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Design Considerations for Cost-Effective Ozone Mass Transfer in Sidestream Systems

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ABSTRACT
Ozone dissolution system design is important for meeting transfer efficiency (TE) goals. Large sidestream pump flow (L) and high venturi inlet pressure improves TE but increases operating cost. Ozone TE was examined at a 25 gpm (97-Lpm) pilot-scale sidestream system with ($SS_{w\text{-}dg}$) and without ($SS_{wo\text{-}dg}$) degas separation. Under constant ozone dose conditions, process operating parameters were varied including sidestream gas/liquid (G/L) ratio, venturi-inlet water pressure, venturi-outlet water pressure, feed gas pressure, and ozone gas concentration. Performance results included determination of TE, ozone exposure (CT_{HDT}), and hydraulic detention time (T_{HDT}). Several design aspects of sidestream ozone systems were examined to improve mass transfer by using remixing devices, protecting ozone gas piping from corrosion, calculating sidestream ozone residual, and driving force for mass transfer. Moisture contamination of ozone supply lines may cause corrosion and/or decomposition of ozone gas that releases heat and destroys ozone. Ozone gas piping design is critical to prevent trapping water that might enter gas pipe during power outage or when units are offline. During plant operation below design flow, multiple constant speed pumps or variable speed pumps were evaluated to reduce overall operating costs.

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Introduction

Sidestream addition (SSA) has emerged as an alternative to fine bubble diffusion (FBD) for ozone gas–liquid mass transfer. Over the past decade, utilities have increasingly preferred SSA systems versus FBD due to the easy accessibility of key process components for maintenance (Thompson and Drago 2015; Wert, Lew, and Rakness 2016). Although capital and operating costs may be greater, SSA eliminates the need for contactor shutdowns and confined space entry to service porous stone diffusers (Neemann et al. 2002; Stockton and Neemann 2010; Taylor, DiGerlando, and Schulz 2013). With either SSA or FBD for ozone mass transfer, a high transfer efficiency (TE) is desired to make optimal use of the ozone gas generated and create a cost-efficient ozone process.

When evaluating ozone mass transfer, there are several design considerations, including the gas–liquid driving force, gas pressure, water pressure, and ozone concentration. Ozone gas is transferred to the water by applying the gas–liquid interface transfer theory (Clark 1996). Using the two-film model of mass transfer, a high gas-phase ozone concentration (zone 1) begins to create an interfacial region with the liquid creating a gas film (zone 2) neighboring a liquid film (zone 3), continuing into a liquid-phase ozone concentration (zone 4) (Figure 1). Many variables exist (e.g., diffusivity, mixing), but the primary considerations for effective mass transfer include the following: (1) large interfacial surface area for transfer to occur, typically achieved with small bubbles, (2) high driving force from gas to liquid phase involving a high gas-phase ozone concentration (% wt.), and (3) high venturi-inlet water pressure. When the soluble ozone residual in the bulk liquid (zone 4) becomes equivalent to the residual in the interfacial region (zones 2 and 3), mass transfer ends due to a lack of driving force.

Design TE for FBD contactors is typically 95%. When diffusers are new and operating as intended with "fine bubbles," >90% TE is achieved at both design production and low production (turndown)

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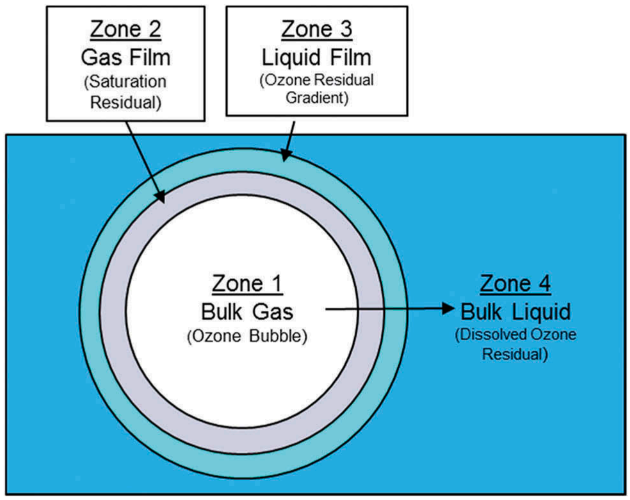


Figure 1. Conceptual two-film model of mass transfer from an ozone gas bubble (Zone 1) to a bulk liquid dissolved ozone residual (Zone 4). Adapted from (Clark 1996).

operating conditions. Diffuser depth is typically 18–22 ft (5.5–6.5 m) below contactor water level to increase the hydrostatic pressure on the gas bubbles. TE in FBD systems can be reduced to <80% due to gasket failure, diffuser failure, or diffuser fouling. Diffusers should be inspected annually to maintain TE at design conditions, which may be problematic due to confined space entry requirements. Sidestream system design TE is commonly 95% as well, which might be a carryover from FBD design criteria. However, achieving 95% TE at design conditions is more involved for sidestream equipment, and 95% TE might not be the optimum TE design value.

In addition to TE, the water flow and ozone production rates may also influence the efficiency of the ozone process. Drinking water treatment plants commonly operate below the design production rate referred to as turndown (i.e., low water flow, low dose, and low ozone production). In FBD systems, lower production rates increase the contact time in the dissolution chamber and could result in considerable ozone exposure (CT) and bromate formation before entering the disinfection zone, where compliance CT is determined (Wert, Lew, and Rakness 2017). Sidestream systems also have turndown considerations. During turndown conditions, the TE can be well above 95% if the sidestream pumps are operated at design value. However, the operating cost ($/MG) is much greater and not optimized. Sidestream pumps are sized with the required power demand (kW or horsepower) to dissolve ozone into the sidestream flow at design production. Full-power pumping can easily dissolve ozone into the sidestream flow at turndown production, but at higher than necessary energy cost. Ozone generator turndown is provided with multiple units, such as two generators to meet design production with one generator in standby. In addition, each generator has the capability to efficiently produce ozone at about 10% of design production for the generator. Under turndown conditions, a lower TE may be acceptable when evaluating the cost of non-transferred ozone gas (i.e., off-gas) versus the power cost to operate the sidestream pump. Improved guidance is needed for sidestream systems to balance TE with capital and operating costs.

To more thoroughly evaluate TE and turndown effects, a research study was performed through a project funded by the Water Research Foundation (Wert, Lew, and Rakness 2016). The project evaluated several variables with respect to achieving efficient mass transfer, operation, and performance at both design and turndown production rates. Moreover, considerations for achieving long-term reliability are discussed, including: (1) eliminating moisture from being trapped inside the ozone supply piping to the sidestream venturi, (2) installing sidestream equipment (pumps, venturis, etc.) to achieve total system energy-efficient performance under design and turndown production rates, (3) implementing sidestream operating control logic to achieve water-quality performance at minimum operating cost (i.e., ozone generation, sidestream pumping), and (4) installing a pressure gauge on the ozone feed-gas piping to determine whether positive or negative pressure exists at the venturi (i.e., injection or eduction). The conclusions from this work improve the available guidance regarding sidestream ozone system design, operation, and optimization.

Materials and methods

Description of a full-scale sidestream ozone system

Sidestream ozone systems are designed either with ($SS_{w\text{-}dg}$) or without ($SS_{wo\text{-}dg}$) degas separation (Rakness 2007). $SS_{wo\text{-}dg}$ incorporates two locations for ozone/oxygen gas–liquid mass transfer: (1) following the venturi in the sidestream flow before bubble coalescence, and (2) during mixing of any undissolved ozone gas when blending the sidestream water flow with the main water flow. After recombining the water flows, a third location for additional gas–liquid mass transfer may exist if using a remixing device (i.e., static mixer) to convert coalesced gas bubbles into finer bubbles before entering the ozone contactor (Figure 2). Eventually, non-dissolved ozone and oxygen gas is

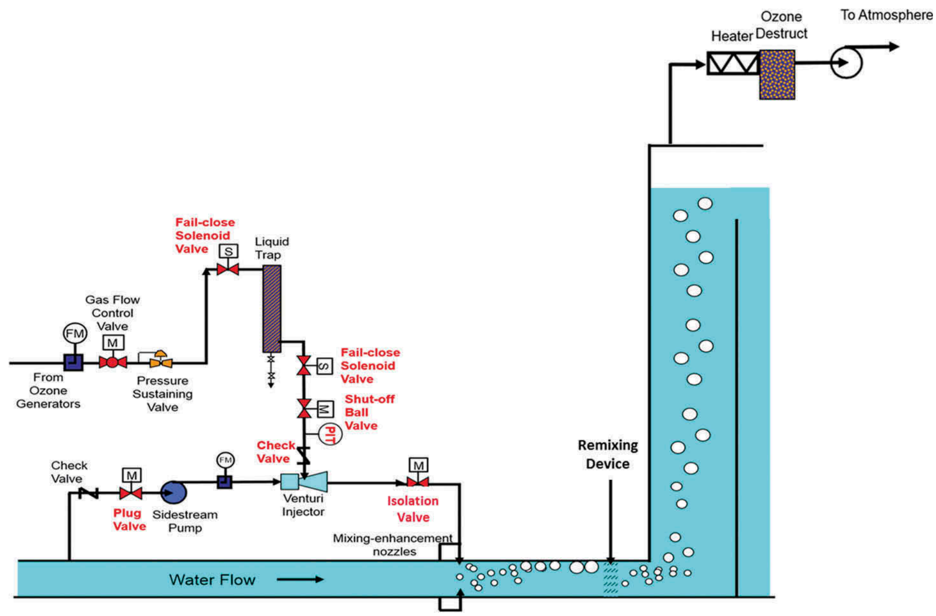


Figure 2. Typical schematic of a full-scale sidestream addition system without degas, including a remixing device for improved ozone transfer.

removed from the headspace of the ozone contactor. Design range for the G/L ratio (volume basis) is between 0.3 and 0.7 and the venturi-inlet water pressure is typically 25–50 psig (Wert, Lew, and Rakness 2016). When possible, $SS_{wo\text{-}dg}$ is selected because sidestream pump size and operating cost are lower. Information concerning oxygen transfer is contained in other documents (Rakness 2005, 2007).

During $SS_{w\text{-}dg}$, all oxygen/ozone gas–liquid mass transfers occur following the venturi and before degas separation (Figure 3). The degas vessel removes any undissolved ozone/oxygen gas from the sidestream water flow before recombining with the main water flow. Design range for the G/L ratio for $SS_{w\text{-}dg}$ is relatively low at 0.1–0.2 and the venturi inlet water pressure is relatively high at 40–80 psig (Wert, Lew, and Rakness 2016). Relatively high sidestream liquid flow and elevated operating pressure are necessary to obtain TE = 95%, which means that sidestream pump size and operating cost for $SS_{w\text{-}dg}$ are greater than those for

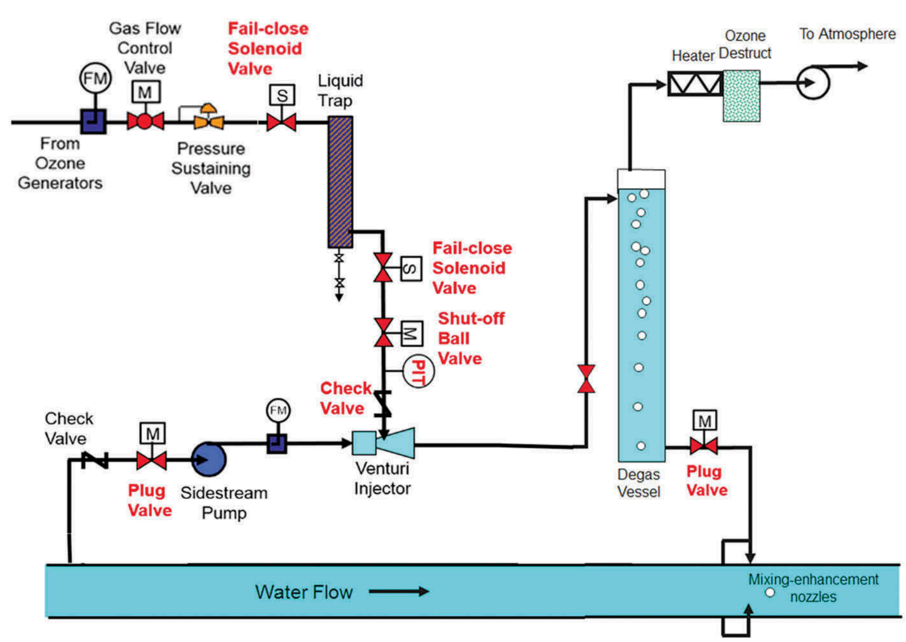


Figure 3. Typical schematic of a full-scale sidestream addition system with a degas vessel.

$SS_{wo\text{-}dg}$. Nevertheless, $SS_{w\text{-}dg}$ is selected when site-specific conditions dictate the following: (1) prior to a pipeline ozone contactor, (2) prior to a shallow ozone contactor, or (3) when minimal dissolved oxygen concentration is desired in the treated water.

Description of a pilot-scale sidestream ozone system

The 25 gpm (95 Lpm) $SS_{w\text{-}dg}$ and $SS_{wo\text{-}dg}$ pilot plants (see Figure 4) were designed in parallel using clear polyvinyl chloride (PVC) to observe bubble coalescence following gas injection. Either operating scheme may be operated at different ozone concentration, G/L ratio, venturi-inlet water pressure, and venturi-outlet water pressure conditions in order to identify performance characteristics concerning ozone TE variables discussed earlier (Wert, Lew, and Rakness 2016). In Figure 4, Area-1 is the $SS_{w\text{-}dg}$ setup that includes the venturi and degas vessel. $SS_{w\text{-}dg}$ water flow is recombined with the mainstream flow through a pipeline flash reactor (PFR) shown in Area-3. Area-2 is the $SS_{wo\text{-}dg}$ venturi and pipe that also recombines sidestream water flow containing undissolved ozone gas with the mainstream water flow through the PFR shown in Area-3. The recombined mainstream flow is directed to a 2-min HDT water-up-flow ozone contactor vessel.

Pilot-scale testing was performed using Colorado River water from Lake Mead, NV. Water-quality characteristics were measured on a weekly basis for the following parameters (average value): pH (7.97), temperature (16°C), and total organic carbon (2.8 mg/L). Ozone exposure (i.e., CT_{HDT}) was based on theoretical hydraulic detention time and did not incorporate the disinfection-related T_{10}/T ratio into the contact time. Operating parameters were varied to achieve target dose, such as gas flow (G), generator power, mainstream water flow, sidestream flow (L), venturi-inlet water pressure, venturi-outlet water pressure, and ozone feed-gas concentration.

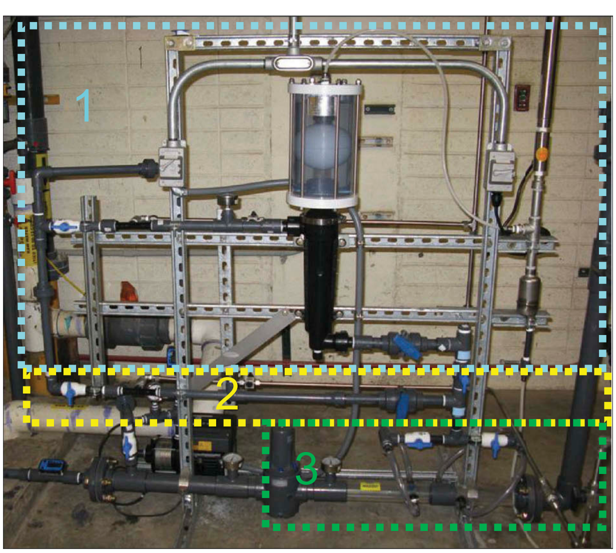


Figure 4. Photo of a pilot-scale sidestream system at SNWA: (1) sidestream with degas ($SS_{w\text{-}dg}$), (2) sidestream without degas ($SS_{wo\text{-}dg}$), and (3) pipeline flash reactor combining sidestream with the main process flow.

Results and discussion

Design considerations for sidestream installations

In the subsequent sections, several design aspects of sidestream ozone systems will be examined to (1) improve mass transfer through the use of remixing devices, (2) protect ozone feed-gas piping from corrosion, (3) determine the required sidestream ozone residual, and (4) determine the appropriate driving force for mass transfer.

Remixing strategies during sidestream without degas

For $SS_{wo\text{-}dg}$, operating G/L ratio can be higher and venturi-inlet water pressure can be lower because ozone transfer occurs in both the sidestream and mainstream water flow. Since G/L is higher, sidestream pump size is smaller for a given design ozone dose and design water flow. Reduced pump capacity and lower operating pressure result in smaller motor size and lower energy consumption. However, reinjected sidestream flow must be thoroughly mixed with the mainstream flow and at high enough pressure to achieve additional ozone mass transfer.

Rapid bubble rise and coalescence occur at the top of the mainstream pipe following blending with the sidestream flow. Under these operating conditions, minimal gas–liquid surface area is available for additional ozone transfer. In these cases, a remixing device may be used to convert coalesced bubbles into fine bubbles, which creates a larger interfacial surface area for gas–liquid transfer. A remixing device is recommended if the distance between the sidestream injection location and entry into the ozone contactor is greater than 3–5 pipe diameters. As an alternative, injection nozzle grid could be installed directly in the first chamber of the contactor. This would inject the sidestream and fine bubbles in the bottom of the first chamber similar to a diffuser grid. With this option, the design should include sufficient depth, chamber sizing, nozzle selection, and arrangement to ensure fine bubble development and adequate mixing to develop stable ozone residual.

Similar to an FBD ozone contactor, higher pressure facilitates ozone transfer in the mainstream flow. Bubble diffusers are placed at water depth >16 ft and often 18–22 ft deep to increase pressure at the diffuser interface, which improves TE. Mainstream piping for $SS_{wo\text{-}dg}$ applications should enter the contactor at similar depth, if possible, especially if sidestream ozone TE is curtailed using a high G/L ratio and low venturi-inlet water pressure.

Minimizing moisture in ozone supply piping

Sidestream water that backflows into the ozone feed-gas piping has disastrous consequences if the water reaches the ozone generator. Moisture trapped in the ozone supply pipe can cause long-term corrosion due to nitric acid formation. In the short term, loss of ozone concentration occurs due to the rapid auto-catalytic decomposition of ozone to oxygen. Not only is there a potential for a reduction of ozone supply and need for elevated ozone dose to achieve treatment goals, but elevated dose can also cause extensive decomposition, which creates significant heat buildup in the ozone pipe. This scenario occurred at one full-scale ozone facility when water was trapped in the pipe from the generator, leading to a roof insulation fire (see Figure 5). At this facility, backflow prevention devices were installed upstream that prevent water from getting into the generator.

Sudden backflow of water from the sidestream water flow pipe into the ozone-gas supply pipe can occur if the sidestream water pressure exceeds the ozone feed-gas pressure. Current sidestream designs seem to be focused on preventing water backflow into the ozone generator. A check valve is installed in the gas supply pipe to prevent a sudden surge of water backflow. A water trap is installed that detects moisture and closes a fast-acting shutoff valve in case water gets too far up

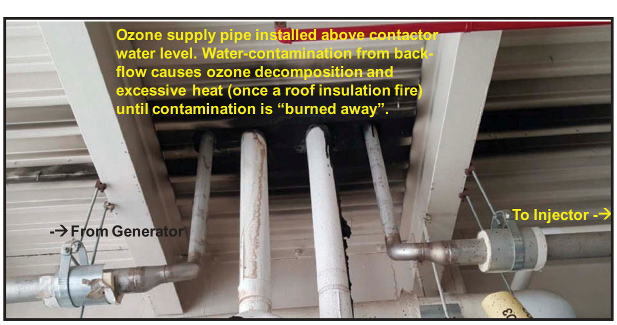


Figure 5. Ozone decomposition may occur in water-contaminated ozone supply piping.

the ozone supply pipe. These features have successfully prevented water backflow into the ozone generator.

However, an issue that seems to be overlooked is water entrapment in the ozone supply piping when the sidestream system is offline. Entrapment can occur in low points of the ozone supply pipe. When ozone gas supply is turned back on, some of the water may flow back into the venturi, but some water may stay at the bottom of the ozone pipe, where nitric acid can form and ozone decomposition can occur. Nitric acid formation develops due to the backflow of moisture past the check valve and damage to ozone supply backflow prevention devices has occurred.

Water entrapment occurs when the sidestream system is offline. When offline, check valves have been unable to prevent leakage of liquid water and water vapor into the ozone gas piping. A tight seal is required to prevent leakage, and a material is required within the check valve that would provide a tight seal and is incompatible with ozone. A check valve can be expected to only prevent a large rush or surge of water from entering the pipe. A check valve does not and cannot provide a complete seal. Liquid water can come directly from the sidestream, or can form due to moisture condensation inside the ozone supply piping when offline. Condensation occurs when ambient air temperature surrounding the ozone pipe is below the dew point temperature of the moisture-containing gas inside the ozone pipe.

Figures 2 and 3 display water backflow devices and layout that are intended to avoid entrapment of liquid water in the ozone supply piping (Rakness and Hunter 2013). The physical layout of the piping and moisture contamination prevention devices should be planned in detail on the design drawings and the correct order should be shown on a process and instrumentation diagram (P&ID). The installation contractor should be given clear direction concerning both detailed piping layout and backflow prevention devices. A P&ID, alone, is insufficient. Brief explanation of the schematic is outlined below.

(1) The 316-SS ozone supply piping enters the venturi from above. This allows entrapped water to be reinjected into the sidestream flow upon return to service.
(2) The check valve prevents bulk water flow into the ozone gas pipe in case of sudden shutdown of sidestream pump operation, or other. A check valve, alone, is insufficient. The check valve will leak or allow moisture to pass into the gas piping when the sidestream unit is offline.

(3) The pressure-indicator-transmitter (PIT) reading allows ozone gas flow only when the measured pressure is below a set point value. Set point pressure might be positive pressure that causes the venturi to be an "injector" rather than an "eductor," but set point would be safely below the operating pressure of the ozone generator.
(4) The shutoff ball valve is closed during routine shutdown of the sidestream unit. The vertical location of the shutoff ball valve ensures that trapped water is contained in the vertical section of the ozone supply pipe. Upon return to service, trapped water will flow down into the sidestream water flow by both gravity and ozone gas flow velocity.
(5) The vertical location of the fail-close valve also ensures that trapped water is contained in the vertical section of the ozone supply piping. The fail-close valve (fast-acting actuator/valve combination) is a device that closes immediately upon indication of loss of power, loss of sidestream water flow, increase of gas pressure (item 3 above), loss of communication, or other situation that could result in moisture conveyed to the generator.
(6) Safety consideration: the liquid trap water backflow protection device will detect water that is collected at the bottom of the unit and will immediately close the upstream and downstream fail-close valves. The liquid trap is activated in case of failure of the above-described units, and should be considered as a necessary addition but one that is seldom used because water drained from the liquid trap releases ozone-containing gas into the surrounding atmosphere. The ozone gas concentration is several thousand parts per million and is an extreme safety hazard for plant staff. Staff must be trained on safely draining water from the liquid trap, such as draining, by submergence, into a container that contains 2–4% potassium iodide (KI) solution that will quench ozone. Another option is to ensure that the control system allows sidestream system startup and oxygen purge before draining the moisture separator.
(7) The pressure sustaining valve (PSV), gas flow control valve, and flow meter are located on the main header to the ozone contactor. Gas flow to each contactor is controlled at this location. If the design includes more than one venturi to each contactor, gas flow control is unnecessary at each venturi because total contactor gas flow will split naturally and sufficiently to each venturi. Some plants have operated successfully without a PSV and the PSV might be considered as optional. If included, the PSV should be a mechanical unit and not a pilot-operated PSV. At more than one plant, pilot-operated PSVs have failed.

Calculating the required sidestream dissolved ozone residual

For $SS_{wo\text{-}dg}$ installations, additional mass transfer occurs when (1) recombining flow, (2) using a remixing device, or (3) in the first ozone contactor chamber, which does not allow for accurate calculation of a target dissolved ozone residual in the sidestream flow. However, for $SS_{w\text{-}dg}$ installations, the required dissolved ozone residual in the sidestream prior to blending with the mainstream flow can be helpful to both the design and operation of the system. Factors affecting required sidestream ozone residual (Equation [1]) include required mainstream initial residual ($MS_{DO3\text{-}Req'd}$; mg/L), mainstream ozone demand (MS_{Demand}; mg/L), sidestream demand (SS_{Demand}; mg/L; Equation [2]), and ratio of mainstream flow to sidestream flow (Q_{total}/Q_{SS}).

$$SS_{DO3} = \left(MS_{DO3\ Req'd} + MS_{Demand} - SS_{Demand} \right) * \left(\frac{Q_{total}}{Q_{SS}} \right) \tag{1}$$

$$SS_{Demand} = \left((MS_{Demand}) * \left(\frac{Q_{SS}}{Q_{Total}} \right) \right) \tag{2}$$

For example, if the required mainstream demand is 1.0 mg/L and sidestream flow is 10%, then 0.1 mg/L of the mainstream demand is met in the sidestream flow (SS_{Demand}). If the required mainstream initial residual is 0.5 mg/L, the required sidestream ozone residual can be calculated as 14.0 mg/L, as illustrated in Equation (3). Additional sidestream operating scenarios are depicted in Figure 6.

$$14\frac{mg}{L} = \left(\left(0.5\frac{mg}{L} + 1.0\frac{mg}{L} - 0.1\frac{mg}{L} \right) * \left(\frac{100}{10} \right) \right) \tag{3}$$

Sidestream flow (% mainstream flow) is a function of applied ozone dose (mg/L), ozone concentration (%wt), and G/L ratio (based on "standard temperature" of 68°F and "standard pressure" of 14.7 psia), as shown in Figure 7. Percent sidestream flow (% of mainstream flow) is less when ozone dose is low, ozone concentration is elevated, and G/L is high. The G/L range shown in Figure 7 is the typical design value for $SS_{w\text{-}dg}$ applications (Wert, Lew, and Rakness 2016). Figures 6 and 7 can be used to estimate the sidestream residual for design

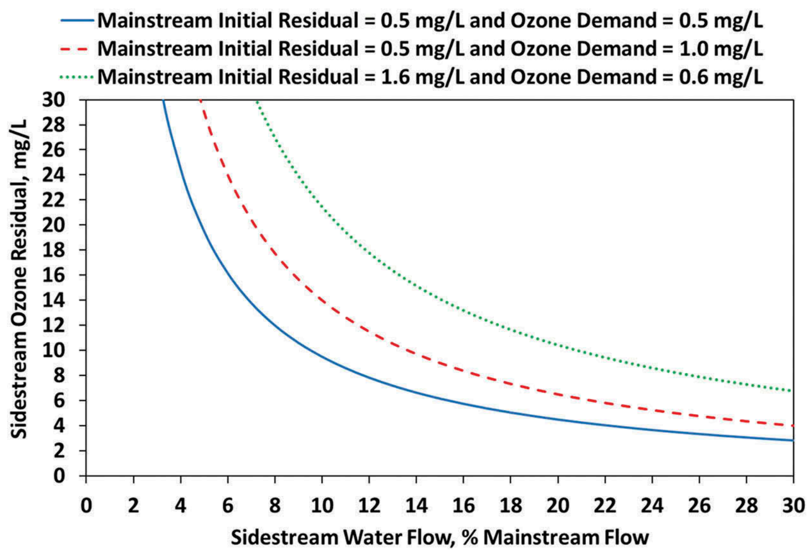


Figure 6. Calculated sidestream residual required for specified sidestream water flow (%), desired mainstream initial residual (mg/L), and mainstream ozone demand (mg/L).

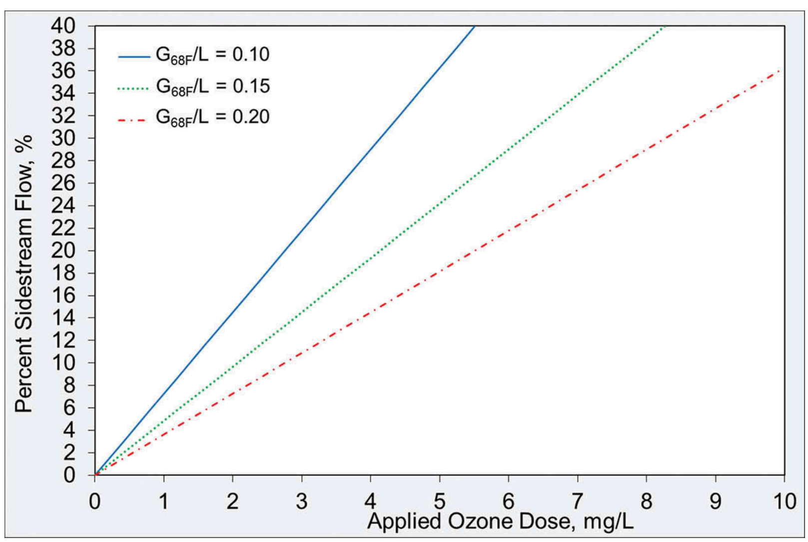


Figure 7. Calculated sidestream water flow (%) versus applied mainstream ozone dosage at different G/L ratios (0.10, 0.15, and 0.20) with constant ozone feed-gas concentration (10% wt.).

applied dose and G/L ratio, but it should be kept in mind that <100% TE occurs. Specifically, at a given applied ozone dose, the sidestream residual is different depending on TE. The transferred ozone dose to the sidestream develops the sidestream ozone residual.

Calculating the required driving force to achieve TE goals

"Driving force" is defined as the saturation residual (Zone 2 in Figure 1) divided by the sidestream residual (Zone 4 in Figure 1), as shown in Equation (4). Ozone saturation residual (Zone 2 in Figure 1) is calculated from Henry's Law (Equation [5]). The constant, 3.75×10^{-7} mg/L per mole fraction, is the conversion factor from ozone-concentration-in-gas volume ratio to mg/L. H_{pres} (Equation [6]) is Henry's constant at operating pressure in atmosphere/mole fraction. $H_{@1atm}$ is from Equation (7) with water temperature (Temp) in °C (Bin 2006).

$$Driving\ Force = \frac{\text{Gas Film Saturation Resi}dual_{mg/L}}{\text{Bulk Flow Sidestream Resi}dual_{mg/L}} \quad (4)$$

$$\text{Saturation Residual}_{mg/L} = \frac{Concentration_{vol/vol}}{H_{pres} \times (3.75 \times 10^{-7})} \quad (5)$$

$$H_{pres} = \frac{H_{@1atm}}{Operating\ \ Pressure_{atm}} \quad (6)$$

$$H_{@1atm} = 1599 \times e^{0.0473 \times Temp} \quad (7)$$

Saturation residual and the corresponding driving force for ozone transfer are the greatest at elevated water pressure, low water temperature, and high ozone concentration (e.g., 10–15%wt). However, ozone concentration in the gas bubble decreases as ozone is transferred into the bulk liquid, sidestream flow. Concentration might start at 10%wt, but when concentration-based ozone TE is 95% and the ozone concentration inside the bubble is only 0.5%wt, the "driving force" for ozone transfer is significantly reduced.

The following example illustrates the impact of water pressure and required sidestream residual on driving force and TE during a $SS_{w\text{-}dg}$ application (Figure 8). Saturation residual was calculated based on water temperature (15°C), venturi-inlet water pressure (60 or 80 psig), and supplied ozone concentration (10%wt) multiplied by the percent non-dissolved ozone. The required bulk flow sidestream residual (2.5 or 8.5 mg/L) was arbitrarily selected for the example. Figure 8 shows how "driving force" decreases when ozone TE increases. For example, at 95% TE, 5% of the supplied ozone gas is undissolved and the ozone concentration in the gas bubble is 0.5%wt. When the required sidestream residual is 8.50 mg/L and the "driving force" is 5 at 60 psig, the resultant ozone TE is estimated to be 85%. To obtain 95% TE, the required "driving force" is 1.6. When the venturi-inlet water pressure increases from 60 psig to 80 psig (94.7 psia), TE improves to 88%, assuming that the required "driving force"

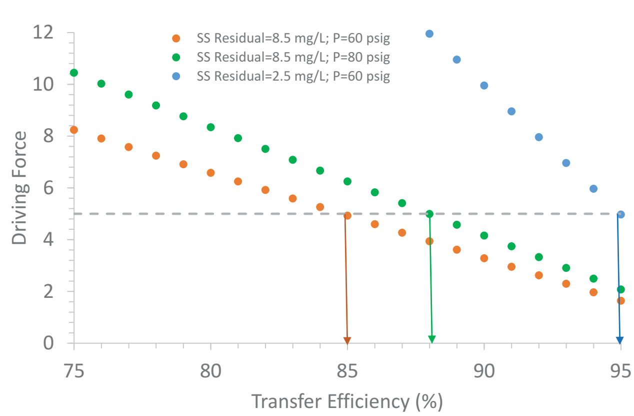


Figure 8. Relationship between driving force and transfer efficiency for different ozone sidestream operating conditions (T = 15°C, ozone gas concentration = 10%wt.).

remains unchanged for the transfer-performance characteristics of the $SS_{w\text{-}dg}$ equipment. TE is also improved when sidestream flow is increased, causing the required sidestream residual to decrease. When the required sidestream residual target decreased from 8.5 mg/L to 2.5 mg/L, a TE of 95% can be achieved with a "driving force" of 5.

Sidestream ozone transfer performance at the pilot plant

Results from pilot testing were used to assess how water flow and pressure impact TE and the resulting operating cost. It is recognized that direct scale-up from pilot testing is not applicable for full-scale design, but trends in the pilot-scale data can be used during full-scale design deliberations. Design and operating considerations are presented for optimizing performance and minimizing total ozone system operating cost.

Test 1: effect of changing the G/L ratio on TE and CT_{HDT}

Five G/L evaluations (#1–5) were completed using $SS_{w\text{-}dg}$ to assess the effect of changing G/L on TE and CT_{HDT} (Table 1). The data show that G/L is changed by varying the ozone gas flow and mainstream liquid flow. The factors that were held constant were sidestream water flow, applied ozone dose, sidestream venturi-inlet and -outlet water pressures, and ozone concentration. The expectation is that ozone TE (Row 8) and exposure CT_{HDT} (Row 14) will decrease as G/L (Row 5) increases. Higher G/L reduces sidestream flow, which increases the required sidestream residual (Zone 4 in Figure 1). Moreover, the sidestream gas inlet pressure (Row 13) changes from negative pressure to positive pressure with increasing G/L ratio, indicating the venturi changes from an eductor to injector, respectively. Since the required "driving force" for transfer ranged between 5 and 6.5 for the pilot plant installation (i.e., might be different for full-scale applications), the saturation residual (Zone 2 in Figure 1) must increase, which means that the off-gas ozone concentration is higher (i.e., TE is lower). Data indicates that Henry's Law can be applied to ozone contacting with sidestream injection. These results can be used, in concept, during full-scale design planning. However, the specific values from the pilot plant should not be transferred directly since scale-up considerations have not been identified.

The $SS_{wo\text{-}dg}$ results for TE and CT_{HDT} are shown for the five G/L ratios tested (Table 1; Evaluations #6–10). In all evaluations, TE and CT_{HDT} are similar at 95% and 25 mg-min/L, respectively. The G/L range of

Table 1. Pilot-scale results illustrating the effect of G/L ratio on TE during $SS_{w\text{-}dg}$ and $SS_{wo\text{-}dg}$.

Row			Sidestream with Degas ($SS_{w\text{-}dg}$)					Sidestream without Degas ($SS_{wo\text{-}dg}$)				
1	Evaluation		1	2	3	4	5	6	7	8	9	10
2	Water Flow	Lpm	43.5	64.3	87.2	107.6	122.0	44.7	64.3	87.0	107.4	118.9
3	Gas Flow, G	sLpm	1.00	1.51	2.02	2.56	2.92	1.00	1.51	2.01	2.50	2.81
4	Sidestream Water Flow, L	Lpm	25.5	25.3	24.9	24.6	24.4	15.1	14.7	14.3	14.3	13.8
5	G/L Ratio	–	0.039	0.060	0.081	0.104	0.120	0.066	0.103	0.141	0.175	0.204
6	Product-gas Ozone Concentration	%wt	8.72	8.58	8.46	8.40	8.35	8.90	8.56	8.57	8.76	8.49
7	Off-gas Ozone Concentration	%wt	0.77	1.01	1.37	1.57	1.77	0.38	0.51	0.49	0.50	0.41
8	Ozone Transfer Efficiency	%	91.2	88.3	83.8	81.3	78.8	95.8	94.0	94.3	94.3	95.2
9	Applied Ozone Dose	mg/L	2.54	2.57	2.50	2.55	2.54	2.55	2.56	2.52	2.60	2.55
10	Transferred Ozone Dose	mg/L	2.33	2.27	2.10	2.08	2.02	2.44	2.41	2.38	2.46	2.43
11	SS Injector-Inlet Water Pressure	psig	60	60	60	60	60	60.0	60.0	60.0	60.0	60.0
12	SS Injector-Outlet Water Pressure	psig	30	30	30	30	30	15.0	15.0	15.0	15.0	15.0
13	SS Injector-Gas Inlet Pressure	psig	−10.0	−5.5	−1.0	1.8	3.8	−3.0	1.5	3.8	7.5	9.5
14	Ozone Exposure CT_{HDT}	mg-min/L	21.1	18.9	17.1	16.7	15.4	22.9	24.6	25.2	27.4	26.6
15	Ozone Half-life	min	17.5	13.5	12.5	13.2	11.7	18.6	14.4	14.9	16.7	15.9
16	Residual at Contactor Inlet	mg/L	1.60	1.60	1.55	1.48	1.51	1.71	1.70	1.62	1.83	1.78
17	% Sidestream Flow	%	58.6	39.3	28.6	22.9	20.0	33.8	22.8	16.4	13.3	11.6
18	Sidestream Ozone Residual	mg/L	3.24	5.11	6.79	8.50	9.59	6.78	6.78	6.78	6.78	6.78
19	Saturation @ Measured OG	mg/L	20.93	27.52	37.53	43.01	48.37	10.43	14.20	13.59	13.75	11.21
20	"Driving Force"	–	6.5	5.4	5.5	5.1	5.0	1.5	2.1	2.0	2.0	1.7

0.066–0.204 was a little broader than that for $SS_{w\text{-}dg}$, particularly at the upper end. Ozone TE in the sidestream itself is expected to have similar response for both $SS_{w\text{-}dg}$ and $SS_{wo\text{-}dg}$. Since the overall TE did not change for $SS_{wo\text{-}dg}$, additional ozone transfer occurred in the mainstream flow. Upon reinjection of sidestream flow with gas bubbles, mixing by the PFR and remixing prior to the ozone contactor created small bubbles, which developed a large surface area for ozone transfer. The depth of the ozone contactor created the necessary driving force for additional ozone transfer.

Test 2: effect of changing venturi-outlet water pressure on TE and CT_{HDT}

At full-scale $SS_{w\text{-}dg}$ installations, a PSV is often installed on the sidestream piping between the degas tower and PFR (Figure 3). By adjusting the PSV settings, venturi-outlet water pressure (and venturi-inlet water pressure) can be controlled. Test 2 evaluated the effect of changing venturi-outlet water pressure only, while keeping venturi-inlet water pressure steady at 60 psig. At the pilot plant, it was possible to independently control water flow and pressure. However, in full-scale applications, water flow and pressure are dependent on the pump flow/head characteristics and ozone contactor geometry.

Three $SS_{w\text{-}dg}$ evaluations were possible using the pilot plant equipment. Changing venturi-outlet water pressure (30, 35, and 40 psig) and keeping venturi-inlet water pressure constant (60 psig) did not influence TE or CT_{HDT}. In all three evaluations, TE and CT_{HDT} were similar at 87% and 18 mg-min/L, respectively. A possible explanation for this occurrence may be that, downstream of the venturi, gas bubbles quickly coalesce and rise to the surface of the sidestream pipe, which significantly reduces the available surface area for ozone gas transfer. Both surface area and "driving force" are important in achieving good ozone transfer.

Five $SS_{wo\text{-}dg}$ evaluations were possible using the pilot plant equipment. Again, changing venturi-outlet water pressure (15, 20, 25, 30, and 40 psig) and keeping venturi-inlet water pressure constant (60 psig) did not influence TE and CT_{HDT}. In all five evaluations, TE and CT_{HDT} were similar at 95% and 25 mg-min/L, respectively. It is noted that a PSV is typically not installed and is unnecessary for $SS_{wo\text{-}dg}$ installations. Mixing by the PFR and remixing in the mainstream pipe prior to the ozone contactor are used to achieve additional ozone transfer that is not accomplished in the sidestream flow.

Test 3: effect of changing venturi-inlet water pressure on TE and CT_{HDT}

In full-scale $SS_{w\text{-}dg}$ applications, when sidestream pressure is adjusted (i.e., PSV setting is modified), not only venturi-outlet water pressure, but also venturi-inlet water pressure changes. During $SS_{w\text{-}dg}$, the effects on TE and CT_{HDT} were evaluated for venturi-inlet water pressures of 60, 49, and 35 psig, as shown in Table 2. Tests were performed at G/L = 0.063 and applied dose at 2.5 mg/L. To obtain similar G/L and applied dose while operating at reduced venturi-inlet water pressures of 45 and 35 psig, the ozone concentration ranged between 11.7%wt and 18.0%wt. Data indicates that TE (Row 8) and CT_{HDT} (Row 14) decreased, which indicates that TE is dependent on venturi-inlet water pressure. As such, the physical location of the venturi becomes important for maximizing TE for any given design criteria. For example, an elevated location high above the sidestream pump would reduce venturi-inlet water pressure and, as such, should be avoided, if possible.

Testing for $SS_{wo\text{-}dg}$ was also completed, with venturi-inlet water pressures reduced from 60 to 28 psig,

Table 2. Effect of changing venturi-inlet water pressure for $SS_{w\text{-}dg}$.

1	Parameter	Units	Evaluation 1	Evaluation 2	Evaluation 3
2	Water Flow	Lpm	94.6	94.7	94.7
3	Gas Flow, G	sLpm	1.60	1.24	1.01
4	Sidestream Water Flow, L	Lpm	25.3	19.6	16.1
5	G/L Ratio	–	0.063	0.063	0.062
6	Product-gas Ozone Concentration	%wt	11.77	14.62	18.01
7	Off-gas Ozone Concentration	%wt	1.54	2.11	3.38
8	Ozone Transfer Efficiency	%	86.9	85.6	81.2
9	Applied Ozone Dose	mg/L	2.57	2.49	2.52
10	Transferred Ozone Dose	mg/L	2.24	2.15	2.07
11	SS Injector-Inlet Pressure	psig	60	49	35
12	SS Injector-Outlet Pressure	psig	30	35	25
13	SS Injector-Gas Inlet Pressure	psig	−4.5	11.0	10.0
14	Ozone Exposure CT_{HDT}	mg-min/L	18.3	15.0	13.4
15	% Sidestream Flow	%	26.8	20.7	17.0
16	Sidestream Ozone Residual	mg/L	7.62	9.47	11.40
17	Saturation @ Measured OG	mg/L	42.76	49.90	62.43
18	"Driving Force"	–	5.6	5.3	5.5

respectively. As with all other $SS_{wo\text{-}dg}$ experiments, the TE was 95% due to the additional transfer that occurred in the mainstream pipe following reinjection of sidestream water flow with gas bubbles.

Test 4: effect of changing ozone concentration on TE and CT_{HDT}

By increasing the ozone concentration, the "driving force" for ozone transfer is improved especially when transfer first begins. However, as discussed earlier, the ozone concentration decreases as transfer occurs and it is the off-gas ozone concentration that influences "driving force" and TE.

Three different ozone concentrations (6.4, 9.7, and 13.2% wt.) were evaluated for $SS_{w\text{-}dg}$. An evaluation for $SS_{wo\text{-}dg}$ and changing ozone concentration was not conducted, but it is expected that TE and CT_{HDT} would, again, be about 95%. Constant applied ozone dose (2.5 mg/L) and G/L ratio (0.060) were maintained by adjusting the mainstream water flow. Other constants included venturi-inlet water pressure (60 psig) and venturi-outlet water pressure (30 psig). In Test 1 at G/L = 0.060, ozone TE was 88% and CT_{HDT} was 19 mg-min/L. As shown in Table 3 for all three evaluations, ozone TE is also 88% and ozone exposure CT_{HDT} is also 19 mg-min/L. In the pilot plant, G/L was held steady by maintaining steady gas flow (G – Row 3) and steady sidestream liquid flow (L – Row 4). Ozone production was elevated by increasing the generator power and ozone concentration (Row 6) to meet the set point dose (Row 9) at higher mainstream water flow. Saturation residual (Row 16) increased because off-gas ozone concentration increased (Row 7). However, sidestream residual (Row 15) also increased and "driving force" was similar (see Figure 8).

In a full-scale plant, sidestream water flow, mainstream flow, and ozone dose are likely unchanged when ozone concentration increases, which means that ozone production is steady and gas flow (G) is reduced. When the gas flow (G) is lower, G/L is lower and ozone TE will increase, as discussed in the results for Test 1.

Energy and operating cost considerations for sidestream systems

$SS_{w\text{-}dg}$ systems are designed and operated at low G/L and high injector-inlet water pressure. As such, sidestream pump size and power demand are greater than for $SS_{wo\text{-}dg}$. Design TE is typically 95%, but this "high" TE might not be optimum with respect to total system operating cost, especially for $SS_{w\text{-}dg}$ systems. For example, total system capital and operating cost might be optimized at 90% TE, or other, because generator size-

Table 3. Effect of changing ozone concentration for $SS_{w\text{-}dg}$.

1	Parameter	Units	Determine Effect of Changing Ozone Concentration on Ozone TE and Exposure (CT_{HDT})		
2	Water Flow	Lpm	48.1	73.8	101.1
3	Gas Flow, G	sLpm	1.50	1.50	1.49
4	Sidestream Water Flow, L	Lpm	25.3	25.5	25.0
5	G/L Ratio	–	0.060	0.059	0.060
6	Product-gas Ozone Concentration	%wt	6.37	9.68	13.23
7	Off-gas Ozone Concentration	%wt	0.75	1.09	1.57
8	Ozone Transfer Efficiency	%	88.2	88.8	88.2
9	Applied Ozone Dose	mg/L	2.51	2.52	2.53
10	Transferred Ozone Dose	mg/L	2.22	2.24	2.24
11	SS Injector-Inlet Pressure	psig	60	60	60
12	SS Injector-Outlet Pressure	psig	30	30	30
13	SS Injector-Gas Inlet Pressure	psig	−5.5	−5.5	−5.5
14	Ozone Exposure CT_{HDT}	mg-min/L	19.7	19.2	18.8
15	Sidestream Ozone Residual	mg/L	3.54	5.84	8.46
16	Saturation @ Measured OG	mg/L	20.74	30.07	43.38
17	"Driving Force" for Ozone Transfer	–	5.9	5.2	5.1

and-capital cost and generator energy-plus-oxygen costs might be lower than that for a large sidestream pump required to achieve 95% TE. Since $SS_{wo\text{-}dg}$ has additional transfer in the mainstream flow, optimization of SS TE is not as important, as long as mixing (i.e., creation of small bubbles) and "driving-force" are sufficient for the required mainstream ozone transfer.

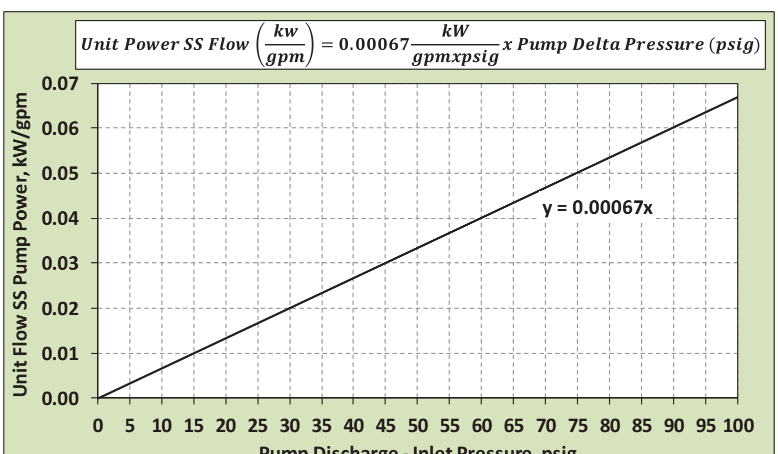
Sidestream pump power demand (kW) is affected by pump and motor efficiency (%), water flow (gpm), and pump discharge minus inlet (delta) pressure. As shown in Figure 9, unit-flow power demand is 0.053 kW/gpm at 80 psig delta pressure and 65% pump x motor efficiency. Unit-flow power is adjustable by proportion, as shown in Equation (7). For example, unit-flow power is 0.0496 kW/gpm at 70% pump x motor efficiency.

$$Unit-flow\ Power\left(\frac{kW}{gpm}\right) = \left[0.00067\frac{kW}{gpmxpsig}xDelta\ Pressure(psig)\right] x\frac{65\%}{Selected\ PxM\%} \quad (8)$$

Optimization is defined as achieving design TE at minimum sidestream pump power. Transfer theory and Test 1 and Test 3 results for $SS_{w\text{-}dg}$ indicate that G/L and injector-inlet water pressure (i.e., pump discharge pressure) had the greatest impact on ozone TE. TE increased as G/L decreased and injector-inlet water pressure increased. Ozone concentration alone (Test 4) had minimal effect. However, ozone concentration will likely affect TE in full-scale applications, because G/L will decrease in full-scale operations when ozone concentration increases.

G/L and injector-inlet water pressure affect not only TE, but also sidestream pump power demand. Selection of low G/L and high injector-inlet water pressure maximizes ozone TE, but can significantly increase sidestream pump flow (L) and power demand. Conversely, selection of high G/L and low injector-inlet water pressure reduces pump power, but also lowers ozone TE. Figure 9 illustrates that sidestream power demand increases as injector-inlet water pressure increases. Figure 10 illustrates that sidestream flow (L) increases as G/L decreases. These two charts are used to discuss design considerations for balancing sidestream ozone TE and sidestream pump power demand.

Typical design criteria for $SS_{w\text{-}dg}$ are G/L from 0.1 to 0.2 and injector-inlet water pressure (i.e., pump discharge pressure) from 40 to 80 psig (Wert, Lew, and Rakness 2016). In Table 4, $SS_{w\text{-}dg}$ pumping power demand is shown to range between 21 and 84 kW for mainstream water flow of 10 MGD, ozone dose at 3.0 mg/L, ozone



Pump Flow	1	gpm	Input
Pump (Outlet - Inlet) Pressure	80	psig	Input
Constant	2.308	ft H_2O / psi	Input
Pump Pressure	184.6	ft H_2O	= 80 x 2.308
Constant	3960	HP / gpm / ft H_2O	Input
Pump Power	0.047	HP	= 1 x 184.6 / 3960
Pump x Motor Efficiency	65.0%	%	= 0.70 x 0.929
Motor Power	0.072	HP	= 0.047 / 0.65
Constant	0.745	kW/HP	Input
Motor Power	0.053	kW	= 0.072 x 0.745
Unit-Power Flow	18.7	gpm / kW	= 1 / 0.053
Unit-Flow Power	0.053	kW / gpm	= 0.053 / 1

Figure 9. Unit-flow sidestream pump power.

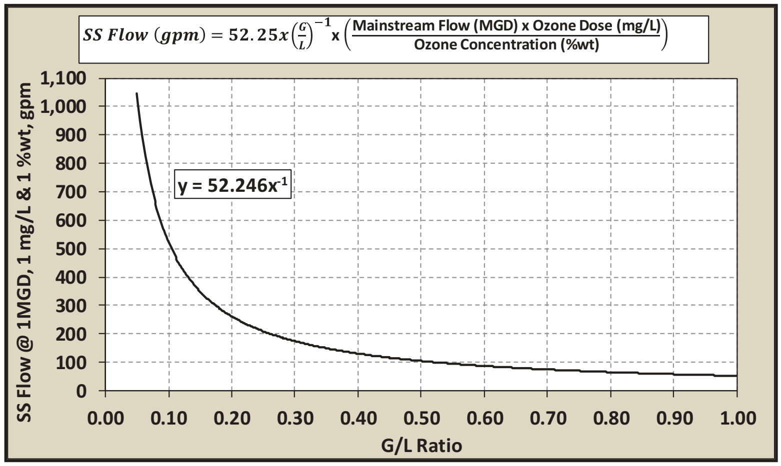


Figure 10. Sidestream flow at 1 MGD mainstream flow, 1 mg/L dose, and 1%wt concentration.

Table 4. Potential range for sidestream pump power for $SS_{w\text{-}dg}$ and $SS_{wo\text{-}dg}$.

Constant	52.25	Constant	0.00067			
Mainstream Flow MGD	Ozone Dose mg/L	Ozone Conc. %wt	G/L –	L gpm	Pump Delta P psig	Pump Power kW
Sidestream-with-Degas Potential Operating Range						
10	3	10	0.1	1568	80	84.0
10	3	10	0.1	1568	40	42.0
10	3	10	0.2	784	80	42.0
10	3	10	0.2	784	40	21.0
Sidestream-without-Degas Potential Operating Range						
10	3	10	0.3	523	50	17.5
10	3	10	0.3	523	25	8.8
10	3	10	0.7	224	50	7.5
10	3	10	0.7	224	25	3.8

concentration of 10%wt, and assumed pump inlet pressure between 40 and 80 psig. The highest power demand is at low G/L and high injector-inlet water pressure, which are design parameters that achieve the highest TE. $SS_{wo\text{-}dg}$ design criteria are G/L from 0.3 to 0.7 and injector-inlet water pressure from 25 to 50 psig (Wert, Lew, and Rakness 2016). Sidestream pump power demand is much lower, ranging from 3.8 to 17.5 kW. As discussed earlier, design G/L and injector-inlet pressure must be selected to achieve the desired TE for $SS_{w\text{-}dg}$, and mainstream transfer must be designed with mixing and "driving-force" considerations to achieve additional transfer for $SS_{wo\text{-}dg}$.

Plant turndown and sidestream pumping configurations

Water plants typically operate below design flow and dose, which is called "turndown." During turndown, ozone production and gas flow (G) are reduced. If sidestream liquid flow (L) and injector-inlet water pressure remain constant, G/L is reduced and ozone TE is better. However, sidestream pump power demand is unchanged and operating cost ($/MG) increases due to the lack of turndown capability of sidestream pumping. To avoid excess energy cost, operation at turndown is achieved by installing multiple sidestream units, such as two 50% constant-speed pump sidestream units at design and one standby (i.e., 2 + 1). In other cases, 3 + 1, or others, might be selected based on site-specific considerations.

In the case of constant-speed sidestream pump design, such as 2 + 1, it is cost effective to delay addition of the second sidestream pump at ozone production >50% design mainstream flow. Figure 11 indicates that total system unit-flow operating cost is similar when operating two sidestream pumps with elevated TE or one sidestream pump, with TE reduced to 67%. The following approach was used to develop the chart: mainstream design water flow is 10 MGD, applied ozone dose was 3.0 mg/L, ozone concentration was 10%wt, and ozone TE was 95%. Design criteria for the $SS_{w\text{-}dg}$ system were G/L of 0.20 and sidestream pump delta pressure of 80 psig. In Table 4, the total required sidestream pump power is 42 kW for these conditions, or 21 kW for each sidestream pump in a 2 + 1 design.

Operating cost was developed with energy price at 0.10 $/kWh, LOX/GOX price at $0.05/$lb_{O2}$, and generator unit power at 5.5 lb/day/kW. Since the required transferred ozone dose was 2.85 mg/L (i.e., 3 mg/L x 95%), the required applied ozone dose and ozone production are greater as TE is reduced. Generator and oxygen feed-gas operating cost is higher when ozone production increases, but sidestream pump power (either 1-SS pump or 2-SS pumps) remains unchanged. Again, the total system operating cost is similar when operating two sidestream pumps with elevated TE or one sidestream pump, with TE reduced to 67%. This means that it is more economical

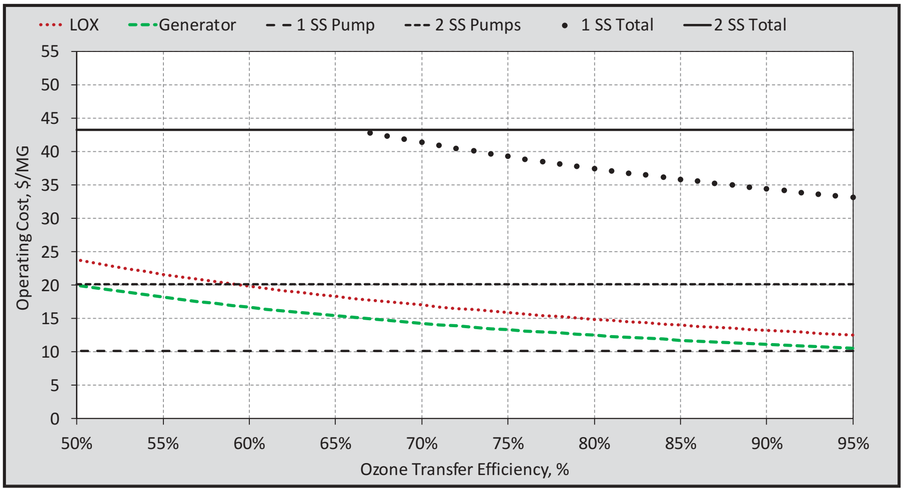


Figure 11. Unit-flow operating cost at 50% design mainstream flow.

to delay start-up/operation of the second sidestream pump when the required ozone production is >50% of the design mainstream flow. During full-scale operation, the point at which the second sidestream pump is activated is when the total system operating cost is greater when operating one pump to achieve the desired water treatment performance.

Full-scale plant control logic will have set points for automatically bringing into service another sidestream pump or removing from service a sidestream pump. Set points might be G/L or gas flow value. The point of the evaluation above is that set point G/L or gas flow does not need to be 50% of design, or 33.3% of design in case of 3 + 1 sidestream design. Set point G/L or gas flow value might be higher. A special study should be conducted to identify optimum set points. Factors affecting set point selection include price of energy, price of LOX, generator efficiency, ozone TE, and sidestream pump power demand.

Another design optimization consideration is the selection of variable speed pumps for adjustment of sidestream flow and operating pressure. By reducing sidestream flow (L), it is possible to maintain design G/L at "reasonable" turndown conditions. "Reasonable" is regulated by pump flow (L) at minimum speed. G/L will be lower at extreme turndown conditions that result in very low gas flow (G). Reducing speed and pump flow (L) will reduce operating cost to a limited extent. In addition, reducing pump pressure will result in even greater savings. However, reducing both flow and pressure must be balanced with effect on ozone TE, since both parameters will influence the overall TE.

A case study illustrates the benefit of reducing both sidestream water flow and pump discharge pressure using VFDs. The Region of Halton, Oakville WTP, has a variable-speed $SS_{w\text{-}dg}$ installation that reduces both sidestream flow and pressure because there is no PSV located between the degas vessel and PFR. The measured pump power demand was 68 kW for design conditions of G/L = 0.15, 51 psig injector-inlet gas pressure, 1780 rpm pump speed, and 65% pump/motor efficiency. At speed 890 rpm, the measured pump power demand was 10 kW, G/L = 0.095, injector-inlet gas pressure was 15 psig, and pump/motor efficiency was 65%.

In the calendar year 2015, average ozone production at the Oakville plant was 16% of design due to low water flow (32% of design) and low applied ozone dose (50% of design). The sidestream pump speed was controlled manually by the plant operators and averaged 1160 rpm. At this speed, the pump power demand was 21 kW (31% of the design). Additional data indicate G/L = 0.059, 22 psig injector-inlet water pressure, and 65% pump motor efficiency. Pump power demand would have been significantly greater if the design prevented flexibility to reduce injector-inlet operating pressure as well as pump flow at lower pump speed. This design flexibility provides plant staff with cost-optimization tools for variable turndown operating conditions.

Conclusions

Design considerations for sidestream ozone injection systems with degas ($SS_{w\text{-}dg}$) and without degas ($SS_{wo\text{-}dg}$) are reviewed in this paper. For either type of sidestream system, moisture contamination of ozone supply lines can create nitric acid, leading to corrosion of the ozone gas stainless steel piping to the venturi, or conditions for the auto-decomposition of ozone gas that releases heat and degrades applied ozone dose. Appropriate order and layout of piping and equipment are necessary to prevent trapping of liquid water that might come from the sidestream during unplanned events such as power failure, or evaporation and condensation that might occur when units are offline. Suggestions for design layout of ozone gas supply piping into the venturi are included in this paper.

Ozone transfer is governed by the gas–liquid transfer theory, which mainly includes gas bubble surface area and driving force for transfer. Ozone TE details are included, including examination of pilot-scale operating data from Water Research Foundation Project 4588 (Wert, Lew, and Rakness 2016) for both $SS_{w\text{-}dg}$ and $SS_{wo\text{-}dg}$ under variable operating conditions, including changing sidestream G/L ratio, venturi-inlet water pressure, venturi-outlet water pressure, and ozone concentration. Key performance results included ozone TE and "total" ozone exposure (CT_{HDT}) through measurement of ozone residual (C) and total hydraulic detention time (T_{HDT}) with exposure to ozone residual.

Traditional sidestream system design focuses on achieving maximum ozone TE, with less attention paid to the amount of energy required to achieve that goal. Large sidestream pump flow and high discharge pressure improve TE, but increase sidestream pump operating cost. Design and operating considerations are presented to help designers and users achieve a more balanced approach for optimizing performance and minimizing total ozone system operating cost.

Dedication

This publication is dedicated to coauthor Kerwin L. Rakness, who passed away on June 9, 2016. Throughout his career, Kerwin exemplified outstanding technical engineering skill, brilliant diplomatic talent, and constructive leadership within the water industry. He graciously taught numerous professionals, including utility managers, operators, technicians, consultants, academics, manufacturers, and regulators, how to effectively use ozone technology to protect human health for millions of people around the world. Many of his experiences were shared in his AWWA book titled "Ozone in Drinking Water Treatment: Process Design, Operation, and Optimization," which is a key reference for anyone working in the municipal ozone field. Kerwin was also very passionate about sharing his experiences and knowledge through the International Ozone Association (IOA).

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Other members of the project team provided valuable insight regarding ozone design and operation, including Jeff Neemann (Black & Veatch), Chris Schulz (CDMSmith), and Glenn Hunter (Process Applications Inc.). Bill Mundy (Regional Municipality of Halton) provided case study information regarding the full-scale performance of three treatment plants utilizing different mass transfer systems. Craig Thompson (West Yost Associates), Joe Drago, and Jean Debroux (Kennedy Jenks) provided access to the ozone utility database. Jim Jackson (Mazzei Injector Company) provided insight regarding the design and operation of the pilot-scale sidestream injection system and pipeline flash reactor.

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