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W. Ludwig Kuhn[1], Bjørn Winther Solemslie[1,2], Jean-Yves Hihn[3] and Ole Gunnar Dahlhaug[1*]

[1] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[2] Norwegian Institute for Nature Research, Trondheim, Norway
[3] UTINAM UMR 6213 CNRS, Univ. Bourgogne Franche Comte, Besançon, France

E-mail: * ole.g.dahlhaug@ntnu.no

Abstract. In Norway, a recent project used a risk matrix to identify about 200 hydropower plants (11 % of the total number) of being in high risk of producing air-supersaturated water. The combined installed capacity of these hydropower plants amounts to more than 45 % of Norway's total installed hydropower capacity. Total dissolved gas (TDG) supersaturation in water is, dependent on the actual saturation value and the duration of the occurrence, lethal to certain types of fish and aquatic invertebrates. Natural degassing is highly dependent on the morphology of the downstream water system, but tends to be insufficiently slow with regard to lethality of TDG supersaturation. The Brokke power plant in southern Norway is known to create TDG supersaturation. Since 2012, continuous monitoring of the TDG level happens at the power plant outlet and several positions in the Otra river downstream. Measurement data has been evaluated and a method has been developed to calculate the liquid-gas mass transfer coefficient k_La as an indicator for the natural degassing efficiency within certain stretches of the river using assumptions for the river's geometry. The results are in agreement with former evaluation of the measurements. At the Waterpower Laboratory at NTNU in Trondheim, Norway, a test rig has been designed and instrumented to prove the effectiveness of degassing methods. An in-house pressure system is used to produce air-supersaturated water, which is then channeled through an open flume. At the flume's inlet, the degassing mechanism is installed. The TDG levels are monitored both upstream and at downstream the degassing device. The k_La will be used to compare natural degassing in the river downstream Brokke power plant to the experimental degassing methods in the Waterpower Laboratory.

1. Introduction

Total dissolved gas (TDG) supersaturation is a hazard for fish and aquatic invertebrates downstream hydropower plants. Although being discovered in the 1970s in the Columbia and Snake rivers (USA) [1–3], and their source being linked to hydropower soon after [4], protective measures by introducing official guidelines and thresholds for TDG levels of 110 % only emerged to date in the USA [5] and Canada, where the latter one only applies to rivers with a depth of more than 1 m [6, 7]. Besides those two countries, research on hydropower-induced TDG supersaturation is only known from China and Norway. Being linked to increased flooding, the problem is supposed to increase in the northern hemisphere due to climate change and subsequently increased extreme-precipitation events [8–12].

In Norway, the problem of hydropower plants producing air-supersaturation was discovered in the mid-1970s and investigated until the early 2000s, ultimately resulting in design guidelines by the authorities [13–19]. A cause for the problem was discovered early on by Mellquist (1979) [13] in secondary (or brook) intakes, which give rise to air entrainment into the tunnels. In addition, the effects of TDG supersaturation on fish were studied. Prevention measures were proposed, including structural adjustments of brook intakes to prevent air entrainment. A summary of air-supersaturation caused by Norwegian hydropower plants is given by Berg's report to the Norwegian Water Resources and Electricity Board - State Power System [20].

A recent Norwegian project called SUPERSAT under the lead of the Norwegian Research Center (NORCE) introduced a risk-matrix to evaluate the risk of hydropower plants for production of air-supersaturated water. The main focus of the project is the Norwegian hydropower sector, as the country has the largest installed hydropower capacity in Europe [21] due to the country's specific topography, which in turn allows for a wide use of mid- and high-head Francis turbine power plants. In addition, hydropower plants in Austria and Germany were classified into different risk levels. As a result, 10.8 % of the Norwegian hydropower plants evaluated, amassing 45.2 % of the total installed capacity, are suspected to have higher risk of producing total dissolved gas supersaturation. A chosen number of power plants in the highest risk class will be equipped with sensors to permanently monitor the TDG level and validate the risk assessment [22, 23].

The TDG saturation within a water body can be displayed by the ratio of total gas pressure (TGP) to ambient pressure, thus giving a percentage where 100 % describes the saturation at equilibrium. A higher TGP leads to values above the equilibrium, thus indicating TDG supersaturation. Increased TDG values will have negative effects on fish and other aquatic invertebrates having their habitat in the river downstream the hydropower plant when exceeding a level of about 110 %, depending on the species being exposed, its age and size as well as the depth of the river [22]. One direct consequence is gas bubble disease (GBD) in fish, i.e. the temporary formation of gas bubbles within the tissue of the fins, the eyes or intestines. Depending on the level of TDG supersaturation and the exposure time, the effects are reversible, yet making the fish more fragile for secondary diseases, or lead to lethal gas embolism within organs or blood vessels. Although the disease has been discovered and described during the emergence of public aquaria in the end of the 19^{th} century [24–26] and later occurred during the implementation of fish hatcheries [27, 28], its connection to hydropower as well as its influence on the aquatic environment downstream hydropower plants are still subject of numerous studies, e.g. [29–35].

Therefore, the research of degassing mechanisms in order to reduce the TDG level in the power plant prior to releasing water into the downstream river or reservoir is increasing. The DeGas project under the lead of the Norwegian University of Science and Technology (NTNU) aims to raise knowledge within this topic. A difficulty in studying TDG supersaturation in hydropower is the amount of water needed for continuous flow experiments as well as scaling from model tests to actual large hydropower plants. The Brokke power plant in Otra, Norway, is the hydropower plant studied most within the SUPERSAT project and has a maximum volumetric flow rate of $136\,\mathrm{m}^3/\mathrm{s}$ [36]. The supersaturation occurs due to air entrainment at secondary intakes and the high pressure coming from 303 m head, leading to dissolution of air into the water body. Even though TDG supersaturation may occur in hydropower plants smaller than that, each power plant has a specific design and different operational settings. As most of the parameters of actual hydropower plants are impractical for laboratory settings, different ways to reach TDG supersaturation and subsequent degassing mechanism testing need to be studied. The aim of the work presented here is to enable standardized and repeatable experiments to evaluate different concepts for degassing.

Most studies found on the topic of hydropower related TDG supersaturation examine either

the effects on the environment, as mentioned earlier, or the reduction of the TDG level by natural or artificial means. Most of the latter cases use actual hydropower plants for their studies, where e.g. degassing by ski-jump spillways [37] or aeration deflectors [22] are tested. Those are site-specific and may not be applicable to a large number of hydropower plants. Laboratory experiments on the other hand have the need of creating an artificial supersaturation within a specified volume of water used during the tests. In addition, the ability to adjust the TDG level is a key element, especially within GBD and degassing studies. Few studies exist that have achieved a substantial increase of the TDG level under controlled circumstances, using either air introduction into pressurized water for TDG saturation values up to 145 % [30] or oxygenation cones for up to 130 % [22]. Both studies focus on the effects of TDG supersaturation on different fish species. No experimental research on the desorption of air from flowing water under laboratory conditions is not known to exist by the authors.

2. Methods

At the Waterpower Laboratory at NTNU, an experiment is designed to investigate different methods to desorb excess dissolved gases from flowing water. The experiment is comprised of two steps: First, a certain volume of water is pressurized and compressed air is introduced into the water body to increase the saturation level. The second step is the controlled release of the water from the pressure vessel into a channel where it passes a degassing device. The TDG level is monitored during the first step as well as before and after the degassing device in the second step. In addition, the temperature, pH value and electroconductivity is monitored. The flow velocity is controlled by the outlet of the pressure vessel and the applied pressure. A detailed description of the different parts of the experimental setup follow in this section.

2.1. Supersaturating water

Different methods of supersaturating water with air exist. Following Henry's law, the solubility of gases is directly proportional to the ambient pressure [38]. A simple method of increasing the saturation within a water body is therefore increasing the ambient pressure and providing an interface between the gaseous and liquid phase. At the Waterpower Laboratory, a pressure tank with a total volume of 18 m^3 is used to pressurize 15 m^3 of water to 2 bar ambient pressure. The pressure is monitored by a GE PTX 610 pressure sensor at the top and another one at the bottom of the tank. In addition, a PT100 thermometer is used to measure the temperature of the water, while an InWaterTech PT4 TDG sensor monitors the TDG level at the bottom of the tank. The TDG sensor consists of a sealed silastic tubing which is coiled on a cartridge. The tube is semipermeable, allowing only gases and water vapor to diffuse through it. An increase in the level of dissolved gases will therefore increase the pressure within the tubing, which is then detected by a pressure sensor. The reading is often referred to as total gas pressure (TGP). This TDG sensor and all the other ones used during the different experiments at the Waterpower Laboratory are calibrated using a method described by [39]. A Grundfos TP 40-50/2 circulation pump is used to mix the water body and assure a uniform contribution of the dissolved gases within the tank. National Instruments DAQ modules and LabVIEW are utilized for data acquisition. Compressed air is supplied to the system from an in-house compression system and regulated to an over-pressure of 1 bar using a Festo MS4-LR pressure regulator. To increase the interfacial area between air and water, an oxygenation stone is functioning as a nozzle, providing a large amount of small air bubbles to the bottom of the pressure tank. Due to the combined ambient pressure inside the tank and the hydrostatic pressure of the water body, the air will partly dissolve while traveling through the water column to the air pocket on top of the tank. Since the supply of air into the pressurized system increases the pressure, an adjustable Brewtools spunding valve with a pressure range of 0.2 bar to 2.2 bar on top of the pressure tank functions as a pressure relief valve.

2.2. Water release
A sudden decrease in the pressure of a vessel will change the saturation of the contained liquid, which then in most cases is supersaturated and will instantaneously start to desorb gas naturally. An example would be the first opening a bottle of soda. To avoid a pressure drop at the outlet of the pressure vessel used to increase the saturation level of the water, hoses with a length of 15 m are used to transfer the water from the pressure vessel to the degassing channel. Each hose is connected to a valve at the outlet of the pressure tank. The length of the hoses lead to a slow pressure decrease due to friction losses, thus smoothening the transition between the pressurized vessel and the atmospheric pressure at the degassing channel.

2.3. Degassing channel
The degassing channel consists of an open channel with a length of 17.8 m and a cross section of 300 mm by 400 mm. The inlet of the channel consists of two diffusers separated by a flow straightener. The channel enables multiple positions for degassing devices, both in between the two diffusers and at any point within the channel. The outlet of the channel is a V-notch weir, which in connection with a VEGA Vegabar 14 pressure sensor with a measurement range of 0.0 bar to 0.1 bar utilized to measure flow, following ISO 1438. The design of both V-notch weir and channel are described in detail in [40]. The flow rate can be controlled through the opening and closing of the valves at the pressure tank outlet. With one open valve, the flow rate is 2 dm^3/s, while opening both valves result in 4 dm^3/s. The TDG level is monitored by several INWATERTECH PT4 TDG sensors placed within the first diffuser, at the channel inlet and at 4.25 m, 9.25 m and 14.25 m downstream the channel inlet. At each of the sensor positions downstream in the channel, a window for visual access is provided. Another window is placed within the second diffuser in the inlet section. pH and conductivity are measured using a SENSOREX pH3400 and CS150 sensor, respectively. Those are placed downstream the degassing device to detect possible changes introduced by the gas desorption.

The design of the channel with its double inlet and the V-notch weir limit the flow velocity within the channel to 3.7 cm/s. This poses a challenge, as the small water depth and slow current do not prevent gas bubbles, caused by natural degassing, from forming up on surfaces. This leads to disturbances of the pressure readings of the TDG sensors due to gas bubbles forming up on its silastic membrane. To prevent this, a timed, local acceleration of the water is provided by EHEIM compactON 5000 pumps underneath the channel, increasing the flow velocity to 1.97 m/s, thus flushing away bubbles attached to the TDG sensors. The pumps take in water at the bottom of the channel and release it directly onto the TDG sensor. The intake and the outlet of the pumps are 100 mm apart, thus insuring the same TDG level of the water being flushed onto the sensors. A drawing of the degassing test rig is provided in figure 1.

2.4. Calculation of the liquid-gas mass transfer coefficient
The liquid-gas mass transfer coefficient k_La is the product of the partial transfer conductance (i.e. the rate of molecular diffusion) of the liquid (k_L, [m/s]) and the interfacial area (a, [m^2/m^3]). It is calculated using an equation for mass transfer between a liquid and a gaseous phase.

$$\emptyset = V\, k_La\, (C_{gas,average} - C^*)\,, \tag{1}$$

Here, $\emptyset$ is the loss of dissolved gas between two measurement points, V is the volume of this section, $C_{gas,average}$ is the average concentration of dissolved gases and C^* is the baseline concentration, i.e. the concentration of dissolved air at a TDG level of 100 %. Given two measurement locations A and B, the loss of dissolved gases is calculated from a concentration difference, while the average gas concentration is calculated using the logarithmic mean.

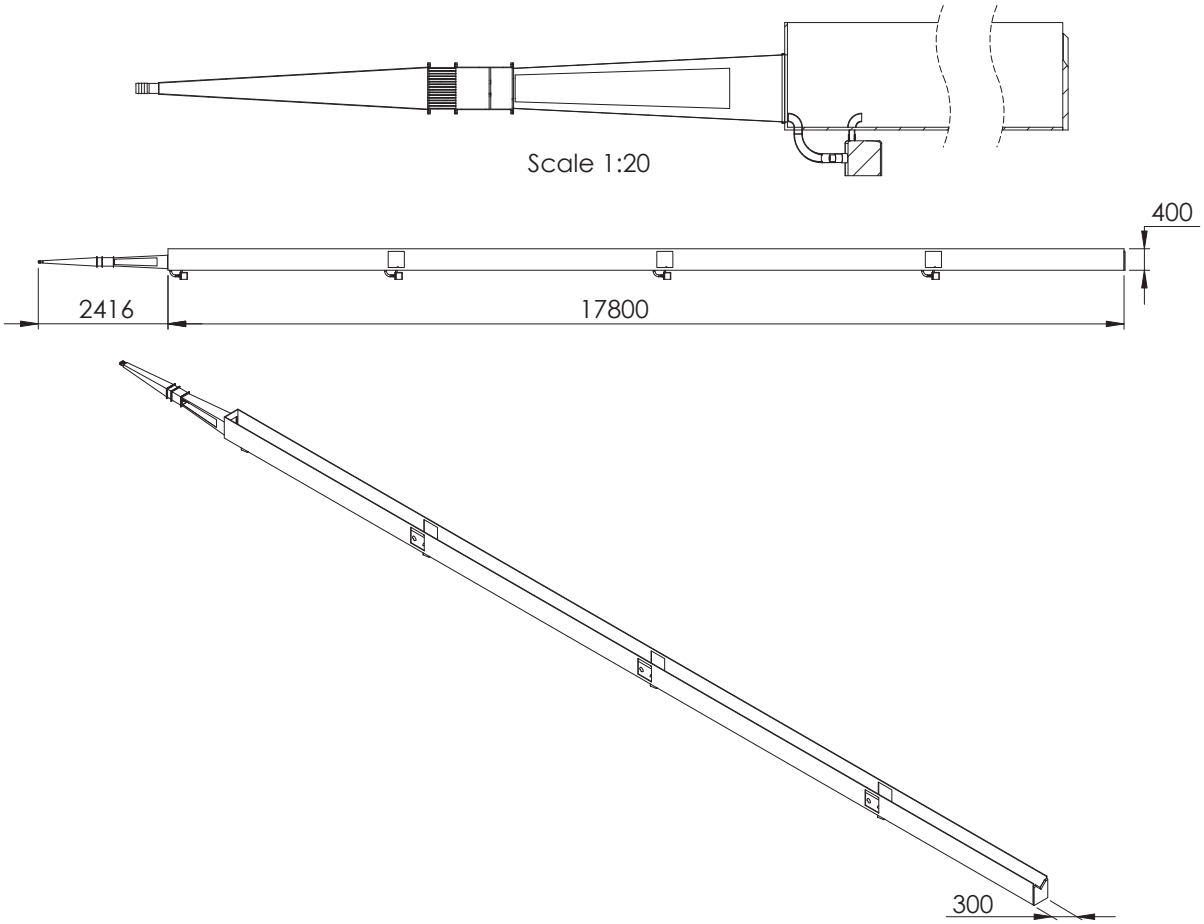


Figure 1: Drawing of the test rig used for testing degassing methods at the Waterpower Laboratory at NTNU. Detailed view of the modular inlet featuring two diffusers and a flow straightener (top), side view (center) and isometric view of the full test rig (bottom). The flow direction is from left to right. Four pumps for local acceleration of the flow are positioned below the channel. The units are mm.

$$\emptyset = (C_A - C_B)\, Q \tag{2}$$

$$C_{gas,average} = \frac{C_A - C_B}{\ln C_A - \ln C_B} \tag{3}$$

$$C^* = 100\,\% \cdot 1.053\,\mathrm{mol{\cdot}m^{-3}} \tag{4}$$

C_A and C_B in the equations above are the concentrations at point A and B, respectively, and $1.053\,\mathrm{mol/m^3}$ is the concentration of air in water at 15 °C and 1 atm. Plugging in equation 2 and 3 into equation 1, an expression for k_La is derived as shown below.

$$Q(C_A - C_B) = V k_L a \left(\frac{C_A - C_B}{\ln C_A - \ln C_B} - C^* \right) \tag{5}$$

$$\Rightarrow k_L a = \frac{Q(C_A - C_B)}{V \left(\frac{C_A - C_B}{\ln C_A - \ln C_B} - C^* \right)} \tag{6}$$

2.5. Field measurements

The TDG level in the Otra river in southern Norway was monitored at the outlet of the Brokke hydropower plant and several downstream positions in the period of 2012 to 2016. During that period, multiple TDG supersaturation events were observed and the cause specified to be secondary intakes at the power plant. The TDG sensors used for monitoring were provided by Fisch- und Wassertechnik [36]. Data from July 10^{th} to December 12^{th}, 2012, was used for the calculation of the gas-liquid mass transfer coefficient k_La, which is evaluated from the decrease of the TDG level between the power plant outlet and the measurement positions 1.2 km, 1.5 km and 8.0 km downstream the power plant.

At the outlet, one measurement was taken every hour. Due to a defect on the probe placed 1.5 km downstream, all data until October 4^{th} was disregarded. From that date, the measurement period of the probe placed at the power plant outlet was changed to one measurement every 30 minutes to be in line with the downstream positions, where the measurements were taken every 30 minutes from the beginning. The river's volume used for the calculation is simplified by assuming conic sections between the Brokke power plant outlet and the downstream positions. The cross sectional areas at the measurement positions are determined from topological models. From those, the rough width of the river at the position was multiplied width the average depth. The resulting cross sections are 145 m^2, 185 m^2, 135 m^2 and 75 m^2 for the outlet of Brokke power plant and 1.2 km, 1.5 km and 8.0 km downstream, respectively. For the volumetric flow rate of the river, the annual average of 93.87 m^3/s for the measurement period from January 2012 to September 2015 is used.

The saturation curves of each wave of supersaturated water detected at the downstream positions are lengthened in time in comparison to the measured values at the power plant outlet. Therefore, a deconvolution of the curves is used to calculate the average concentration during the saturation event and between the measurement points. During the deconvolution, a polynomial fit is used on the measurement data, which is then shifted both in x- and y-direction to correct for the time-shift between the measurements. The process is displayed in figure 2 for one TDG supersaturation event occurring at Brokke power plant.

The gas-liquid mass transfer coefficient is again calculated from equation 1. Ø is here estimated from the difference of the average concentration during a measurement at two different points (here A and B), while $C_{gas,average}$ is represented by the average between the initial concentration at point A and the concentration of the deconvoluted measurement curve from point B:

$$\text{Ø} = \left(\frac{\int C_A dt}{t_A} - \frac{\int C_B dt}{t_B} \right) Q \tag{7}$$

$$C_{gas,average} = \frac{1}{2} \left(\frac{\int C_A dt + \int C_{B'} dt}{t_A} \right). \tag{8}$$

Here, t_A and t_B are the total time of occurrence of the supersaturation event at point A and B, respectively. The $'$ denotes deconvoluted values.

3. Results

3.1. Natural degassing in the Otra river

The decrease of TDG due to natural degassing within the Otra river downstream the Brokke hydropower plant is evaluated between the power plant outlet and 1.2 km, 1.5 km and 8.0 km downstream. The coefficient chosen for evaluation of the decrease is the gas-liquid mass transfer coefficient k_La, calculated from Equation 1, using Equations 7 and 8. As initial value for the calculation (point A in the equations), the power plant outlet is used in all cases. The

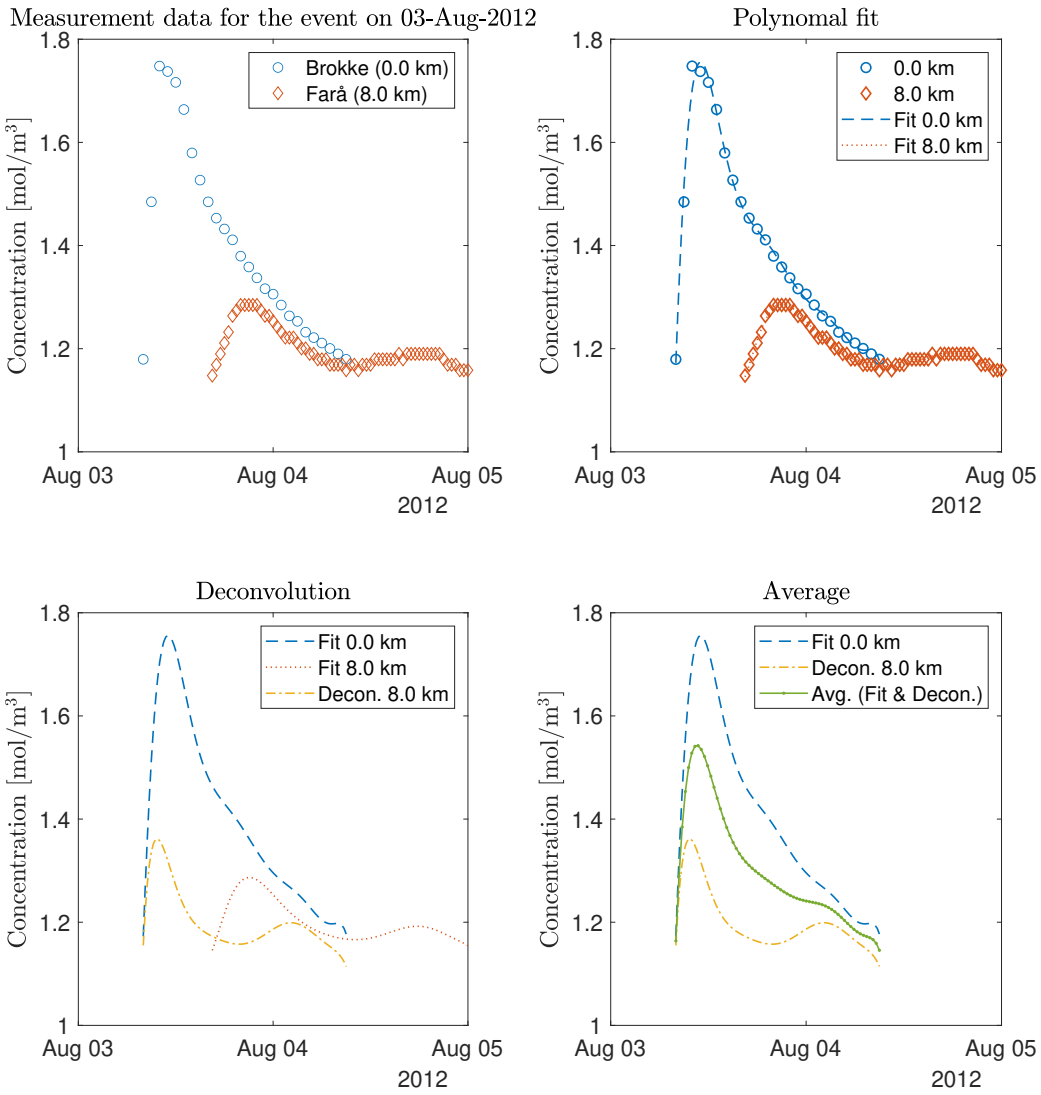
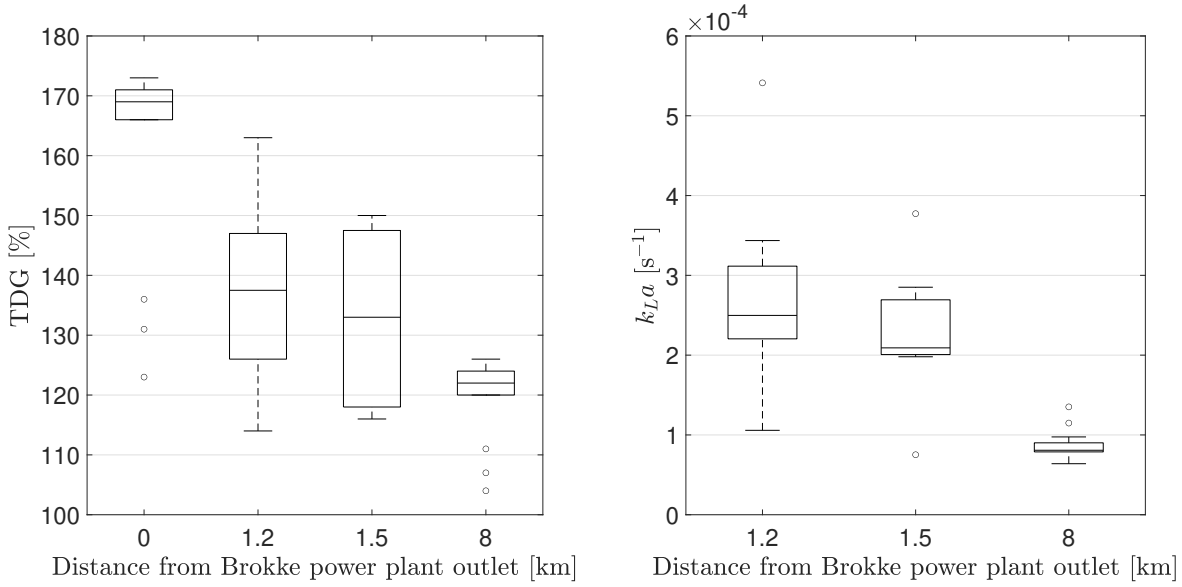


Figure 2: Step-by-step process of calculating the average concentration from measurement data by polynomial fitting and deconvolution.

measurement data from the positions downstream are respectively used as point B in the calculation.

In figure 3, both the range of maximum measured TDG values at the different measurement positions during the different TDG supersaturation events (3a) and the range of resulting calculated k_La values between the power plant outlet and the respective downstream measurement position (3b) are shown for 14 events during the second half-year 2012. For the maximum TDG level at the 1.5 km measurement position and the k_La values between this position and the outlet, only 7 events were used. The actual values for the maximum measured TDG level and respective k_La values for the TDG supersaturation events are listed in table 1.

The calculated k_La values between the outlet of Brokke power plant and the respective



(a) Maximum measured TDG level (b) Calculated k_La values

Figure 3: Range of maximum TDG level and calculated k_La values at Brokke power plant outlet and downstream measurement positions for TDG supersaturation events during 2012.

downstream measurement positions, shown in figure 3b, are highest during the first kilometers of river. Correspondingly, the TDG level, as shown in figure 3a, decreases rapidly between the outlet and the first measurement position (1.2 km downstream), while the subsequent decrease is less distinct with regard to the distance to the last measurement station. This is in agreement with the findings of [36]. The range of k_La values is higher for the first kilometers of river, whereas the values at 8 km downstream are close together. They correspond well with the range of measured maximum TDG level at 1.2 km and 1.5 km downstream.

3.2. Supersaturating water for laboratory experiments

The increase in TDG level within the in-house pressure system has been investigated. A decrease in time to reach the desired level is achieved by increased system pressure and increased interfacial area between the injected air and the water. Several air inflow pressures into the pressurized system have been tested. The saturation increase over time has a peak at an air inflow pressure of 1.5 bar above the system pressure at the air inlet, independent of the system pressure. Below this pressure, the inflow of air into the water is too little to have a fast increase in saturation. A higher air pressure results in too much coalescence of bubbles before separation from the oxygenation stones, thus leading to slower saturation due to a decrease in interfacial area. The highest rate of saturation increase is achieved at 1.5 bar relative air pressure at the inlet in combination with 20 mwc system pressure (measured at the top of the pressure tank), and is on average 20 pp/h [41]. The decrease in time to desired saturation is linear dependent on the system pressure, following Henry's law. The maximum system pressure is limited by the pressure relief valve installed on top of the pressure tank, which has a maximum threshold pressure of 2.2 bar.

3.3. Resulting test rig for laboratory degassing experiments

The test rig was designed, built and instrumented at the Waterpower Laboratory at NTNU in order to test different degassing mechanisms. The intention is to increase the removal of dissolved air from water to reduce the TDG level to ecologically tolerable levels, i.e. below 110 % TDG

level [42]. Its open channel and adjustability for the positioning of a degassing device together with the possibility to adjust the flow rate within the channel makes it possible to investigate different means of gas desorption from flowing water. The flow within the channel is laminar and uniform, and the transfer of water with a TDG supersaturation from the pressure system to the channel happens without significant losses. The TDG sensors are installed at the bottom of the channel behind the outlet of the respective aquarium pump, facing the flow with the bottom opening. The placement at the bottom helps reducing the attachment of bubbles on the silastic membrane, and the timed removal of bubbles by flushing them away with accelerated water from the pumps works. Tests show that the TDG level is monitored well and that the sensors react to different levels of saturation. The response time to reach 95 % of the actual measurand's value (t_{95}) of the sensors is 7 minutes according to the manufacturer [43]. In TDG supersaturation cases, the time to reach saturation is 10 minutes to 15 minutes depending on the degree of TDG supersaturation.

4. Discussion

4.1. Evaluating natural degassing in a the Otra river

Summarizing figure 3b and table 1, the average liquid-gas mass transfer coefficient for natural degassing of TDG supersaturated water in the Otra river downstream Brokke power plant is $2.69 \cdot 10^{-4}\,\mathrm{s}^{-1}$, $2.25 \cdot 10^{-4}\,\mathrm{s}^{-1}$ and $0.87 \cdot 10^{-4}\,\mathrm{s}^{-1}$ for 1.2 km, 1.5 km and 8.0 km downstream, respectively. The high values at the first measurement station is also elevating the k_La values at the measurement positions further downstream, as the TDG level decline is less distinct. A calculation of the average k_La between the measurement positions at 1.2 km and 8.0 km downstream gives a value of $0.46 \cdot 10^{-4}\,\mathrm{s}^{-1}$, which is roughly half of the value from the outlet of Brokke power plant and 8.0 km downstream. This has two reasons: Firstly, the TDG level has its peak at the outlet of the power plant, without any further increase happening downstream. The TGP is therefore highest in the first stretches of the river, meaning that the pressure difference at the interface between water and air (i.e. the water surface) is high, leading to a high natural driving force towards equilibrium. The driving force decreases together with the TDG level. Secondly, the river geometry differs significantly upstream and downstream approximately 2 km downstream Brokke power plant, as the river then widens from this point. This widening of the river yields a lowering of the flow velocity and thereby a reduction in the turbulence levels in the flow. As turbulence may be considered a linear driver of natural degassing, this plays a role in the difference in average k_La values.

As shown before, the calculation of the k_La values follows some simplifications and assumptions regarding the volume, geometry and flow rate of the river between the measurement stations. Therefore, the results are just applicable to the Otra river downstream Brokke power plant and serve as a mere indication of natural degassing in a river. In addition, the long measurement intervals make an exact determination of the maximum TDG during the TDG supersaturation events difficult, but it is assumed that general trends are well captured by the available data. The calculated k_La values are therefore regarded as good indicators for natural degassing efficiency in the Otra river downstream the Brokke hydropower plant.

4.2. Establishment of a test rig for testing of different degassing methods

Supersaturating water for experiments in laboratory conditions is dependent on the pressure and the volume of water within a pressurized system. Ideal conditions are found in high-pressure systems with an air inflow at 1.5 bar relative pressure at the inlet. The aim is an increased interfacial together with an increased retention time of the air to make dissolution possible. The system used at the Waterpower Laboratory is limited with regard to volume and pressure available, as the pressure relief valve has a maximum threshold pressure of 2.2 bar. Still, TDG

supersaturation of 15 m^3 of water to use for degassing experiments is achieved in a reasonable time.

The k_La values for natural degassing in a river are used as a baseline for a comparison with laboratory experiments at the Waterpower Laboratory at NTNU. The test rig designed for degassing experiments under controlled laboratory conditions is supplied with TDG supersaturated water from a pressure system using long pressure hoses to smoothen the pressure difference between the two systems. The transfer of the water from the pressure system to the degassing channel happens without natural degassing losses. The instrumentation used for measuring the TDG level is reliable, but the response time in TDG supersaturation conditions is with 10 minutes to 15 minutes long, especially when compared to optical dissolved oxygen probes, which reach a $t_{95} < 60$ seconds. The decision to measure the TDG level despite its long response time is due to possible differences in degassing efficiencies of the different dissolved gases (mainly nitrogen and oxygen). GBD in fish mostly stems from dissolved nitrogen [42], which is not possible to be measured in real time and in situ. Therefore, measuring the TDG level is a good alternative to include dissolved nitrogen.

5. Conclusion

A method has been developed to calculate the liquid-gas mass transfer coefficient k_La from measurement data of the total dissolved gas (TDG) level during TDG supersaturation events in the Otra river downstream Brokke power plant in southern Norway using assumptions for the river's geometry and flow rate. As the supersaturation stems from the power plant, the highest TDG levels are measured at the power plant outlet. The k_La values are correspondingly the highest between the power plant outlet and the first measurement station 1.2 km downstream. The average values for the river stretches between the Brokke power plant outlet and the downstream measurement stations are $2.69 \cdot 10^{-4}\,s^{-1}$, $2.25 \cdot 10^{-4}\,s^{-1}$ and $0.87 \cdot 10^{-4}\,s^{-1}$ for 1.2 km, 1.5 km and 8.0 km, respectively. These values are achieved by assuming the river's geometry and flow rate, but serve as a baseline for comparison with technical solutions to TDG supersaturation.

The degassing mechanisms to be tested at the Waterpower Laboratory at NTNU are expected to increase the k_La. In order to achieve an instantaneous reduction of the TDG level to biologically tolerable values, this increase needs to be substantial. This is possible by increasing either the partial transfer conductance k_L or the interfacial area a, or both together. The degassing test rig with its instrumentation will make in-depth testing of different methods for an increased desorption of gas from flowing water possible.

Acknowledgments

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Appendix

Table 1: Maximum measured TDG level at different positions in the Otra river and corresponding calculated k_La values for TDG supersaturation events in 2012.

Date	Maximum TDG				Calculated k_La [s^{-1}]		
	Brokke	1.2 km	1.5 km	8.0 km	1.2 km	1.5 km	8.0 km
23.07.2012	169 %	126 %	N/A	120 %	$3.12 \cdot 10^{-4}$	N/A	$0.70 \cdot 10^{-4}$
03.08.2012	166 %	128 %	N/A	122 %	$3.06 \cdot 10^{-4}$	N/A	$0.79 \cdot 10^{-4}$
07.08.2012	171 %	136 %	N/A	121 %	$3.16 \cdot 10^{-4}$	N/A	$0.81 \cdot 10^{-4}$
28.08.2012	169 %	146 %	N/A	122 %	$2.58 \cdot 10^{-4}$	N/A	$0.90 \cdot 10^{-4}$
30.08.2012	169 %	136 %	N/A	120 %	$2.71 \cdot 10^{-4}$	N/A	$0.80 \cdot 10^{-4}$
11.09.2012	172 %	153 %	N/A	126 %	$2.20 \cdot 10^{-4}$	N/A	$0.85 \cdot 10^{-4}$
14.09.2012	173 %	163 %	N/A	124 %	$1.75 \cdot 10^{-4}$	N/A	$0.80 \cdot 10^{-4}$
18.10.2012	166 %	139 %	133 %	123 %	$2.36 \cdot 10^{-4}$	$2.09 \cdot 10^{-4}$	$0.81 \cdot 10^{-4}$
20.10.2012	169 %	147 %	149 %	125 %	$2.23 \cdot 10^{-4}$	$2.09 \cdot 10^{-4}$	$0.78 \cdot 10^{-4}$
10.11.2012	136 %	114 %	116 %	104 %	$5.41 \cdot 10^{-4}$	$3.77 \cdot 10^{-4}$	$1.35 \cdot 10^{-4}$
12.11.2012	131 %	118 %	118 %	107 %	$2.41 \cdot 10^{-4}$	$2.22 \cdot 10^{-4}$	$1.15 \cdot 10^{-4}$
14.11.2012	169 %	146 %	143 %	124 %	$2.18 \cdot 10^{-4}$	$1.98 \cdot 10^{-4}$	$0.81 \cdot 10^{-4}$
20.11.2012	171 %	154 %	150 %	126 %	$3.44 \cdot 10^{-4}$	$2.85 \cdot 10^{-4}$	$0.98 \cdot 10^{-4}$
26.11.2012	123 %	117 %	118 %	111 %	$1.06 \cdot 10^{-4}$	$0.75 \cdot 10^{-4}$	$0.64 \cdot 10^{-4}$

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