includes multiple zones of injection as needed to optimize distribution and dispersion of the dissolved oxygen as well as unique channel injectors to minimize bubble size should they form. The injected water passes through a series of bifurcating channels in the injectors as it depressurizes, controlling bubble formation and size distribution.

Figure 1 illustrates the DGI system process. Water from the body being treated is drawn into the DGI system via pumps and is pressurized to the desired operating pressure. The pressurized water and pressurized oxygen are introduced into the DGI saturator, which is a patent-pending high efficiency device optimized for energy efficiency and infusion efficiency. Infusion efficiency in excess of 95% is routinely achieved. The oxygen-laden water then exits the saturator and flows to the zoned injection array and multiple patent-pending bifurcating channel injectors.

DGI® TECHNOLOGY AT-A-GLANCE

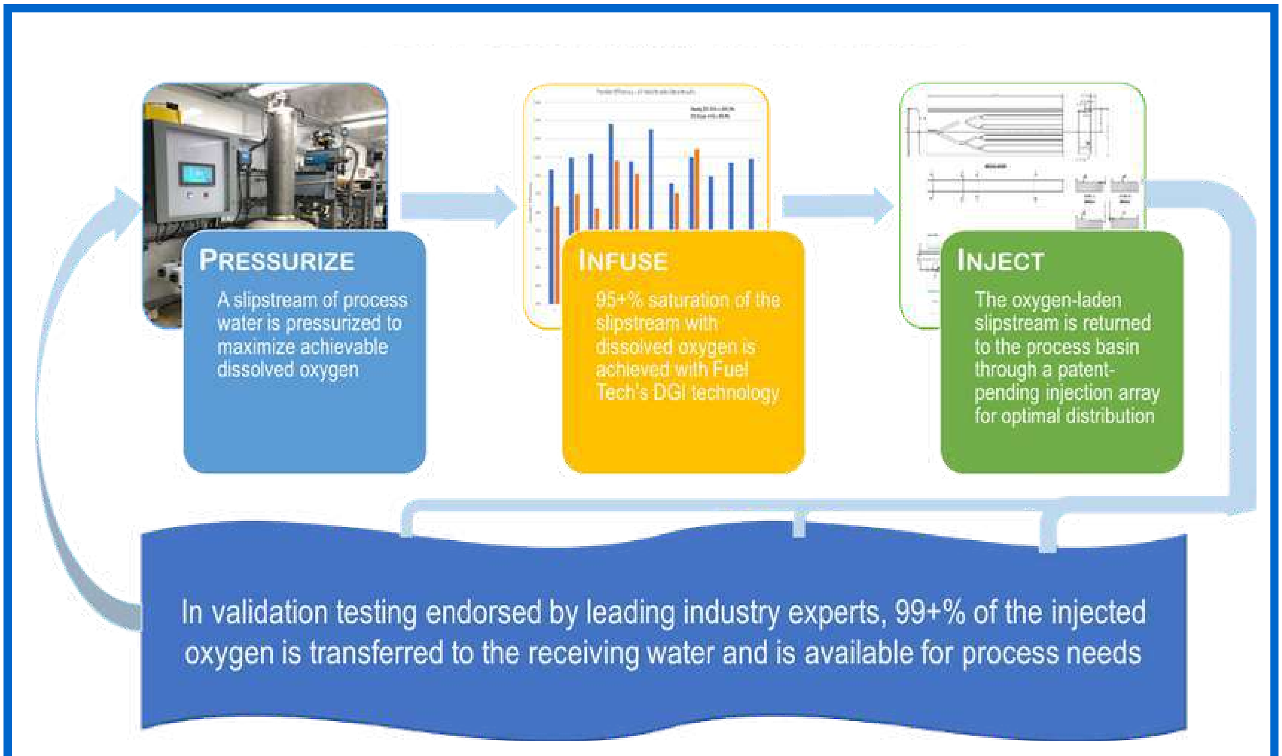

Figure 1: Illustration of the DGI process

Aeration and oxygenation technologies are validated for oxygen transfer efficiency to the treatment reservoir via standardized testing, typically the "Measurement of Oxygen Transfer in Clean Water" standard published by American Society of Civil Engineers (ASCE) and its Environmental & Waters Resources Institute (EWR). The latest version of this standard is ASCE/EWRI 2-06. This standard is suitable for testing oxygen transfer efficiency of aeration and oxygenation technologies that rely on gas transfer from bubbles to the receiving water. While the DGI system pre-dissolves oxygen for delivery into the receiving water directly, due to the high rate of dissolved oxygen introduction and the depressurization of the DGI effluent upon injection into the receiving water, bubble generation can be a secondary outcome. It is thus both necessary and desirable to validate that any bubbles so formed are reabsorbed in the receiving water and not lost to the water's surface. A modified version of the ASCE/EWRI method was conceived to test the DGI system and endorsed by two industry experts to validate the technology's oxygen transfer efficiency.

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TESTING PROTOCOL

TESTING PROTOCOL

The purpose of the desired validation test is to quantify the mass fraction of oxygen that remains in the receiving water (as dissolved oxygen) as compared to the mass of oxygen introduced by the DGI® system. The ASCE-EWRI test description includes definitions of familiar terms, methods for the calibration of probes, as well as specifications for the temperature and quality of the potable test water. All these definitions and quality standards were incorporated in this test, as appropriate.

A primary result of the standard test protocol is expressed as the standard oxygen transfer rate (SOTR), a hypothetical mass of oxygen transferred per unit of time at zero dissolved oxygen concentration. Validated SOTR results using industry-accepted testing can then be used in system design for real-world applications by correcting the SOTR to the actual operating conditions expected to predict performance.

Another testing result especially critical for evaluating oxygenation technologies is oxygen transfer effectiveness, or the ratio of oxygen actually transferred to the receiving water to the oxygen processed by the oxygenation technology. The use of high purity oxygen is an added cost of such technologies, and the efficient use of that consumable is a key element. Oxygen transfer effectiveness is important to all aeration or oxygenation technologies in applications where fast and efficient oxygen transfer is desired.

The primary modification to the standard test that is necessary in evaluating the DGI system lies in the data analysis. Oxygen transfer via a technology primarily relying on bubble generation results in an asymptotic curve approaching the saturated oxygen level. In contrast, the expected oxygen transfer rate for the DGI system is expected to be linear, as the primary oxygen transfer mechanism is the simple mixing of one dissolved oxygen stream (the oxygen-laden DGI slip stream) with another (the receiving water). Any divergence from this linearity or from the expected pure mixing rate is of interest, as it may represent the effect of secondary bubble generation. Such bubbles could be lost at the water surface or may be reabsorbed into the water at a different rate than the expected linear rate of dissolved oxygen introduction.

Experimental Setup

The setup for testing the SOTR and oxygen transfer efficiency of the DGI system is shown in Figure 2. The main testing vessel is cylindrical, approximately 36 inches in diameter and 75 inches tall with a small conical section at the bottom. The total working volume of the tank is approximately 325 gallons. A mixer within the tank, mounted off-center but near middle depth, provides for water circulation that promotes a homogenous dissolved oxygen concentration during testing. Effluent from the DGI system is introduced via a single channel injector incorporating patent-pending technology that is mounted at about the same depth as the mixer, but on the opposite side of the tank.

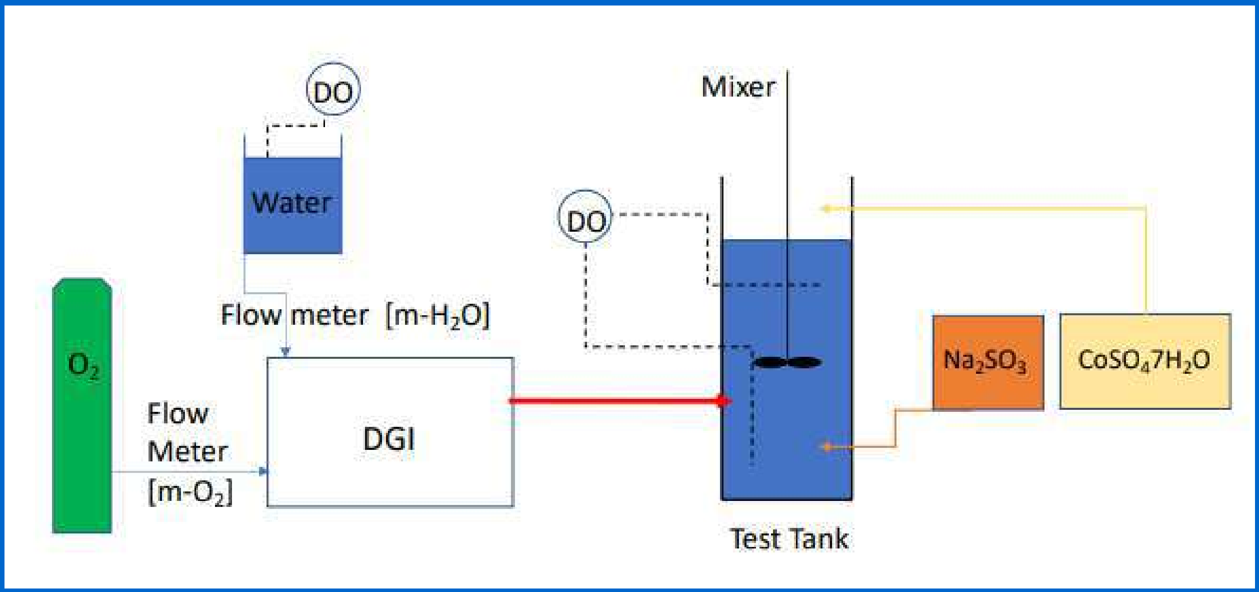

Figure 2: Schematic of test setup

During testing, the introduction of sodium sulfite and cobalt sulfite is used to remove dissolved oxygen from the water. In a first version of the testing, termed the “slope-DO test,” the sodium sulfite is used to clear the test water of dissolved oxygen at the test start. No additional chemicals are then added to the tank and the DGI injection begins. As the DGI system adds dissolved oxygen, any remaining sodium sulfite is consumed and then the dissolved oxygen in the tank begins to rise. Data are collected on the rate of oxygen flowing through the DGI system, metered within the system equipment, and compared to the rate of dissolved oxygen increase in the tank during testing.

In a second version of the testing, termed the “steady-DO test,” the oxygen-consuming sodium sulfite is metered into the test tank concurrently with the DGI injection. The goal of the steady state test is to balance the consumption of dissolved oxygen via sodium sulfite with the introduction of dissolved oxygen via the DGI system, such that a nearly constant dissolved oxygen level is achieved throughout the tank. This steady-state test is viewed as more closely mimicking a real-world application where oxygen consumption is ongoing and a desired dissolved oxygen setpoint is maintained by the applied aeration or oxygenation technology.

Expected Calculations

The fundamental calculation of transfer efficiency is simply a mass balance of the oxygen flowing into the DGI as compared to the mass of oxygen accounted for in the test tank over the duration of the test. In each case, the mass rate (expressed as O_2, in mg/min) is computed from the gathered data as shown in the appendix tables.

Execution of the Testing Protocol

The final equipment is shown in the following photos (Figure 3). A 325-gallon tank was selected to provide sufficient water volume for a slow rise in dissolved oxygen using our smallest channel injector. Initial testing determined the best location of the mixer, the DGI channel injector, the chemical addition and the DO probes to ensure a well-mixed tank for assessing the total change in dissolved oxygen.

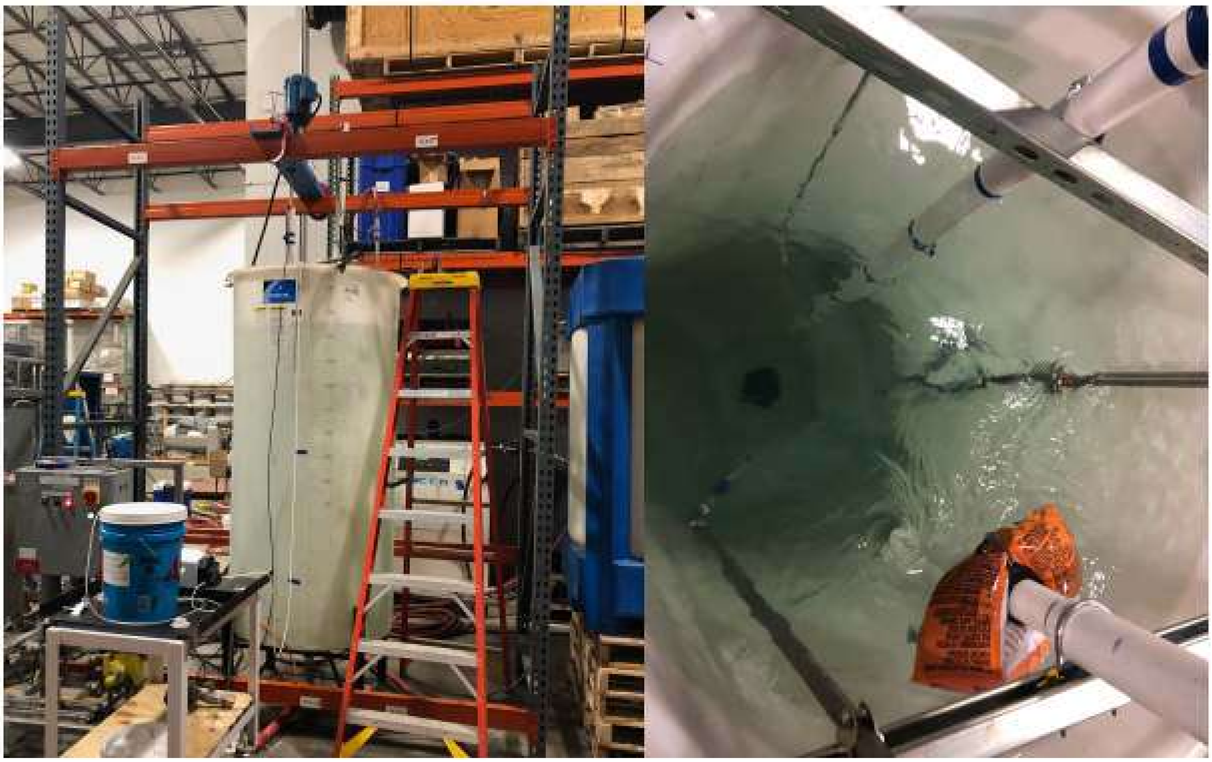

Figure 3: Test setup

The mixer and the DGI channel injector average depth during testing is 23.5 inches from the water surface. The two DO probes, located about one foot from the bottom of the tank and floating one foot from the water surface, tracked together remarkably well. This demonstrated that there would be no area of the test tank in which the DO would be significantly different from these two equal readings. The preliminary DO trends also demonstrated that the provided concentration of cobalt catalyst was sufficient to provide rapid reaction between the sodium sulfite solution and the provided dissolved oxygen.

Data Quality Assurance

Each day, the system was given sufficient time to reach stable operation, and subsequent data analysis was used to check the stability of the oxygen flow before considering any individual data point as valid. The criteria was based on the calculated standard deviation divided by the average value over the test duration.

Results of the Transfer Efficiency Testing

The test data were gathered on eight days between May 9 and May 19, 2022. The steady-DO results averaged 100% as is shown in Figure 4. Given the accuracy of the oxygen flow meter and the uncertainty analysis, it is fair to conclude that essentially all of the oxygen fed to the DGI appeared as dissolved oxygen in the test tank, either measured directly or more accurately through reaction with the 10%(wt) sodium sulfite solution. The transfer efficiency results are shown in the figure, as well as the average uncertainty.

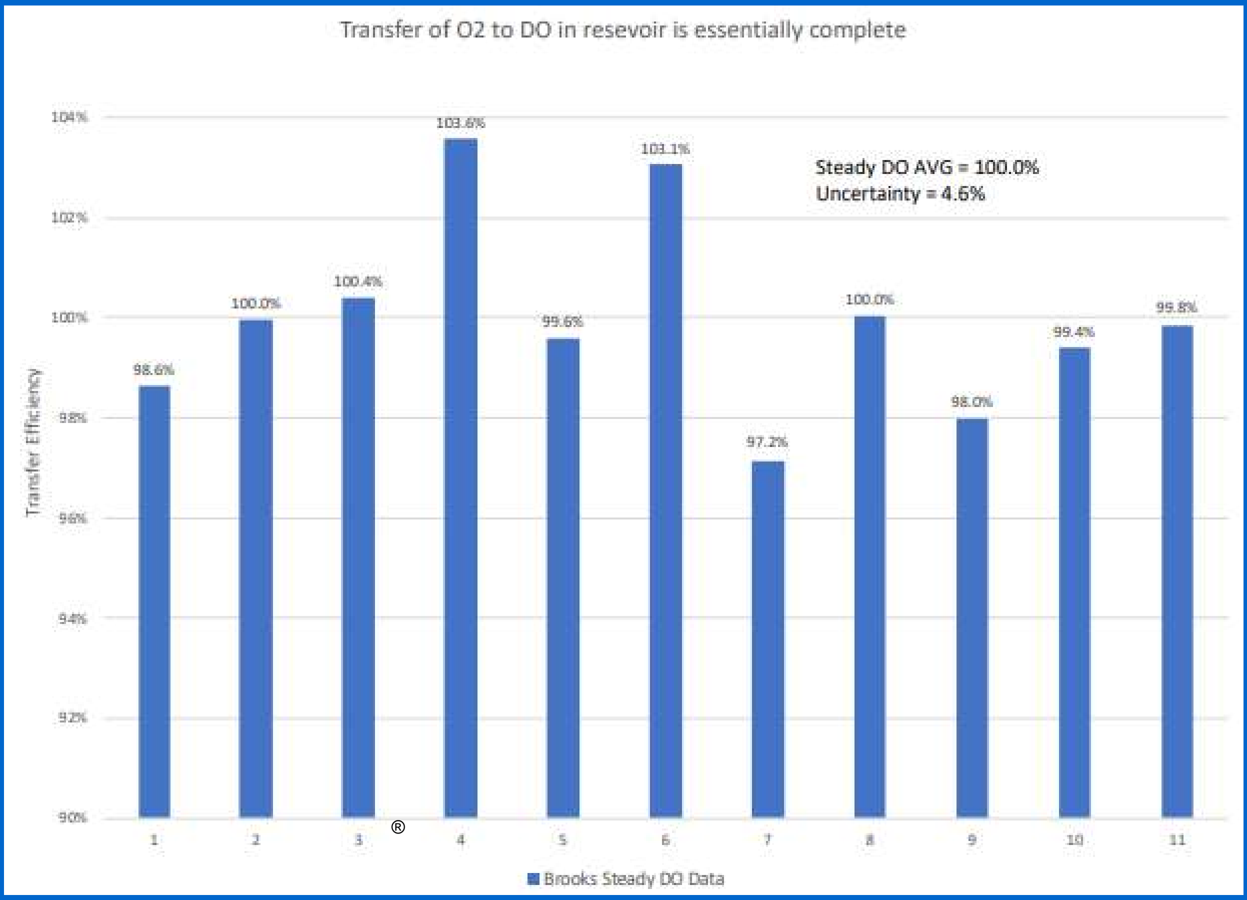

Figure 4: Transfer efficiency results & uncertainty assessment, brooks meter

Instrumentation & Uncertainty Analysis

Instruments used for the key test measurements are as follows:

- **Oxygen Flow Rate –** The O_2 flow rate was measured with a Brooks O_2 mass flow meter, and calibrated by Brooks. It is a Model 5860E with a rated accuracy of + 1% of full scale (F/S), set at a value of 1 standard liter per minute (SLPM). During testing, the flow rate was at the lower end of the F/S range, typically around 0.20 - 0.24 SLPM. Therefore, as a percent of reading the accuracy was between about 4.2 – 4.9% depending on the flow value.
- **Water Flow Rate –** The water flow rate was measured with a magnetic-inductive flow meter, Model SM7601, manufactured by IFM. The instrument range is 0.06 – 13.2 gpm, with a rated accuracy is + 0.8%.
- **Tank Dissolved Oxygen –** Two In-Situ LDO Model 2 probes were used to measure the dissolved oxygen at two locations in the tank during testing. The sensors have a range of 0 – 60 mg/L, with an accuracy of + 0.1 mg/L from 0-20 mg/L, and + 2.0% from 20-60 mg/L.
- **Na2SO3 Solution Flow Rate –** For the steady-DO tests, the sodium sulfite solution flow rate was determined by recording the elapsed time to fill a calibrated volumetric cylinder. The volumetric flow was calculated from the measured volume and the elapsed time.

Uncertainty Analysis

The uncertainty in the calculated oxygen transfer efficiency was determined following the methodology outlined in American Society of Mechanical Engineers (ASME) Performance Test Code (PTC) 19.1 – Test Uncertainty. This Code is based on the uncertainty-propagation methodology consistent with the International Organization for Standardization (ISO) Guide to the Expression of Uncertainty in Measurement. The uncertainty calculation takes in account both systematic and random uncertainties. The systematic uncertainty is the portion of the total error that stays fixed, such as a test instrument's rated accuracy. Random uncertainty is the portion of the total error due to variations in the measurement during the test run

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FINAL SUMMARY

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FINAL SUMMARY

Rigorous testing has been completed to assess the transfer efficiency of dissolved oxygen from the Fuel Tech DGI system to a receiving body of water. The DGI system is capable of infusing oxygen into a process water stream with a unique infusion vessel that approaches the theoretical maximum.

The purpose of this transfer efficiency testing was to quantify the mass fraction of oxygen that remains in the receiving water (as dissolved oxygen) as compared to the mass of oxygen introduced by the DGI system. The ASCE-EWRI test description includes definitions of familiar terms, methods for the calibration of probes, as well as specifications for the temperature and quality of the potable test water.

The DGI system is fundamentally unique, and so a modified version of the standard test protocol was developed, reviewed and executed. The test protocol quantified the ability of the DGI system to provide dissolved oxygen that is available to supply chemical and biological oxygen demand in the receiving water.

The test results discussed in this report support the conclusion that, within the limits of measurement accuracy, essentially 100% of the supplied oxygen gas is delivered to the treatment reservoir and is available to meet any type of dissolved oxygen demand.

The DGI channel injector was located only 24 inches below the water surface, and yet there was no evidence that any significant oxygen was lost to the atmosphere from the open-top 325-gallon test tank. The DGI system is thus an appropriate and efficient technology for shallow-water oxygenation applications.

There was no visual indication of bubbles forming in the tank during testing, as the patent-pending channel injector design successfully minimized any visible bubbles. The efficiency results support the argument that, although microscopic or nano-sized bubbles might form transiently near the injector outlet, they are quickly reabsorbed into the receiving water where they are available to meet aqueous biological and chemical demand.

Conclusions

- A thorough and reviewed test procedure was developed in cooperation with independent technical experts to assess the efficiency of oxygen delivery from the Fuel Tech DGI system
- Rigorous transfer efficiency testing was completed for the DGI oxygen infusion process using industry standards for assessing dissolved oxygen transfer and reaction availability.
- Essentially all of the oxygen supplied to the DGI system was delivered to the treatment reservoir as dissolved oxygen with no loss to the atmosphere, within the described measurement uncertainties.
- The DGI channel injector was completely effective in transferring the oxygen-infused water stream to the reservoir water while located only 24 inches below the water surface.
- There was no measurable loss of oxygen to the environment, no visible bubbles rising in the water, and no delay in the availability of the supplied oxygen to react in the aqueous phase.

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ENDORSEMENTS

Endorsements of Technical Report RD 212

I certify that I participated in the development of the test protocol to assess the transfer efficiency of oxygen dissolved within Fuel Tech's DGI process, and that the conclusions in the report have been reviewed, and are supported and proper based on the data gathered in accordance with the test protocol.

David Redmon Date: July 25, 2022

David T. Redmon ®

Dave has been in the consulting business for 34 years, 24 of which were spent with Ewing Engineering Company. Dave has numerous patents related to fine bubble aeration systems. He was the co-developer of the modern day offgas analysis equipment and methodology (April 1981). He is a charter member of the ASCE Oxygen Transfer Standards Committee and is still an active member.

I certify that I participated in the development of the test protocol to assess the transfer efficiency of oxygen dissolved within Fuel Tech's DGI process, and that the conclusions in the report have been reviewed, and are supported and proper based on the data gathered in accordance with the test protocol.

Glen T. Daigger, Ph.D., PE, Date: July 13, 2022

Dr. Glen T. Daigger

Glen has more than 30 years of experience in wastewater treatment plant evaluation, troubleshooting, and process design. Between 1994 and 1996, he served as professor and head of the Environmental Systems Engineering Department at Clemson University. He is the author of numerous reports, articles, and conference presentations on wastewater treatment and sustainable infrastructure. Glen has also held the position of President of the INternational Water Association for two consecutive terms.

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Fuel Tech develops and commercializes state-of-the-art proprietary technologies for air pollution control, process optimization, water treatment, and advanced engineering services. These technologies enable customers to operate in a cost-effective and environmentally sustainable manner. Fuel Tech is a leader in nitrogen oxide (NOx) reduction and particulate control technologies and its solutions have been in installed on over 1,300 utility, industrial and municipal units worldwide.

The Company's FUEL CHEM® technology improves the efficiency, reliability, fuel flexibility, boiler heat rate, and environmental status of combustion units by controlling slagging, fouling, corrosion and opacity. Water treatment technologies include DGI® Dissolved Gas Infusion Systems which utilize a patented channel injector to deliver supersaturated oxygen solutions and other gas-water combinations to target process applications or environmental issues. This infusion process has a variety of applications in the water and wastewater industries, including remediation, aeration, biological treatment and wastewater odor management. Many of Fuel Tech's products and services rely heavily on the Company's exceptional Computational Fluid Dynamics modeling capabilities, which are enhanced by internally developed, high-end visualization software.