Single-stage Vacuum Deaeration Technology for Achieving Low Dissolved Gas in Process Water[i]

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ABSTRACT: A novel mechanical approach to single-stage vacuum deaeration has been developed in order to remove dissolved gases to extremely low levels in process water.

The technology uses process intensification principles to improve mass transfer processes involving gases and liquids. By imparting high shear and centrifugal forces on a liquid to create extremely small droplets, a large surface area is exposed through which efficient gas absorption and gas removal can occur. Once the small droplets are created, a vacuum pump is used to remove dissolved gases to low levels not achievable with other vacuum deaeration designs.

Applications for the technology include dissolved gas removal from liquids for beverage bottling, ion exchange, ultrapure applications, downhole water injection, boiler feedwater, and many other process water pre-treatment applications.

TECHNOLOGY BACKGROUND

ROTATING PACKED BEDS Rotating packed beds (RPBS) have been around for more than three decades attempting to use large gravitational fields to improve mass transfer efficiency. The fundamental differentiating idea behind RPBs was generating high gravitational forces by rotating a packed rotor at high speeds, instead of relying on the singular force of gravity in packed or trayed columns.

The origin of RPBs goes back to the 1970's and Colin Ramshaw's work in the chemical process industry at ICI, most notably in trying to find an alternative to conventional distillation towers. Since then, a significant body of research has grown involving the use of rotating packed beds. The majority of this work consists of fundamental studies of RPBs, while very little has been written about industrial-scale installations. Partly, this is due to the fact that there have been relatively few industrial installations of RPBs. As well, some installations have been shrouded in corporate secrecy and others have failed to uncover true value for customers.

GASTRAN TECHNOLOGY The current generation of designs can be configured to run either using a stripping gas such as air or nitrogen, or placed under vacuum to enable the removal of dissolved gases. The current generation of RPBs is shown in Figure 1.

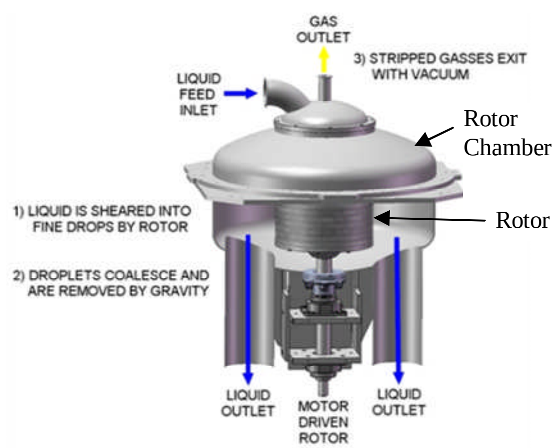

Figure 1: Vacuum Deaeration Technology

The spinning rotor is driven by a motor and generates large centrifugal forces. Liquids fed into the center of the rotor are forced through the porous packing material, shearing the water into nano-sized droplets and sending it into the outer chamber. It is during this extremely short period of time that the water droplets are exposed to the vacuum, enabling the deaeration to occur. The dissolved gases in the water are evacuated out the top of the chamber to a vacuum pump. The deaerated water collects in the chamber and then drains out the bottom.

When a stripping gas is used, the set up is very similar. A gas is fed into the rotor chamber and evacuated out the top of the unit. The flow of the gas is counter-current to the flow of the liquid, maximizing the mass transfer efficiency.

In either set up, the key to good deaeration efficiency is the intense shearing action creating the tiny droplets. This exposes large surface area to the vacuum or stripping gas in order to promote high mass transfer coefficients.

VACUUM DEAERATION PERFORMANCE MEASUREMENT

Laboratory work has been performed to study the technology's performance and key parameters involved in vacuum removal of dissolved oxygen from water. The work has led to an optimized design. The testing has also lead to the development of an overall model that is used to predict performance at customer installations.

EXPERIMENTAL SETUP The experimental work was performed on a laboratory scale system with a maximum rated flow of 5 gallons per minute (gpm). The system set up is shown in Figure 2. An AirTech oil recirculating vacuum pump was used to achieve the low levels of vacuum required for the testing. The dissolved oxygen levels were measured with a Rosemount 499A TrDO. Liquid flowrates during the testing ranged from 1 to 5 gpm with an incoming dissolved oxygen level of 5 to 8 parts per million (ppm). City water was fed continuously through the system during the experiments at temperatures ranging from 6 to 20°C.

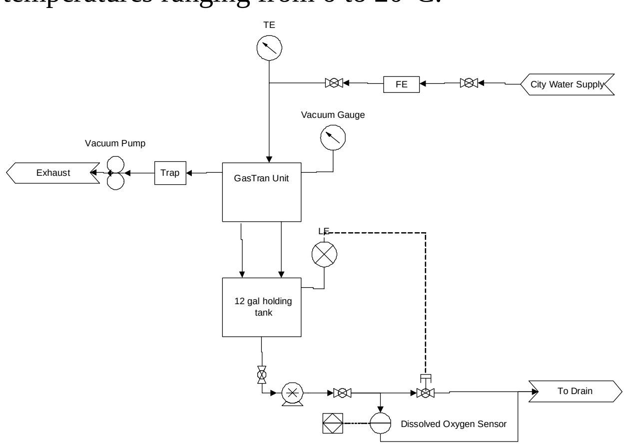

Figure 2 - Experimental Set Up

DERIVATION OF PERFORMANCE During the experimentation, system performance was characterized using the Number of Transfer Units (NTU). The NTU is a unit of measure that ignores the difference between a stagewise process (tray tower) and the continuous contacting process this technology uses. It is similar to the concept of equilibrium stages but is used especially when the equilibrium distribution curve is straight (as is the case with oxygen and water). A higher number of transfer units means a higher overall level of mass transfer occurs in the system. It is defined by the equation below:

$$NTU = \int_{x_2}^{x_1} \frac{dx}{x^* - x} + \frac{1}{2} \ln \frac{1 - x_1}{1 - x_2}$$

where x is the concentration of oxygen in the water and x* is the equilibrium concentration of oxygen in water at the system temperature and pressure. Because this is a dilute solution the equation can be further simplified to:

$$NTU = \int_{x_2}^{x_1} \frac{dx}{x^* - x}$$

Because the system is under vacuum and the equilibrium does not vary much across the rotor chamber the NTU can be approximated using the equation below:

$$NTU \approx \ln\left(\frac{C_{O2in} - C_{equilibrium}}{C_{O2out} - C_{equilibirum}}\right)$$

where C is the concentration in mg/L

RESULTS Some results from these experiments are shown in Figure 3. This data was taken from runs that were performed at an optimized configuration on the 5 gpm system. The incoming water from these runs was 8 ppm dissolved oxygen at 8°C. The performance of the technology increases as deeper vacuum levels are achieved leading to NTU values of 4.3 – 4.5 and dissolved oxygen levels of 235 ppb. The technology is achieving this performance level across only a few inches of rotor packing.

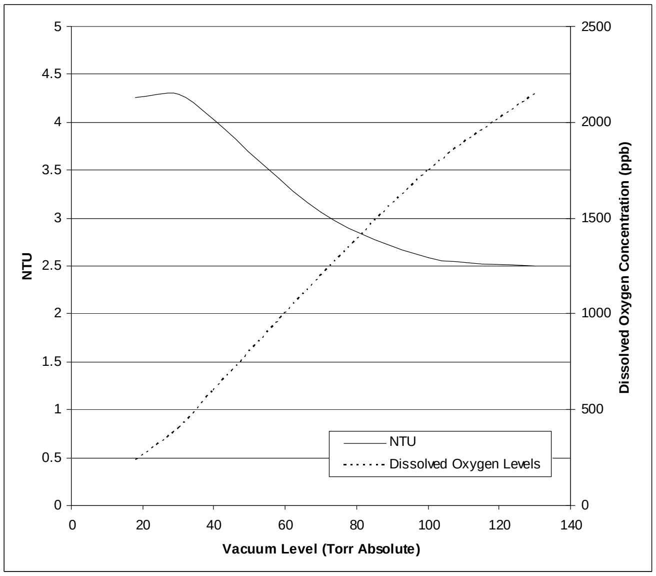

Figure 3 - DO and NTUs by Vacuum Level

This data led to the optimization of larger scale installations. These systems are running at water flowrates up to 300 gpm and are operating in the 3.5 – 4.0 NTU performance range, delivering water that contains 200 – 400 ppb dissolved oxygen at 8°C.

THE BENEFITS OF VACUUM DEAERATION

A variety of industries and applications require low dissolved gas content in their process water. One industry that is currently making significant strides to improve their standards for dissolved oxygen (DO) content and subsequent product quality is the carbonated soft drink (CSD) bottling and canning industry.

CSD FILLING PROCESS CSD packaging plants commonly follow the process flow for bottle or can filling that is shown in Figure 4.

SIDE-EFFECTS OF HIGH DISSOLVED OXYGEN IN CSD The presence of DO in the process water produces several consequences detrimental to the control of the CO_2 level in the final package, as well as the accurate control of bottle fill levels while minimizing product waste.

Due to the interaction between dissolved O_2 and CO_2 in solution, dissolved oxygen acts to increase the partial pressure of CO_2 required to carbonate to the defined specification. This interaction decreases the real carbon dioxide solubility in water and also acts as a promoter for increased carbon dioxide degasification during mixing and rapid pressure changes.

To increase the overall solubility of CO_2, many bottling lines compensate with higher pressures in the carbonation step and/or lower water temperatures. This causes several unintended consequences in the process.

COMPENSATING WITH HIGHER PRESSURES The main problem with increasing pressures to obtain carbonation requirements are the higher pressure drops as the liquid transitions from process pressure to atmospheric pressure. Taken by itself, a larger pressure drop is not a significant issue. But when DO is still present in solution, most fillers will suffer from increased foaming as the CO_2 rapidly expands out of solution. This escape of the CO_2 often is seen as a "volcanic" eruption out of the bottle as a foamy liquid. When the foam escapes, the result can be a "low fill" condition in the bottle, meaning the liquid volume does not meet the minimum specification. These bottles get rejected as an expensive yield loss after capping. The foam itself is problematic in part because it ends up loading the plant's wastewater stream with sugar. Wastewater streams are most commonly discharged from the plants to a municipal treatment and high sugar content can result in fines or surcharges back to the plant.

COMPENSATING WITH LOWER TEMPERATURES The other compensation method for carbonation control is to decrease the liquid temperature. This increases the solubility of carbon dioxide by lowering the necessary partial pressure required to dissolve the carbon dioxide. The CO_2 is thus more soluble and more stable when DO is present. The obvious problem with this is the high cost of cooling.

Figure 4 – Overview of CSD Filling Process

TRADE-OFFS BETWEEN CARBONATION AND FOAMING In an effort to reduce foaming and minimize cooling costs (especially in warmer locations), the tempting choice can be to maintain lower pressures and not cool the water. The likely result can be low carbonation levels, which could lead to off-spec product or reduced shelf life, since the primary limiter to shelf life in CSD products is carbonation leakage (i.e. "flat" product).

CO_2 STRIPPING TO LOWER DO LEVELS Using CO_2 stripping towers to achieve low DO levels has been considered one way to achieve better carbonation control in the final product. Given enough CO_2, dissolved oxygen in these towers can be lowered to 1,000 ppb or less. High CO_2 costs and poor stripping efficiency, however, make this option an expensive one. With increasing awareness around controlling carbon emissions, the carbon dioxide off-gas from these strippers becomes an even less cost-effective and environmentally-friendly alternative.

This option is also problematic for proportional flow control blending systems, such as those incorporating mass flow metering. Coupled with a CO_2 stripper, these blenders fail to achieve their prescribed benefits, since CO_2 bubbles lower the liquid density and disturb the flow metering.

MEMBRANE DEAERATION An alternative approach to deaeration starting about five years ago has been to use hollow-fiber, hydrophobic membranes. The process water passes through the membranes, while a vacuum pressure applied to the core of the membrane removes the dissolved gases. The gas molecules are small enough to fit through the holes in the membrane material, while the water molecules are not. Sometimes this vacuum pressure is applied together with a sweep gas of either carbon dioxide or nitrogen in order to reduce the equilibrium concentration of the stripped gas.

Several practical problems have prevented membranes from delivering sustained deaeration performance below 1 part per million DO. Primary among them is rapid degradation and fouling of the membrane material from inconsistent incoming water quality and dissolved solids.

Another major drawback to membranes is their cleanability. Most CSD bottling plants run some type of regular Clean In Place (CIP) procedure to clean and sanitize bottling equipment, but installed membranes systems have repeatedly shown rapid deterioration with frequent exposure to high CIP temperatures (typically 82 °C or higher) and pH fluctuations (from caustic and acid washes). On occasion, even membrane housings have permanently deformed to the point of catastrophic failure when exposed to high CIP temperatures. Some installers of membrane systems attempt to isolate the membranes during CIP cycles in order to slow deterioration, but this solution prevents the membrane system from being adequately cleaned and leaves it vulnerable to biological growth.

Despite large investments by CSD bottling plants and costly replacements of cartridges over the last several years, membranes have failed to deliver a significant and sustained lower DO to the rest of the bottling line.

FOUNDATION TO BETTER BLENDING AND CARBONATION Given the challenges CSD bottlers face with carbonation and syrup blending, sustaining low DO below 500 ppb in the deaeration step provides a solid foundation for carbonation stability, overall product quality, and increased line efficiency. Furthermore, achieving low DO without the addition of CO_2 prior to carbonation is the most logical and best economic option, leaving vacuum deaeration as a clear choice.

Installing a vacuum deaeration system capable of sustained low DO does not by itself guarantee success, however. Making the transition to better quality and faster bottling speeds requires a holistic approach to the production line. Each step affects the subsequent parts of the process. Equipment and operating parameters will require re-tuning and adjustment both prior to and after installation, until the entire line begins to work in harmony.

SYSTEM SPECIFICATIONS The dimensions for an entire 300 gallon per minute (gpm) skidded system incorporating the vacuum technology, including water handling and controls, are approximately 4'x5'x12', meaning it fits easily into existing plant floors.

Figure 5 shows a picture of a skidded system at a CSD plant. The technology including the rotor housing is at the top of the picture.

System performance is monitored and data is recorded. No degradation in performance has been observed over more than two years of continuous operation across multiple installations. The technology does not have wear parts requiring regular replacement.

The system is sanitized as part of the regular CIP procedure for each plant.

Figure 5 - Vacuum Deaeration System

ADDITIONAL MARKETS FOR VACUUM DEAERATION

Besides the successful applications of the technology in CSD, many additional markets provide a good fit with the core strengths of the technology.

DECARBONATION FOR DEIONIZED WATER PRE-TREATMENT Many ultrapure water applications require very low levels of dissolved ions in their water. This requirement is necessitated for a variety of reasons including corrosion and scaling reduction as well as process contamination.

Decarbonation using a vacuum deaeration technology effectively lowers dissolved CO_2 content that otherwise would consume ion exchange resin capacity and hurt electrodeionization (EDI) and mixed bed resin performance.

The technology provides consistent decarbonation performance without fouling. Its compact size and low profile provides a significant advantage over vacuum towers in terms of pressure loss and space requirements.

DEAERATION FOR ONSHORE AND OFFSHORE OIL RECOVERY Offshore and onshore secondary oil recovery commonly utilize a waterflood approach to wash oil from depleted reservoirs using seawater or brackish water. In order to minimize corrosion of the downhole piping and bacterial contamination of the piping and reservoir, degasification technologies are utilized to remove dissolved oxygen, carbon dioxide, and hydrogen sulfide (H_2S).

The vacuum deaeration technology of this paper provides an enormous size and weight advantage over conventional vacuum towers. This advantage provides a cost benefit because the lower weight and space requirements translate into direct savings in the upfront cost of the platform.

ADDITIONAL SET UPS FOR LOWER DISSOLVED GAS REQUIREMENTS Additional set ups are possible using the vacuum to obtain even lower dissolved gas concentrations.

Among these options is the use of a stripping gas in combination with the vacuum. A stripping gas such as nitrogen can be introduced into the rotor chamber in small quantities to lower the equilibrium concentration and provide a driving force for removing the dissolved gases.

SUMMARY

A novel mechanical approach to vacuum deaeration has been developed out of earlier work done on rotating packed bed concepts.

Laboratory studies were completed to optimize the design and develop models for predicting performance at different operating conditions.

The technology has been scaled up to 300 gpm sizes and obtains approximately 4.0 NTUs at maximum rated flows. This enables the technology to produce deaerated water with dissolved oxygen content of 200 – 400 ppb at 8°C in CSD plants, depending on the incoming DO concentration.

The compact size, performance in removing dissolved gases, and the sustained performance of the technology give it a distinct advantage over alternative technologies for deaeration in a variety of industries.

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[i] Presented at the International Water Conference – San Antonio, TX October 2008