University of Bergen

Geophysical Institute

Masters Thesis

Energy - Electrical Power Systems

Artificial gas supersaturated water from small hydropower plants: methods to detect air entrainment at intakes

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Abstract

Hydropower plants with submerged intake and Francis turbine can release artificial Total Dissolved Gas (TDG) supersaturated water from the plants outlet, if air is drawn into the pressure pipe at intake and dissolved in water at high pressure. Air entrainment at intake can be initiated by debris covered trash rack [1]. Fish exposed to TDG supersaturated water can develop Gas Bubble Disease (GBD), which is harmful and can result in fish death.

A common used small hydropower plant design consist of submerged intake, intake air vent, pressure pipe and Francis turbine. The report, "*Gassovermetning i vassdrag – en kunnskapsoppsummering*" [1], published in 2018, recommend pressure loss measurements at intake trash rack in combination with TDG monitoring in the plants outlet river as mitigations, where air entrainment is initiated by covered trash rack. The mitigation principle is described to be promising but not concluded, and in general, several topics related to supersaturation in rivers is relevant for further research [1].

This thesis have investigated if measurement of air entrainment through intake air vents can be an alternative method to indirectly detect supersaturation from the plants outlet where air entrainment is initiated by covered trash rack. Two field tests have been performed at Grønhaug Kraftverk AS to investigate the measurement principles and plant behavior at covered trash rack with the following air entrainment at intake. Coverage of trash rack have been done manually to simulate situations where trash rack is highly attached by e.g. debris and leaves. The first field tests have been performed with abnormal operation conditions at low discharge. The second test utilized higher discharge to gain tests result from plant behavior at normal operation conditions.

Results from field tests at Grønhaug plant indicate that measurement of air flow through intake air vent can be an alternative and simple method to detect release of TDG supersaturation from the plants outlet, with submerged intake as a prerequisite. Further, test result is used to assess air vent measurement principle against head loss measurements at trash rack and TDG monitoring in the plants outlet. Obtained results is also used to investigate possible design improvements to avoid air entrainment at intake, and in more detail parameters that initiate and stop air entrainment at intake.

Acknowledgment

The work presented in this master thesis have been performed at the electric power laboratory at Høgskulen på Vestlandet (HVL) in Bergen, with needed field preparation and testing at Grønhaug Hydropower plant in Modalen. Several people have contributed on the path to finalized thesis, and it is my pleasure to express gratitude to all guidance, help and support received during my work.

First, I would like to thank my advisor Vegard Steinsland from the Department of Computer science, Electrical engineering and Mathematical sciences at HVL. His advice have been an essential support during the work with several interesting common discussions. I would also like to thank my co-supervisor Bjørn Johan Arntzen for his help with the report. Grønhaug Kraftverk AS have given an unique opportunity to perform live tests of air entrainment at an hydropower plant in operation. Free access to field planning and preparations have been given to all parts of the plant, and during field test, the assistance have been highly flexible and vital for the result.

At the electric power laboratory at HVL, Lars Manger Ekroll, from Department of Computer science, Electrical engineering and Mathematical sciences, has given many advises from his extensive knowledge in sensors and practical field work, which have been important for obtained results. Only a few field test days have been possible at Grønhaug plant throughout the thesis period due to weather and river conditions, and good preparations have been essential. I would also like to give a special thanks to Ulrich Pulg, Sebastian Franz Stranzl and Martin Enqvist at the Norwegian research institute Norce for rental of TDG sensor and logger, installation guidance and in general for sharing their extensive knowledge about supersaturation in rivers. Last, I would also thank Bjarne Vaage at Småkraft AS for sharing common design practices with regards to important topics for this thesis.

A.G.S.

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Acronyms

BNC Bayonet Neill–Concelman 72

CFD Computational Fluid Dynamics 61, 78

CT Current Transformer XIII, XIV, 21, 32

FS Full Scale XIII

FSO Full Scale Output XIII

GBD Gas Bubble Disease iii, 1

GSM Groupe Spéciale Mobile ix, 24

HVL Høgskulen på Vestlandet iv, ix, XIV, 7, 20, 27, 28

MDM Membrane Diffusion Method 18

NVE Norges vassdrags- og energidirektorat xii, 4, 7, 66

PLC Programmable Logic Controller 72

TDG Total Dissolved Gas iii, iv, ix–xii, XII, XIII, XXIII, 1–3, 5–10, 17–21, 24, 25, 30–33, 35–46, 49, 50, 52–54, 58, 61–75, 77, 78

TGP Total Gas Pressure 17–19, 45

VT Voltage Transformer XIII, XIV, 21, 32

Symbols

a [m] Trash rack space between bars 14, 15
A [m^2] Internal cross-section area of pipe 13, 19, 23, 24
A_1 [m^2] Internal cross-section area of pipe 13
A_2 [m^2] Internal cross-section area of pipe 13

b [m] Trash rack bar width 14, 15

C_f [µF] Low pass filter capacitor XV

d_1 [m] Internal diameter of pressure pipe 16

F_r [−] Froude Number 16

g [m/s^2] Gravitational acceleration 13–16, 26

h_1 [m] Height between pressure pipe senter and intake water level 16
h_2 [m] Height between top of pressure pipe and intake water level 16
h_{ph} [m] Pressure head 26
H [m] Total energy pr unit weight of fluid 13
ΔH_c [m] Energy loss contraction 15
ΔH_e [m] Energy loss 14
ΔH_t [m] Energy loss trash rack 15

k_F [−] Trash rack bar shape coeffisient 14, 15
K_m [−] Air sensor flow coeffisient 23, 24
k_v [−] Trash rack debris blockage coeffisient 15
k_δ [−] Trash rack coefficient for none pendicular approaching flow 14, 15

$\dot{m}$ [kg/s] Mass flow rate 13
M [−] Mach number 13

p [Pa] Pressure 13, 26
p_{Atm} [Pa] Atomspheric pressure 18

P_b [−] Trash rack blockage ratio 15

p_{H_2O} [Pa] Vapour pressure of water 17, 18

p_i [Pa] Impact pressure 19

p_{N_2} [Pa] Partial pressure of dissolved nitrogen 17, 18

p_{O_2} [Pa] Partial pressure of dissolved oxygen 17, 18

p_s [Pa] Static pressure 19

p_1 [Pa] Pressure 14

p_2 [Pa] Pressure 14

Δp [Pa] Differencial pressure 18, 19, 23, 24

Q [m^3/s] Fluid volume flow 13, 19, 23, 24

R_f [Ω] Low pass filter resistor XV

v [m/s] Fluid average cross-sectional velocity 12, 13

v_d [m/s] Speed of water in pressured pipe 15, 16

v_R [m/s] Gross water speed through trash rack 14, 15

v_1 [m/s] Fluid average cross-sectional velocity 13, 14

v_2 [m/s] Fluid average cross-sectional velocity 13, 14

z [m] Height above datum 13

z_1 [m] Height above datum 14

z_2 [m] Height above datum 14

α [degree] Trash rack inclination angle from horizontal 15

δ [degree] Trash rack flow angle from pendicular approach 15

ρ [kg/m^3] Density 13, 14, 19, 23, 24, 26

ρ_1 [kg/m^3] Density 13

ρ_2 [kg/m^3] Density 13

θ [degree] Trash rack anlge of inclination from horizontal - Kirschmer 14, 15

1 Introduction

1.1 Background

The major source of electricity generation in Norway are from hydropower plants [2]. Also worldwide, hydropower are an important and renewable source of electricity generation [3]. Even if hydropower electricity generation are renewable it still has environmental impacts [4]. One of the negative environmental effects that can be a result of hydropower plants operation and installations are Total Dissolved Gas (TDG) supersaturated water in lakes or rivers downstream the hydropower plants [1]. TDG supersaturated water are unwanted and can result in developing of Gas Bubble Disease (GBD) in fishes, where high level of TDG supersaturation can be deadly. E.g. as in 2018, several dead fishes were observed in the river Ekso due to high level of supersaturated water released from the larger Francis hydropower plant Myster, most likely due to intake trash rack covered by debris [1]. Lower level of supersaturation over a longer period can be harmful. TDG supersaturation can also be toxic for other aquatic organisms [1].

TDG supersaturated water is an condition where the amount of air dissolved in water are higher then the equilibrium with the atmosphere at given ambient atmospheric pressure and temperature at the water surface [5]. TDG supersaturation can be present by natural occurrences as a result of solar heating of water, natural water falls in rivers with the possible pressurizing and dissolving of air in water, and in ground water [6]. Artificial TDG supersaturation can be given by air entrainment and the following air dissolved in water by high pressure in hydropower plants pipe systems, but also as e.g. air entrainment in pressurized pump systems or industrial cooling water systems [6]. Essential for the different occurrence of TDG supersaturation of water given above are temperature and pressure. When air dissolved in water at high pressure experience lower pressure, or water temperature increase rapidly, which reduce the capability of water to keep air in solution, water can be TDG supersaturated [1].

In hydropower plants, several sources can lead to supersaturated water. Brook intakes can give supersaturation e.g. if the intake and shaft are not correct dimensioned, use of vertical shaft and too small shaft cross-sections [7]. Submerged intake trash rack covered by debris can lead to air entrainment and the following supersaturation [1]. Use of diversion tunnel which bypass turbines during stop in hydropower production are also experienced to give air entrainment and the following supersaturation [8] [9]. Other sources to supersaturation from hydropower plant can be e.g. air injected into turbines during operation outside favourable operation conditions [1] [10], and water that falls into deep pools e.g. through radial gates, with possibility for air to follow water into depths with the following dissolving of in water at higher hydrostatic pressure [6].

During engineering of a new hydropower plant, several mitigating design choices can be taken to prevent developing of supersaturation by the hydropower plant. Focus on preventing supersaturation should be the first priority, rather then to find solutions to reduce present supersaturating of water. Many advise are given for brook intakes, e.g. as avoidance of vertical and long shafts, and enough shaft cross section [7]. In general, to reduce the probability of supersaturation, it is important to consider engineering solutions that avoids air entrainment where air can be pressurized by water, e.g. correct design of flood gates [1] and sufficient submerged intake [7]. In existing plants, which experience problems with supersaturation, mitigation actions as installation of vacuum intake (brook intake), submerge intakes, system for cleaning of trash rack and adjustment of plant operation can be implemented [1].

If supersaturation is initiated, it is essential to detect and quickly reduce the level of supersaturation from the hydropower plant, to minimize the consequence for fish and other aquatic respiring organism affected by the supersaturation. The level of consequences will depend on several factors as e.g. duration, degree of supersaturation, water depth, dilution with not supersaturated water, aerating condition in the river and also type of turbine [1]. Pelton turbine are experienced to aerate supersaturated water through water jets in free air in the turbine, where the same aeration not are present for reaction turbines, as e.g. Francis turbine [7].

Through the last years, TDG supersaturation as a result of hydropower production are observed in multiple rivers in Norway. These observations represent only a small part of the hydropower affected rivers, and monitoring and knowledge about the extent of hydropower initiated supersaturation are important and in general described to be missing [1]. Further mapping and research are recommended related to several topics for hydropower induced TDG supersaturation in rivers [1].

1.2 Literature Review

Artificial TDG supersaturation in rives are an known challenge in countries as Norway, Canada, USA and increasingly in Kina, but in the rest of the world this challenge are limited described in literature [1]. As early as in the 60's, supersaturation from dams were identified in Colombia river in USA [11], and in the Saint John River in Canada, aerating of turbine was identified to induce supersaturation from the hydropower plant [10]. In Kina, different examples of identified supersaturation related to dams can be found, as for the Zipingpu dam project [12]. In Norway, problems with air blow outs and supersaturation from brook intakes are well known and described in the report "*Bekkeinntak på kraftverkstunneler*" from 1986 [7]. Air entrainment and the following supersaturation due to use of diversion tunnel were described in 1984 by Heggberget for the river Nidelven [8]. In the last decade, monitoring of potential artificial TDG supersaturation have been done in different rivers in Norway, where result is included in the knowledge summarizing report "*Gassovermetning i vassdrag – en kunnskapsoppsummering*" [1].

The report, "*Gassovermetning i vassdrag – en kunnskapsoppsummering*" [1], gives an updated status on the topic artificial TDG supersaturation in rives, based on Norwegian and international literature in addition to own experience and work. The areas of research needs are described to be extensive, mainly related to:

- Biological impact by TDG supersaturation in rivers, not only limited to the tolerance level for different fish species, but also other organisms [1].
- Unknown level of TDG supersaturation present in rivers in Norway, and Europe, gives need for mapping and monitoring to understand the extent of the problem, especially hydropower plants with high risk for inducing supersaturated water [1].
- Effect of present mitigation actions needs to be monitored for existing hydropower plants, and an assessment of present knowledge and methods is needed. In additional, proposal of new cost friendly methods to avoid air entrainment, or aeration of supersaturated water in existing hydropower plants, is described [1].

To avoid TDG supersaturation from Francis plants with submerged intake and possible coverage of intake trash rack, reference [1] proposes use of differential pressure at intake trash rack and monitoring of TDG, where this method is described to be mature but missing long time duration verification [1].

At present time, two ongoing studies are identified in Norway related to TDG supersaturation in rivers, in line with research needs described in reference [1]. These studies, as an continuation of the extensive knowledge summary published in 2018 [1], confirms the present focus on the topic supersaturation in rivers in Norway. The first ongoing study investigate the effect of degassing by ultrasound on present supersaturation [13], the second investigate supersaturation effects on ecosystem in rivers, mitigation actions and solutions [14].

1.3 Project description

In Norway, an large amount of small hydropower plants with an capacity below 10 MW are set in operation. The Norwegian hydropower plants database at Norges vassdrags- og energidirektorat (NVE) describes 813 hydropower plants in the category 1 – 10 MW are operating in addition to 579 hydropower plants with capacity up to 1 MW [15]. Approximately half of the registered turbines with rating below 10 MW is Francis turbines, still understood that the NVE database is missing input and can only be used as an indication about the numbers and type of turbines used in small hydropower plants [16].

In several studies identifying supersaturation by measurements, large hydropower plants or medium to large small hydropower plants have been investigated [1] [8] [10] [12] [17]. Even if large hydropower plants will release larger volume of supersaturated water due to higher level of discharge and water volumes involved, smaller hydropower plants discharge can be released to smaller rivers where the relative volume of discharge from the plant still can be appreciable. Smaller river can also result in less water depth and by that less possibility for fish to compensate supersaturation by depth. Tributary rivers can facilitate spawn and smolt habitat for salmon and salmon trout, where salmon trout specially can migrate to smaller rivers and brooks to avoid competition with salmon [18]. This underlines that also small hydropower plants is important with regards to avoid release of supersaturated water.

The risk for release of supersaturated water from hydropower plants are varying depending on the plant design and local conditions, as also the consequence for biological life in corresponding river. E.g., brook intakes with Francis or Kaplan turbine, submerged intake trash rack with risk of air entrainment due to debris coverage during operation, and plants with air filled part of the operation system as air cushion surge chamber, are plant design that have higher risk of release of supersaturation during operation [1]. For small hydropower plants, a typical design can consist of submerged intake, intake air vent, pressure pipe and Francis turbine, which then will be in the group of hydropower plants with higher risk of air entrainment and the following release of supersaturated water [1]. Intake design will vary for each specific local site, but large part of the small hydropower Francis turbine plants are expected to have similarly general setup as described above and in chapter 2.2.

This thesis will further on focus on small hydropower plant with submerged intake, intake air vent, pressure pipe and Francis turbine. Smaller hydropower plants will have limited turnover budgets and by that in general more vulnerable for additional cost during operation, e.g. if monitoring are needed to clarify if the plant are contribution with supersaturation, and also if mitigation actions needs to be implemented to reduce air entrainment and supersaturation from existing plants.

In chapter 1.2, proposed research needs for supersaturation in rivers are given. Long time duration monitoring to reveal eventually supersaturation problems from high risk plants is recommended, as will be relevant for plants with submerged intake vulnerable for debris coverage, i.e. the chosen small hydropower plant design for this thesis. Plants with submerged intake and Francis turbine is proposed mitigated with differential pressure measurement at intake trash rack and monitoring of TDG in the plants outlet river, described to be mature principles but missing long time duration verification [1]. Installation of manual or automatic trash rack debris remover to quickly mitigate when intake differential pressure is high, are also discussed [1], but can be costly for small plant [19] [20]. Monitoring of supersaturation directly is described both to be in need of correct knowledge [1], but also to be technical simple as water level measurements [17]. In general, cost friendly methods to avoid air entrainment is described [1]. With regards to TDG sensors, it is not found distributed installation guidelines or information for small hydropower plants, and implementing of this type of measure is in general understand to be seldom and need for external experts is expected. Currently, no specific limit for hydropower released artificial TDG supersaturation in Norway is given, resulting in missing requirements for TDG measurements [21]. At new hydropower plants licence approval, measures to limit release of hydropower induced TDG supersaturated water is a prerequisite [21].

As a contribution to the ongoing and presented research needs related to the topic supersaturation in rivers, this thesis will investigate if air measurement in intake air vent can be an simple and cost-friendly alternative for continuously monitoring and indirectly detection of supersaturation induced by small hydropower plants with submerged intake and Francis turbine. Field tests will be performed at Grønhaug Kraftverk AS to investigate the air velocity sensor relationship with supersaturation from the plant. In additional, differential pressure measurement of trash rack and direct measurement of TDG in Grønhaug Kraftverk outlet will be performed and assessed against the air sensor in intake air vent. Other parameters as pressure head in power station and turbine discharge will also be measured an assessed with regards to indirect detection of supersaturation. The investigation performed in this thesis is intended to contribute to higher focus on simple and standardized solutions for small hydropower plants with regards to supersaturation, where the main focus normally in general will be large plants with large water volumes discharged from the plant.

1.4 Objective

The objective of this thesis is to verify if air velocity measurement in intake air vents at small Francis hydropower plants, can be used as an low cost and simple indirect method of detecting artificial induced supersaturation from plants with submerged intake and Francis turbine. Air velocity measurements will be compared with methods recommended in reference [1], i.e. differential pressure measurements at intake trash rack and direct measurement of TDG at plants outlet river. The main objectives is listed as:

- Plan and perform field tests to investigate if monitoring of air entrainment at intake air vents indirectly can detect release of TDG supersaturation water from the plants outlet.
- Compare air vents monitoring principle with indirect detection of release of TDG supersaturation, against differential pressure measurements at intake trash rack and direct monitoring of TDG supersaturation in the plants outlet river.
- Investigate possible design recommendations to reduce air entrainment at plants intake, and standardisation of measurements for similarly small hydropower plants.
- Proposed simple actions to stop present air entrainment at intake, to avoid long duration of TDG supersaturation released by operation of the plant.

1.5 Grønhaug Kraftverk AS

As described in chapter 1.3, this thesis have been given the unique opportunity to perform field tests at Grønhaug Kraftverk AS in Modalen in Vestland county in Norway. This chapter gives a brief overview of Grønhaug hydropower plant main data and design, which are important for the understanding of performed field tests and following results.

The main data for Grønhaug plant are given in table 1.1. Based on a maximum production about 1 MW, Francis turbine and air vent at submerged intake, Grønhaug is well suited for field tests needed to investigate the objectives related to trash rack coverage, air entrainment at intake vents and artificial TDG supersaturation release from the plants outlet. Figure 1.1 present an overview of the intake area and also the power station with downstream river. In the rest of this thesis report, Grønhaug Kraftverk AS will be described as Grønhaug plant.

Grønhaug Kraftverk AS main data	
Gross head	153 m
Turbine	Francis, horizontal
Maximum turbine output	1.1 MW
Maximum discharge turbine	0.93 m^3/s
Start production	Year 2000
Type of hydropower plant	Run-off-river [22], limited magazine
Intake	submerged

Table 1.1: *Main data for Grønhaug Kraftverk AS, based on input from plant owner and NVE hydropower plant database [23]*

(a) Grønhaug plant intake dam area (b) Grønhaug plant power station and outlet area

Figure 1.1: *Grønhaug plant intake area and power station with plant outlet*

1.6 Thesis Structure

This thesis is structured into six chapters, given by introduction, theory, method, results, discussion, conclusion with further work, included appendices. A short description is given to each main chapter:

1. **Theory**: This chapter present essential theory used by this thesis. Theory related to air supersaturation in rivers is given, followed by presentation of relevant main components in a hydropower plant. Relevant hydraulics is presented, as Bernoulli's equation and air drawing vortexes. Last, the most essential sensor measurement theory is given.

2. **Method**: The method chapters describes planning and developed methods used for field tests at Grønhaug plant. First, an overview of chosen sensors and locations is given, where the most essential sensors is described in detail. Secondly, a short overview of the developed test setup, assembled and tested at the electric power laboratory at Høgskulen på Vestlandet (HVL), is given, included topology drawing of all sensors. Finally, test setup in Grønhaug plant is given.

3. **Result**: Results are presented chronologically order, where the first chapter gives result obtained from field tests performed in November 2021, and the second chapter present the result from tests in April 2022. Graphs is embedded directly in text editor to strive for high degree of readability, after filtering in MatLab.

4. **Discussion**: The first part of the discussions is given for the result from field test in November 2021, before assessment of results from April 2022 is presented. Focus is validity for the gained data and also how obtained data can be understood and used. The next part present an assessment of air vent measurements related to pressure head at trash rack and TDG monitoring at plants outlet, included gained design recommendations. The last part go through alternative methods to detect supersaturation from hydropower plants, and also briefly actions that can be performed to stop initiated air entrainment at intakes.

5. **Conclusion and further work**: This chapter summarize the main conclusions and design recommendation obtained from field results and discussions. In addition, proposed further work to strengthen the listed conclusions is given.

6. **References**: References is based on the IEEE citation style.

7. **Appendices**: Appendices presents additional graphs, more detailed information about equipment and sensors, and calculations. In addition, raw data and data files from both field tests is included, used as input to graphs presented in this thesis.

2 Theory

This theory chapter describes first theory needed to understand TDG supersaturation in general, related to hydropower plants, as basis for field tests and discussions. Secondly, general hydropower plant components and topology is described for typical plant design relevant for field tests, result and discussions. Third, the most relevant hydraulics theory is described, before essential measurement sensor principle theory used to plan and execute needed measurement at field test is given. Measurement theory priority is given to the most important parameters for field testing, monitoring of air flow and TDG supersaturation.

2.1 Dissolved gas supersaturation

All natural water contains dissolved air. At stable temperature and ambient surface pressure, a certain amount of air are dissolved in water as individual molecules between the water molecules [7]. Atmospheric pressure is an essential parameter for the dissolved air in water. If the water contains more dissolved air then the corresponding equilibrium at the water surface with present atmospheric pressure, the water are supersaturated and the water release air at the water surface [5].

Further, under the water surface, the hydrostatic pressure at a given water volume increase as the water depth increase, and by that also the water ability to keep the dissolved gasses in solution. This is according to Henry's Law, which describes that at a given temperature, the mas of a gas that can be dissolved in a liquid are proportional with the present pressure on the liquid. Water at depth will therefore have higher capacity to keep dissolved gasses in solution then water close to the water surface [24]. E.g. at 10 m depth, about 2 atmospheric pressures are present at the water volume (10 m water represent approximately 1 atmospheric pressure), and with 200 % TDG supersaturation at the surface, the water volume at 10 m water depth will experience approximately 100 % TDG, close to equilibrium. This increased capability to dissolve gasses at increasing pressure (water depth) result in that air from air-water mixture, e.g. after passing a spillway, are dissolved in water at higher pressure in the water depth [5]. See figure 2.1, inspired by reference [1] and [5], for an visual presentation of experienced TDG supersaturation at different water depths, given initial supersaturation at water surface. The presentation in figure 2.1, which gives 10 % TDG reduction each 1 m depth increase, is not accurate but often used to present the pressure relationship [1] [5]. Accurate numbers for compensation at increasing depth can be found in literature, both tables and equation as presented in reference [25], related to hydrostatic pressure in water.

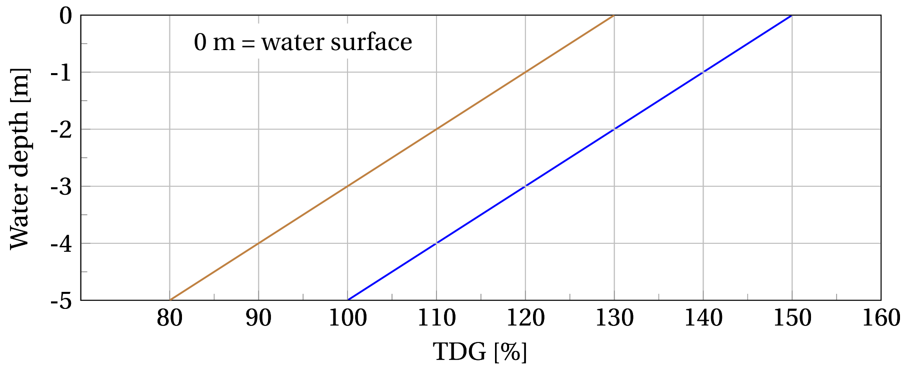


Figure 2.1: *Simplified principal overview of TDG supersaturation experience by fish at different water depth, based on level of supersaturation at water surface (0* m *water depth). Orange line represent 130 % TDG supersaturation water, blue line represent 150 % TDG, indicating the extent of hydrostatic pressure compensation as the water depth increase.*

Also water temperature is an important parameter for the extent of supersaturation, with the opposite result compared to pressure. With increasing temperature, the capacity for a given water volume to keep dissolved gasses in solution decreases. Hence, if a water volume at equilibrium (saturated) are heated, the water becomes supersaturated as a result of the increase in water temperature [24]. Marking L [26] describes an increase in saturation by about 2 % at 1 °C increase in water temperature [26].

When discussing TDG supersaturation in water, it is important to understand the difference between air dissolved in water, and air mixed in water. Air mixed in water are visible as bubbles, where large extent of small air bubbles can be seen as a white almost as milk in the water. Air dissolved in water are not visible. Still, an indirect sign of TDG supersaturated water can be visible by the release of very small air bubbles from highly supersaturated water as part of the process to gain equilibrium with atmospheric pressure, visible as white almost as milk in water [7]. In literature, several possible limits for visible indirect sign of supersaturation are proposed, e.g. TDG supersaturation above 120 % [27], 130-140 % [1] and 150 % [7], where air release from lower supersaturated levels are described to be an invisible diffusion process [7].

2.2 General hydropower plant topology

This chapter gives a short general description of small hydropower plants with submerged intake, pressure pipe (high pressure plant [28]) and Francis turbine, which is the main setup used in this thesis. Not all part of a small hydropower plant, defined as below 10 MW rating [22], is described, only relevant components and topics is included. Relevant hydraulics theory is described in chapter 2.3.

Figure 2.2 gives a general presentation of a common used small hydropower plant design with Francis turbine. There are several different types of intake area design present for small hydropower plants [19], figure 2.2 introduce an overview of a possible small hydropower plant setup. In the intake area, the two most relevant main equipment is the intake trash rack and the intake air vent. There will also be needed a gate or valve to be able to isolate the pressure pipe during maintenance or pressure pipe damage [22]. Intake trash rack main function is to prevent debris and unwanted objects to enter the pressure pipe and the turbine [22]. The mission to stop debris and other objects can as a consequence result in partly covered trash rack by debris, which gives head loss over the trash rack [29]. Removal of debris from trash rack can be done in many ways depending on local conditions, e.g. automatic trash rack cleaner or manual by hand-tools which might be relevant for small hydropower. Theory for head loss calculations for trash rack and critical submerge of intake are given in chapter 2.3. The air vent at the intake are needed during dewatering and filling of the pressure pipe [28], where e.g. under-pressure are prevented by the air vent during dewatering [22]. During emergency stop from the hydropower plant intake area by valve or gate, depended on the present design, air vents can give air access to compensate for under-pressure and possible collapse of pressure pipe until the flow of water is stopped by the power plant [30]. Based on the described functionality, air vent will also have an important role when trash rack are covered by debris, which without air vent can lead to under-pressure in pressure pipe.

At the power station, a valve is installed in front of the turbine for maintenance purposes and emergency stop function. In high head plants, the valve are also used to avoid damage (leakage) on the turbine guide vanes during stop of production [22].

There are two main categories of turbines described in literature: Impulse and reaction turbines. Impulse turbines, as Pelton, the pressure energy in water are converted into kinetic energy through nozzles, sending the water as water jets in free air into a runner with buckets [28] [31]. The free air aeration of water above free water surface seems to be favourable with regards to avoid supersaturated water from turbine [1], and the focus are therefore given to reaction turbines with regards to supersaturated water, specially Francis turbine.

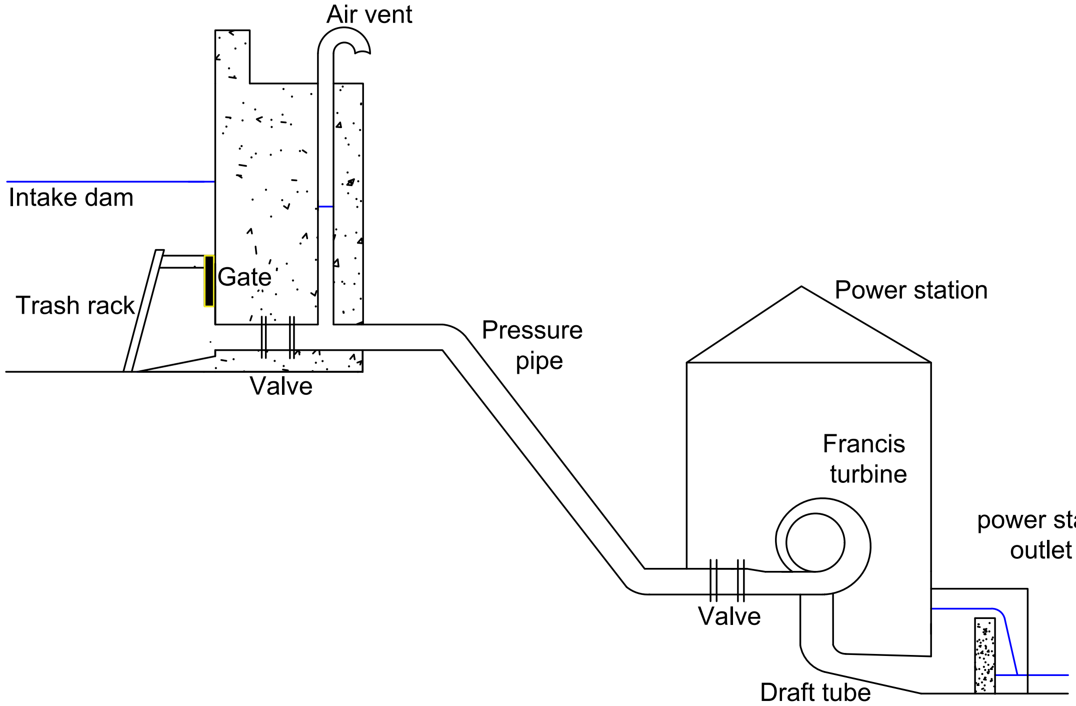


Figure 2.2: *Overall overview of small hydropower plant with submerged intake, pressure pipe and horizontal Francis turbine*

The reaction turbines, as Francis and Kaplan turbines, the turbine casing and runner are completely filled by water. The reaction turbine utilize both potential and kinetic energy, and the flow through the turbine are pressurized in a closed casing [31]. The turbine can be mounted over or under the downstream river or basin level, where above downstream water level are limited by risk of cavitation. Normally, an draft tube are installed from the reaction turbine to the downstream river to utilize the available head between intake or reservoir, and downstream river or basin [29]. For the Francis turbine, regulation of discharge through the turbine, to fit the turbine output to the needed generator power production, is done by regulating the guide vane position for the turbine [29].

2.3 Hydraulics

2.3.1 Continuity Equation

When a fluid are moving through an cross-section area normal to the flow direction, the volume flow rate can be expressed by equation 2.1 [32]. For fluid flow through pipes, the fluid velocity profile varies through the cross-section area, where the velocity are at highest in the cross-sectional center. This difference in velocity through the given flow cross-section can in many problems be neglected and symbol v describes the mean velocity though the pipe cross-section area [33]. The corresponding mass flow rate through the same cross-section area can be expressed by equation 2.2 [33].

$$Q = v \cdot A \tag{2.1}$$

$$\dot{m} = \rho \cdot Q = \rho \cdot v \cdot A \tag{2.2}$$

With steady flow through a pipe, the mas flow rate of fluid entering the pipe are the same as the mas flow rate of fluid leaving the pipe, given that there is no additional fluid added or extracted from the pipe in between. Equation 2.3 describes the relationship between the mas of entering and leaving fluid [33], and details the equation of continuity. ρ_1, A_1 and v_1 is the density, cross-section area and velocity at the entering section, where ρ_2, A_2 and v_2 is the density, cross-section area and velocity at the leaving section.

$$\rho_1 \cdot A_1 \cdot v_1 = \rho_2 \cdot A_2 \cdot v_2 = \dot{m} \tag{2.3}$$

$$A_1 \cdot v_1 = A_2 \cdot v_2 = Q \tag{2.4}$$

If the fluid is considered incompressible, equation 2.4 in its simple form can be used [32]. Equation 2.4 is not just valid for pipe cross-section areas, but also other areas as open channel fluid flow [34].

Water are considered incompressible for steady flow situations, where the water flow do not change during time. At pressure variations, e.g. water hammer or change in discharge for a turbine, the water can be compressible with change in density [34]. For the gas air, 0.33 M are considered as an limit to defined the gas compressible, based on defining 5 % as the maximum relative change in density [35].

2.3.2 Bernoulli's Equation

An fluid element inside a pipe with incompressible flowing fluid possess three forms of energy, potential energy, kinetic energy and pressure energy. Based on these three forms of energy, the total energy possessed by the element are given by equation 2.5, where H is the total energy pr unit mass, z is the height from datum, $\frac{v^2}{2g}$ is the velocity head and $\frac{p}{\rho g}$ is the pressure head [32].

$$\frac{p}{\rho g} + \frac{v^2}{2g} + z = H \tag{2.5}$$

If the element moves on a stream line between two points in a pipe, see point 1 and 2 in figure 2.3, where no energy are lost or added between the points, the total energy at the two points is the same, as described by equation 2.6. Equation 2.6 is defined as Bernoulli's Equation [32], which are valid for steady and incompressible fluid flow [35]. In a real fluid flow there will be losses e.g. as friction, pipe expansions and pipe contractions, which need to be included (ΔH_e), see equation 2.7. Also, as described in chapter 2.3.1, the velocity profile of a fluid cross section area are assumed to be uniform, ref. equation 2.1, which introduce uncertainties that can be improved, if necessary, by a velocity distribution coefficient [34]. At steady flow, water can be defined as incompressible [28].

$$z_1 + \frac{p_1}{\rho g} + \frac{{v_1}^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{{v_2}^2}{2g} \tag{2.6}$$

$$z_1 + \frac{p_1}{\rho g} + \frac{{v_1}^2}{2g} = z_2 + \frac{p_2}{\rho g} + \frac{{v_2}^2}{2g} + \Delta H_e \tag{2.7}$$

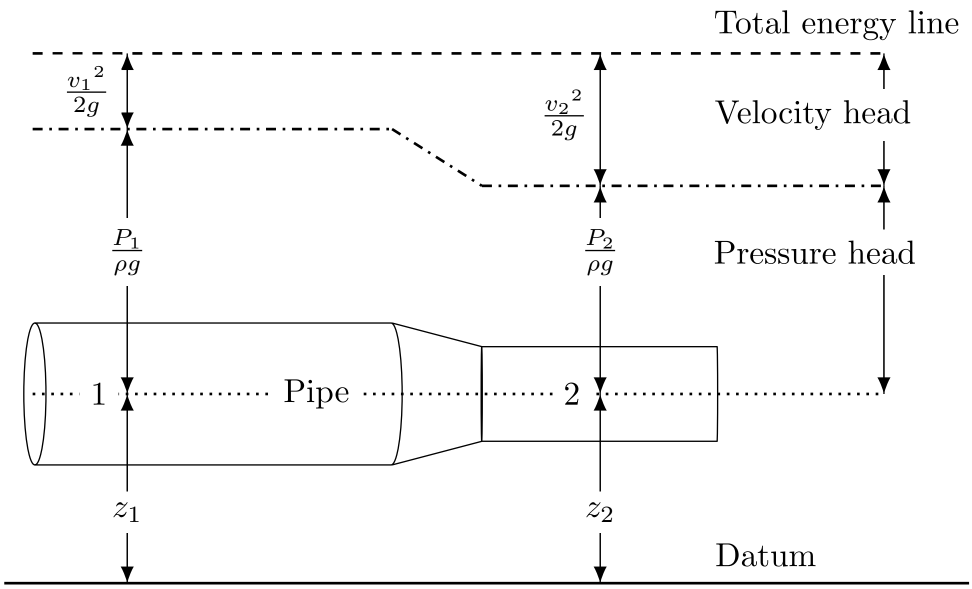


Figure 2.3: *Overview of the energy involved for a lossless fluid flow through a pipe*

2.3.3 Head loss at trash rack

It is developed several equations describing head loss for intake trash rack. The first fundamental investigation at trash rack losses were performed by Kirschmer in 1926, which equation was proposed extended by Mosonyi in 1966 to take into account the angle of approaching flow relative to the trash rack bars direction [36], see equation 2.8 [19].

Equation 2.8 calculate head loss based on bar shape (k_F), bars size and spacing (a,b), trash rack inclination (θ) and flow approach (k_δ), but do not take into consideration external coverage (i.e. ice, debris, leaves) of trash rack. The loss coefficient k_δ are tabulated values [19]. v_R are gross water speed through trash rack.

$$\Delta H_t = k_\delta \cdot \left(\frac{b}{a}\right)^{\left(\frac{4}{3}\right)} \cdot k_F \cdot \sin\theta \cdot \frac{{v_R}^2}{2g} \tag{2.8}$$

Later, Meusburger developed equation 2.10, which also includes losses at intake trash rack when partly covered by external pollution as ice and leaves [36].

$$k_\delta = \left(1 - \frac{\delta}{90°}\right) \cdot {P_b}^{-1.4\cdot\tan\delta} \tag{2.9}$$

$$\Delta H_t = k_\delta \cdot k_v \cdot \left(\frac{P_b}{1-P_b}\right)^{\left(\frac{3}{2}\right)} \cdot k_F \cdot \sin\alpha \cdot \frac{{v_R}^2}{2g} \tag{2.10}$$

Coefficients as k_F are by Meusburger included from Krischmer equation [36]. k_δ are presented in equation 2.9, where δ is the angle of flow approach relative to trash rack bars. k_v is defined based on position and extent of external debris blocking on trash rack flow area, P_b is the blockage ratio of trash rack (bars, beams) and α are the angle between the passing flow midt horizontal line and the vertical angle of trash rack. k_v are tested up to 25 % coverage [36] and by that not verified for higher degree of external coverage.

At the point where the water enters the pressure pipe inside the intake hood, an sudden contraction take place. In Grønhaug plant, the contraction are not rounded, and the equation to calculate pressure pipe entrance losses can be given by equation 2.11 [32]. v_d represent water velocity in pressure pipe.

$$\Delta H_c = 0.5\frac{{v_d}^2}{2g} \tag{2.11}$$

2.3.4 Air drawing vortices at intake structures

Intake structures can by e.g. asymmetric approached flow conditions develop air drawing vortices at the intake [37]. Air drawing vortices may give challenges as head losses at intake, cavitation and vibration, unwanted air in the pressure pipe, reduced efficiency of hydraulic machines, uneven flow distribution among others, and should be avoided [37]. The consequences for the hydropower plant are depended on the air drawing vortex strength, length between intake and turbine, pressure head and turbine type [19] [38].

The are several reasons for vortex formation at intake structures. The book "*Swirling flow problems at intakes*" [37] lists eccentric orientation of intake, asymmetric approached flow conditions, obstructions and non-uniform velocity distribution as essential parameters. If the intake are prone to air drawing vortex, sufficient submerged intake are described as an important measure to avoid air entrainment. Several guidelines and recommendations exist for defining the critical submerged depth to avoid air entrainment. None of these recommendations can be used as a final fully reliable answer. This due to the large extend of different local parameters such as geometry and flow approach, but also since circulation in general are not included [37]. Equation 2.12 and 2.13 are considered relevant for Grønhaug plant to assess the level of submerge of intake during testing. The same equations are also proposed in [19]. Equation 2.12 is based on proper flow conditions but no special installed measurements to avoid vortex. Minimum $\left(\frac{d_1}{h_1}\right)_{cr}$ are set to 1.5 [19] [37]. Equation 2.13 have an more conservative approach. Figure 2.4 indicate the definition for the different parameters d_1, h_1 and h_2 in equation 2.12 and 2.13. Froude number F_r are given by equation 2.14 [37]. v_d represent water velocity in pressure pipe.

$$\left(\frac{d_1}{h_1}\right)_{cr} = 0.5 + 2.0 \cdot F_r \tag{2.12}$$

$$\left(\frac{d_1}{h_2}\right)_{cr} = 1.0 + 2.3 \cdot F_r \tag{2.13}$$

$$F_r = \frac{v_d}{\sqrt{g \cdot d_1}} \tag{2.14}$$

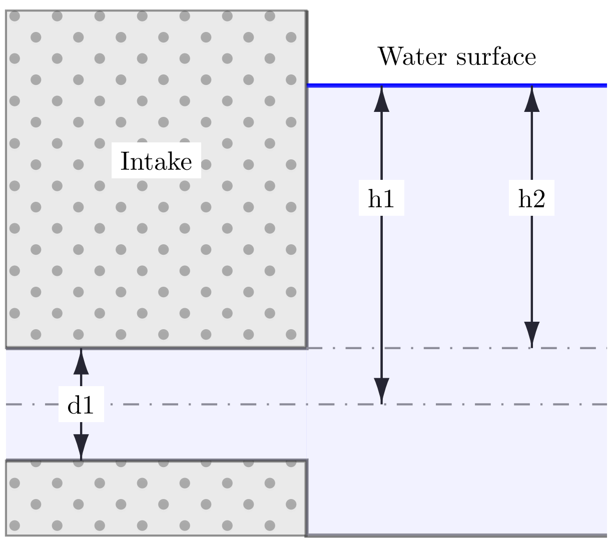


Figure 2.4: *Overview of intake parameters used in equation 2.12 and 2.13*

2.3.5 Air blowouts from pressure pipe

This thesis focus on air entrainment in pressure pipe related to pressurizing and resulting artificial supersaturated water as a result downstream the hydropower station outlet. Air entrainment have a also other consequences. In literature, air blow outs is described as one of the major unwanted possible consequences of air entrainment, in addition to significant head loss, reduced production and other problems for plant operation [7], as stimulate to initiate cavitation and vibration [37].

With respect to air blow outs, the most dangerous is not the air itself, but the water that air pushes towards the intake as the air expand on the way upwards [7] [28]. Air under pressure are compressed and at 10 m water depth, the volume of air are half the volume at normal atmospheric pressure, and by that also expanding when exposed to lower pressure [7] when travelling upwards the pressure pipe.

Air bubbles in water rises against lower pressure due to buoyancy. At vertical shafts, at water speed below 0.15-0.20 m/s, the air bubbles rises upwards in water. Speed of water are therefore essential with regards to the bubble buoyancy rise gain in water flow, together with bubble size and geometric factors as angle of shaft for a brook intake. For an 45 ° brook intake shaft, the boundary water speed for naturally release of air bubbles in water are proposed to be ≈ 0.6 m/s. Water speed below this limits, at the given conditions, result in air bubbles rising towards lower pressure. At high water speed, more air bubbles are transported within the water flow, where the water can be trapped in air pockets in tunnels, dissolved under pressure or following the water flow. For brook intake shafts, as input to a hydropower tunnel, high water speed result in that large volume of air can be transported through the shaft and in to the larger tunnels where unwanted air pocket can be established. At water speed below the limit for natural air bubble buoyancy, the large air pocket can be released as blow outs. Sudden increase in intake area flow, result in completely water filled shaft from the intake, when free water flow are present lower in the system, are highly unwanted with regards to risk for air blow out, air entrainment and capacity [7].

2.4 Measurement principles

2.4.1 Dissolved gas supersaturation

The TDG level in water are most often described in terms of Total Gas Pressure (TGP), where TGP is defined as the sum of the partial pressure (tension) of all dissolved gases in the water, included the water vapour pressure [6]. Air consist of different gasses, where about 21 % is oxygen (O_2) and 78 % is nitrogen (N_2) in dry air at earth surface [39].

Related to the amount of air dissolved in water, TGP are defined according to equation 2.15 [6].

$$TGP = p_{N_2} + p_{O_2} + p_{H_2O} \tag{2.15}$$

$$TGP\% = 100 \cdot \frac{p_{N_2} + p_{O_2} + p_{H_2O}}{p_{Atm}} = 100 \cdot \frac{TGP}{p_{Atm}} \tag{2.16}$$

In equation 2.15, p_{N_2} includes partial pressures of argon and all other minor atmospheric gases. p_{O_2} are the partial pressure for oxygen and p_{H_2O} the vapour pressure of water. Normally, the atmospheric pressure above the water surface and the TGP in water are close to equilibrium [7]. When the TGP, hence the sum of partial pressures for all dissolved gasses and water vapour, exceeds the atmospheric pressure at the water surface, the water is supersaturated with the dissolved gases [6]. The opposite situation are present when the TGP is lower then the atmospheric pressure above the water surface. TDG saturation are often described by the relationship between TGP in water and present atmospheric pressure, as expressed by equation 2.16 [6].

Individual atmospheric dissolved gasses can be supersaturated without destructive consequences for aquatic life as long as the sum of the partial gasses, TGP in water, are lower or the same as the present atmospheric pressure [26] [40]. The preferred method to measure TGP in water is by directly measurement of the TGP in water, related to atmospheric pressure. Instrument that perform this type of measurements are commonly described as "Weiss-saturometer" [40], utilizing the Membrane Diffusion Method (MDM). The probe consist of a silicone rubber tubing, permeable to dissolved gases and water vapour, but not to liquid water. The probe are connected to a pressure measure device, measuring the difference between TGP in water and atmospheric pressure, defined as Δp in equation 2.17 [40].

$$TGP = p_{Atm} + \Delta p \tag{2.17}$$

$$TGP\% = 100 \cdot \frac{p_{Atm} + \Delta p}{p_{Atm}} \tag{2.18}$$

Weiss saturometers have error sources that are important to consider during field measurements. The diffusion of dissolved gas into the probe takes time, and to gain equilibrium it is estimated that approximately 5 - 30 min are needed, depending on pressure difference and surface area of the probe. If the probe are installed above the compensation depth (the depth where water are supersaturated and air bobbles can be created by the seek of equilibrium process in water), air bobbles on the probe can disturb the readings. To mitigate this, the air bobbles can be removed mechanical by keep water in motion (certain water speed), shaking or similarly if not lowered below the compensation depth [25]. Equation 2.18 reveals that the same Δp measured at sites with different atmospheric pressure will lead to deviating TGP%, which need to be considered when comparing measurement data from different sites [6]. The risk for aquatic life in water is related to Δp [25]. Weiss-saturometer principle are also identified to be used by the Norwegian research institute Norce in several studies the last years to detect supersaturation in rivers in Norway [1] [41] [42]. For standardization and simplification, in this thesis, the common terms TDG and TDG % will be used to present measured TGP% at field tests.

2.4.2 Air velocity

There are several principles that can be used when air flow measurements are needed. Hot wire anemometers, vane anemometers and differential pressure (e.g.pitot tubes) are examples of measurement principles that indicate air velocity [43] [35], and by that, air volume flow can be defined according to theory in chapter 2.3.1. Pitot tube principle are assessed to be the best suited principle for air velocity measurements in this thesis, and therefore only pitot tube principle will be described further.

The pitot tube measures the total pressure (impact pressure) and the static pressure, and the difference between these pressure measurements indicates the dynamic pressure, which then are related to the air speed. The total pressure are measured against the flow direction and includes only pressure energy. The static pressure are measured parallel to the flow direction and includes both kinetic and pressure energy. At ranges of air speed below 100 m/s, the density difference for air at the static and impact holes are negligible and theory for incompressible fluid can be used, ref. chapter 2.3.1 [33]. Equation 2.19 gives the air volume flow [33], where p_i and p_s is the impact and static pressure.

$$Q = A \cdot \sqrt{2 \cdot \frac{(p_i - p_s)}{\rho}} \tag{2.19}$$

There are two different main groups of pitot tubes, single or average pitot tubes [35]. Single pitot tubes only measures a single point in the flow, where the average pitot tubes measures the average pressure over the sensor length and thereby can measure the air speed with lower probability for errors [35].

3 Method

Basis for the method developed in this thesis is to investigate the relationship between debris covered intake trash rack, air entrainment through intake air vent and the following supersaturation of water from the hydropower plant outlet. To be able to understand the relationship between the different plant parameters and behaviour during covered intake trash rack, field test with needed plant parameter measured have been performed. Grønhaug plant, see chapter 1.5, have give access to perform field tests, and developed method is based on Grønhaug as the test object. By this, field test investigate the relationship between covered trash rack, air entrainment through the intake vents and supersaturated water from the plants outlet, can be performed. The method chapter are divided into several sub chapters, reflecting the chronological sequence of the planning and execution of field tests. The last sub chapter briefly describes the safety measures assess for the performed field tests.

3.1 Introduction to field tests

Grønhaug plant was in normal operation during performed field tests, and necessary planning and preparation have therefore been a clear prerequisite to get access to perform tests, and also to get the needed measurements and results. First, based on literature review and detailed assessment of Grønhaug plant design, parameters that are relevant to measure during testing have been identified, with the following theoretical planning of measurement principles and sensor location. Secondly, purchasing, familiarization and pretest have been done at electric power laboratory at HVL, followed by site preparations and tests at the Grønhaug plant. Two field test have been performed at Grønhaug plant. The first test was executed in November 2021 as a pretest to confirm the relation between intake coverage and air entrainment, without equipment or trained personnel to confirm level of TDG. The second test was performed in mid April 2022 to strengthen the result and conclusions with direct measurements of level of TDG in the plants outlet. For both field tests a certain river discharge and access to intake trash rack was required to gain needed results. This highly and extensively restricted the possible test days, with rain period in autumn, and snow, ice, snow melting and rain during winter and spring time.

3.2 Plant parameters to be monitored

At field tests of air entrainment at an operating hydropower plant, several parameters is relevant to monitor. The most important parameter is air entrainment at intake dam, and level of TDG downstream the power plant, which is the basis for this thesis. Chosen measurement equipment and relevant equitations for air sensors and level of TDG will be described briefly in subchapter 3.2.1 and 3.2.2. Also measurements equipment and calculations for pressure loss above intake trash rack and pressure head in power station is described in detail, see chapter 3.2.3 and 3.2.4. In additional, other parameters as turbine guide vane position, generator power production and water level at intake dam is measured to better understand the plant influence by air entrainment. Table 3.1 summarize all parameters prepared for measuring during field testing, included chosen measurement sensors. Id. number in table 3.1 is given to relate parameter information with position in figure 3.1.

Id.	Parameter	Location	Sensor	Manufactorer	Range
1	Air velocity	Intake dam vent	MFS-C-125	Micatrone SE	1 – 50 m/s
2	TDG	Power station - outlet in river	High pressure saturometer	Fisch- und Wassert.	80-200 TDG
3	Pressure head	Power station - pressure pipe upstream turbine	3100B0016G 01B000	GEM Sensors & Controls	0 – 160 bar
4	Guide vane position	Turbine	Unknown	Temposonic	0 – 100 %
5	Water level	Intake dam	PTX 1830	Druck	0 – 350 mbar
6	Water level	Intake dam obsolete vent	LMP 305	BD SENSORS	0 – 350 mbar
7	Water level	Intake dam obsolete vent	UB4000-F42-I-V15	Pepperl+Fuchs	0.2 – 4.0 m
8	Generator current	Generator Current Transformer (CT)	Fluke 435 & i5s	Fluke	0.0 – 5.0 A
9	Generator voltage	Generator Voltage Transformer (VT)	Fluke 435	Fluke	1 – 1000 V_{rms}

Table 3.1: *Parameters monitored during field tests at Grønhaug plant. Id. number given at the different parameters can be found indicated in figure 3.1*

Higher level of details for used equipment and sensors is given in appendix B. Figure 3.1 gives a principle overview of used sensor locations in Grønhaug plant based on table 3.1. The water level in intake obsolete air vent is measured to gain the pressure loss above intake trash rack and intake pipe entrance.

At the first test, an ultrasonic sensor have been used, where at the second test a more accurate measurement have been done by a pressure sensor inside the intake obsolete vent. Generator voltage and power have only been measured at the test performed in November 2021.

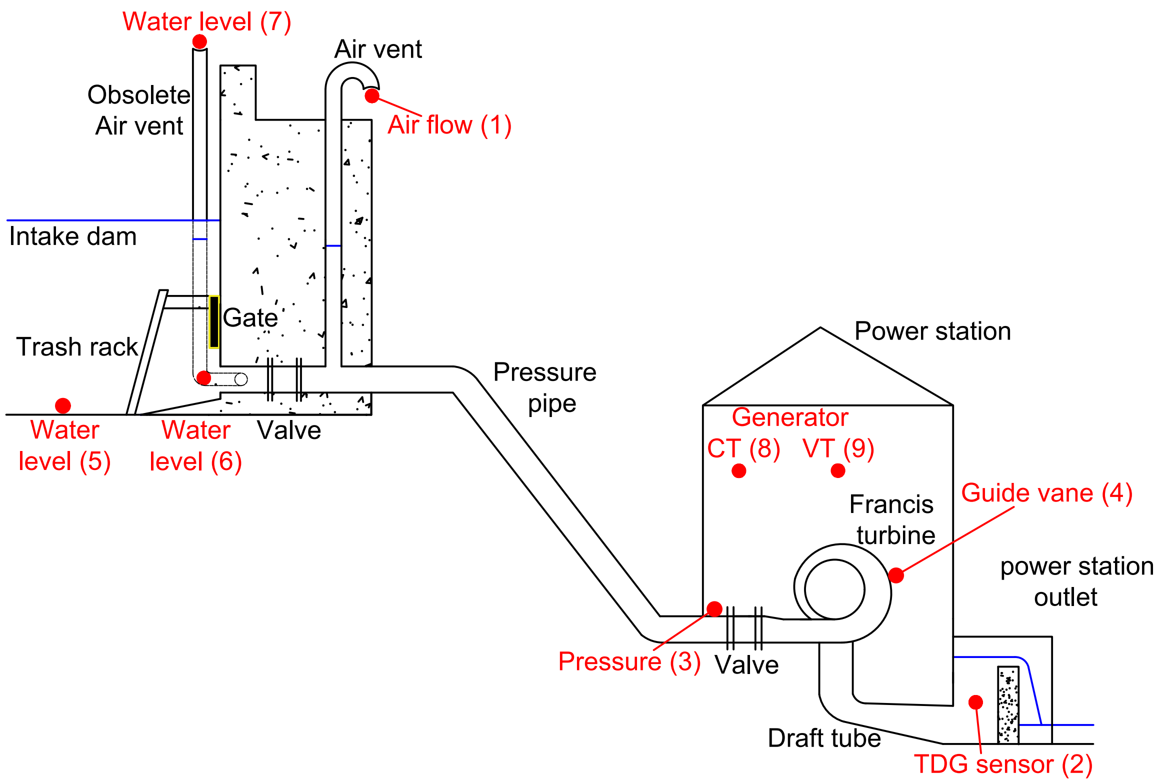


Figure 3.1: *Principle drawing for sensor location during field tests at Grønhaug plant. Numbers at the different parameters is given to align with sensor information in table 3.1.*

3.2.1 Air flow measurements in intake ventilation pipe

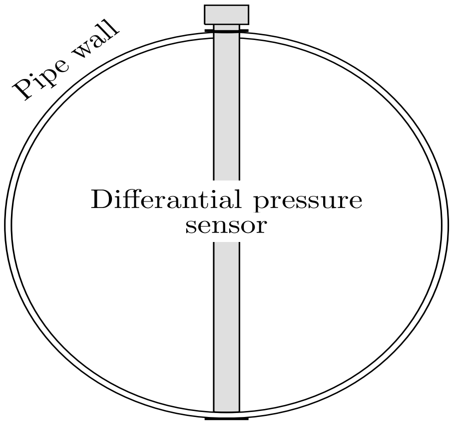
Air entrainment at intake are measured by an air velocity sensor in the intake air vent. The intake air vent can be exposed to blowouts containing both water and air, see chapter 2.3.5, and the air velocity sensor therefore need to be robust and handle polluted air (water) in additional to high air speed.

An average pitot tube sensor are chosen for the air measurements, see table 3.2 and chapter 2.4.2. The sensor principle are sub defined as Annubar with higher differential pressure between impact pressure and induced static pressure then standard average pitot tubes [35]. This gives higher accuracy at lower air velocities [44].

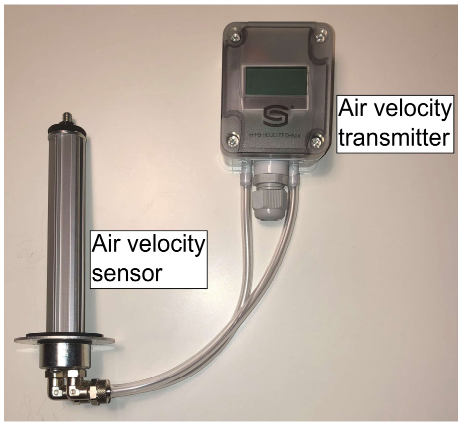
Parameter	**Location**	**Equipment**	**Model**	**Manufacturer**	**Range**
Air velocity	Intake vent	Diff. press. sensor	Micatrone SE	MFS-C-125	1 – 50 m/s
Air velocity	Intake vent	Diff. press. transmitter	S+S Regeltechnik	PREMASGARD 1121-I LCD	± 1000 Pa

Table 3.2: *Air differential pressure sensor with differential pressure transmitter*

The sensor measures average pressure over the complete length of the ventilation pipe as indicated in figure 3.2, not only single points in the flow. Based on sensor tests at electric power laboratory at Western Norway University of Applied Science, also reverse air flow direction measurements are included. Higher measurement error (increasing with higher pressure difference) are observed at reverse direction, still the sensor are tested to give an good indication of reverse direction air speed. The air velocity sensor pressure measurements are connected to an standard differential pressure transmitter



(a) Position of air velocity sensor



(b) Air velocity sensor with pressure transmitter

Figure 3.2: *Air differential pressure sensor with differential pressure transmitter*

Air flow calculations are based on equation 2.19, where the manufacturer product specific equation are given in equation 3.1, included flow sensor coefficient K_m [45]. Q is the air volume flow, A the internal cross section area of pipe, and Δp is the differential pressure measured by the sensor. Due to relatively low air speed, see chapter 2.3.1, air are considered incompressible for the given measurements. Density need to be adjusted for temperature and local atmosphere pressure [35] [45]. With internal diameter of temporary pipe for sensor at 116.4 mm and K_m given as 0.7855 based on Micatrone calculation tools [46], equation 3.2 is used as basis for the measurement, where ρ is adjusted based on temperature and atmospheric pressure at test dates.

$$Q = A \cdot K_m \cdot \sqrt{\Delta p \cdot \frac{1.2}{\rho}} \tag{3.1}$$

$$Q = 0.00836 \cdot \sqrt{\Delta p \cdot \frac{1.2}{\rho}} \tag{3.2}$$

3.2.2 Level of dissolved gas supersaturation

At the field test performed in November 2021, visual observation, documented by pictures, are planned to observe if indirect visible sign of TDG supersaturation are present during testing. Indirect sign of TDG supersaturation is normally not visible at levels below 120 % [27], see chapter 2.1.

At the field test performed in April 2022, direct measurements of supersaturation have been performed with a "Weiss saturometer" temporary installed in the outlet stream from the Grønhaug plant, protected by a perforated plastic 75mm pipe, see chapter 3.4. Theory relevant for Weiss saturometer are described in chapter 2.4. Function test of sensor and junction box have been done i regular bobble water, which gives approximately TDG at 120 %. The equipment are borrowed from the Norwegian research institute Norce, where the logger junction box is developed by Norce, equipped with an Groupe Spéciale Mobile (GSM) antenna which send all data directly to Norce database for online monitoring. Table 3.3 and figure 3.3 present the used equipment.

Figure 3.3: *TDG sensor with logger junction box, GSM antenna and power supply*

Parameter	**Location**	**Equipment**	**Model**	**Manufacturer**	**Range**
TDG	Station outlet	TDG sensor with water temp. monitoring	High pressure saturometer	Fisch und Wassertechnik	80-200 TDG
TDG	Station	Logger with amb. pressure monitoring	Norce ver. 7	Norce	

Table 3.3: *TDG sensor with logger system*

3.2.3 Pressure loss at intake area

To find pressure loss above the intake trash rack, pressure head inside the intake trash rack hood can be measured, compared to water level in intake dam outside the intake hood. Due to hydropower plant in full operation and by that limited access to intake trash rack hood, sensor in intake hood was not preferred, and pressure head (water level) in intake obsolete air vent was measured. Total pressure loss at intake hood area can then be found by the difference between intake dam water level, and pressure head in obsolete air vent by use of Bernoulli's equation, if turbine discharge is known. See equation 2.7. Losses will then not only be valid for trash rack, but consist of total losses in intake hood included entrance of pressure pipe. The main focus is not to identify detailed level of losses in the different test situations, but the water level inside intake air vent compared to water level in pressure pipe in intake area. Equation 3.3 is used to calculate water level in obsolete air vent when using submerged pressure sensor for measurement of water level.

Water level (pressure head) measurement in intake obsolete air vent is done differently at the different field tests. Ultrasonic sensor, measuring the water level from top of air vent were used at the field tests in November 2021. For the field tests in April 2022, a submerged gauge pressure sensor (LMP 305) is lowered in the obsolete air vent, protected by a 32 mm plastic pipe. Details of field installation of sensors is presented in chapter 3.4. Table 3.4 present the different sensors used for water level in intake dam and intake obsolete air vent.

Parameter	**Location**	**Equipment**	**Model**	**Manufacturer**	**Range**
Water level	Intake dam	Submerged pressure sensor	PTX 1830	Druck	0 – 350 mbar
Water level	Obsolete air vent	Submerged pressure sensor	LMP 305	BD SENSORS	0 – 350 mbar
Water level	Obsolete air vent	Ultrasonic sensor	UB4000-F42-I-V15	Pepper+Fuchs	0 – 4 m

Table 3.4: *Ultrasonic sensor and submerged gauge pressure sensors for measurement of water level in intake dam and obsolete air vent*

3.2.4 Pressure head in Grønhaug power station

As presented in figure 3.10a, a pressure transmitter of the type 3100-B-0016G-01-B000 by GEM sensors, with a range of 0 – 16 bar gauge, have been installed and used. The pressure sensor measure the pressure head at the given point at the pipe, and are installed on the same manifold as a local manometer, which then can be used for calibration purposes. The pipe connection point is on an reduction cone from 0.5 m to 0.4 m pipe diameter, estimated to approximately 0.46 m pipe diameter at measure point. Pressure head measurements can be calculated in meters by equation 3.3 [34], were p is the measured pressure from the sensor, which by gravity and water density can give the pressure head in m for the given conditions.

$$h_{ph} = \frac{p}{\rho g} \tag{3.3}$$

With regards to measure and calculation error, several conditions disturb the resulting pressure head calculations. Depending on the turbine discharge, the water speed will vary, and by that the velocity head will vary, but will be limited compared to measurement values. E.g., at 0.8 m^3/s discharge the velocity head will be approximately 1.2 m, and at 0.2 m^3/s discharge the velocity head will be approximately 0.08 m, which gives approximately 1 % error of the pressure head readings span during testing between 110 – 140 m. Further, the density for water will be changed based on the given amount of air bobbles in the water flow. This is not considered in the calculations in equation 3.3 for water density. Also, the pressure pipe outage is in a reduction cone upfront a valve, which gives disturbed flow, and precise pressure measurements taking into account atmospheric pressure conditions and compressibility are not included [47]. Still, the purpose of the pressure measurements is to see the general change in pressure, and also the pressure head behaviour (fluctuating) when air are entrained in pressure pipe, not to measure accurate pressure head values, and the given errors are therefore accepted for field tests.

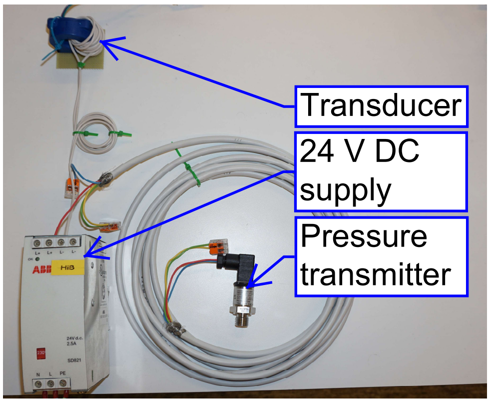


Figure 3.4: *Pressure transmitter with 24V DC supply and transducer*

3.3 Developed test setup and preparations at laboratory

All parameters given in table 3.1 needs to be connected to a logger device to be able to log and extract the measured data. PicoScope 4824, with the computer logger program PicoLog, are chosen, and the measurement methods are further developed to link sensors and transmitters to the given logger device. Figure 3.5 give a brief overview of test setup designed for field tests at Grønhaug plant, included main components and circuits for sensors and logger device. The test setup is structured to capture both new temporary sensors and equipment needed for field tests, in addition to existing plant parameters as intake dam water level.

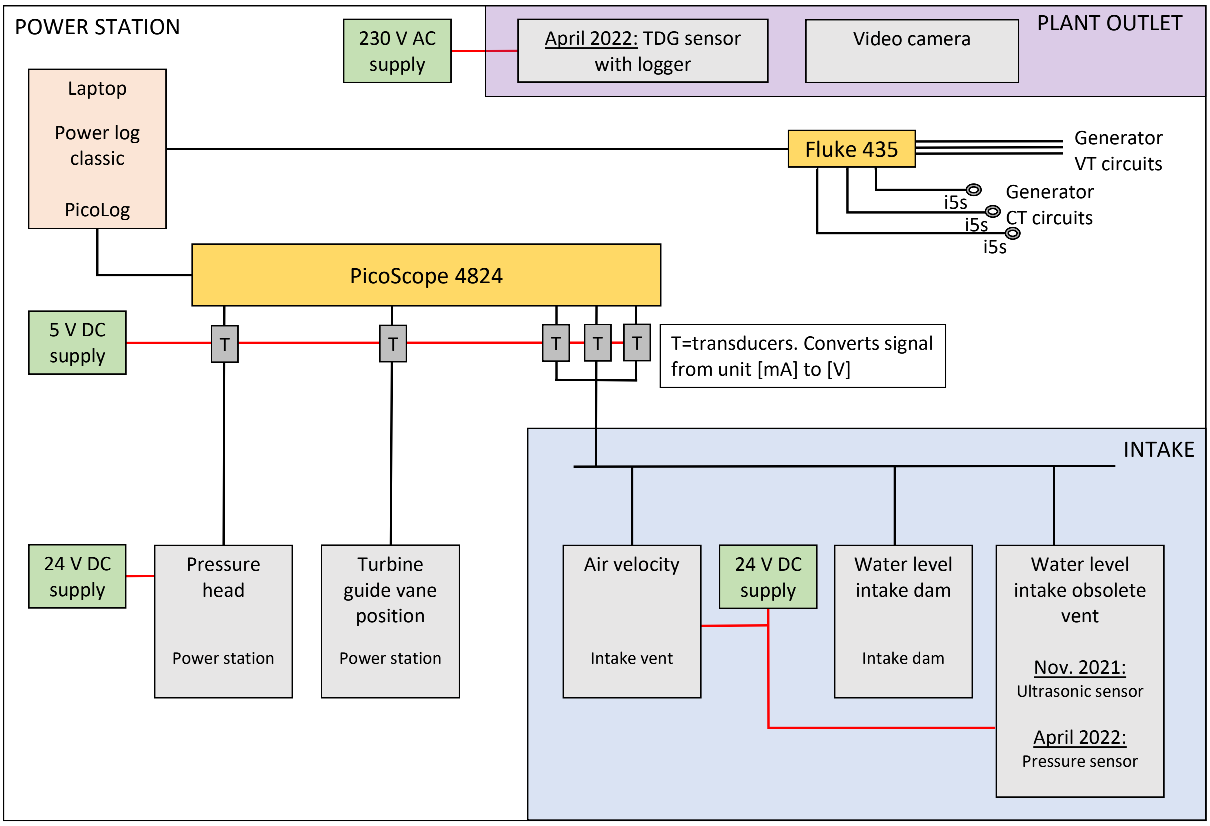


Figure 3.5: *Measurement topology drawing for field tests at Grønhaug plant*

To limit the preparation time at Grønhaug plant, all wires, connections, junction boxes and equipment were prepared as far as possible at the electric power laboratory at HVL. See figure 3.6 for a brief overview of the work done at the laboratory before field tests in November 2021. Some of the sensors needed external transmitters, and also loop power supply as indicated on figure 3.5, which have been prepared in the laboratory. Sensors and transmitters have been parametrized for 4 – 20 mA signal as output to reduce the probability for disturbance of the measured signals [33]. Since the PicoScope 4824 only have voltage inputs, transducers are used to convert mA signals to voltage signals, improved by use of RC low-pass filter at the signal input, see details in appendix B.

After assembling and wiring of circuits and components, test, calibration and familiarization have been performed. The air sensor with transmitter were mounted on temporary pipe extension for intake vent, calibrated and tested in both forward and reverse air velocity by use of strong mechanical air speed regulated vacuum cleaner. The reverse direction gives lower but still surprising good accuracy, good enough for the intended use, see chapter 3.2.1. The loops for turbine guide vane position and water level at intake dam is parameters used in operation in Grønhaug plant, hence only the transducer with relevant circuits have been prepared and tested at the laboratory.

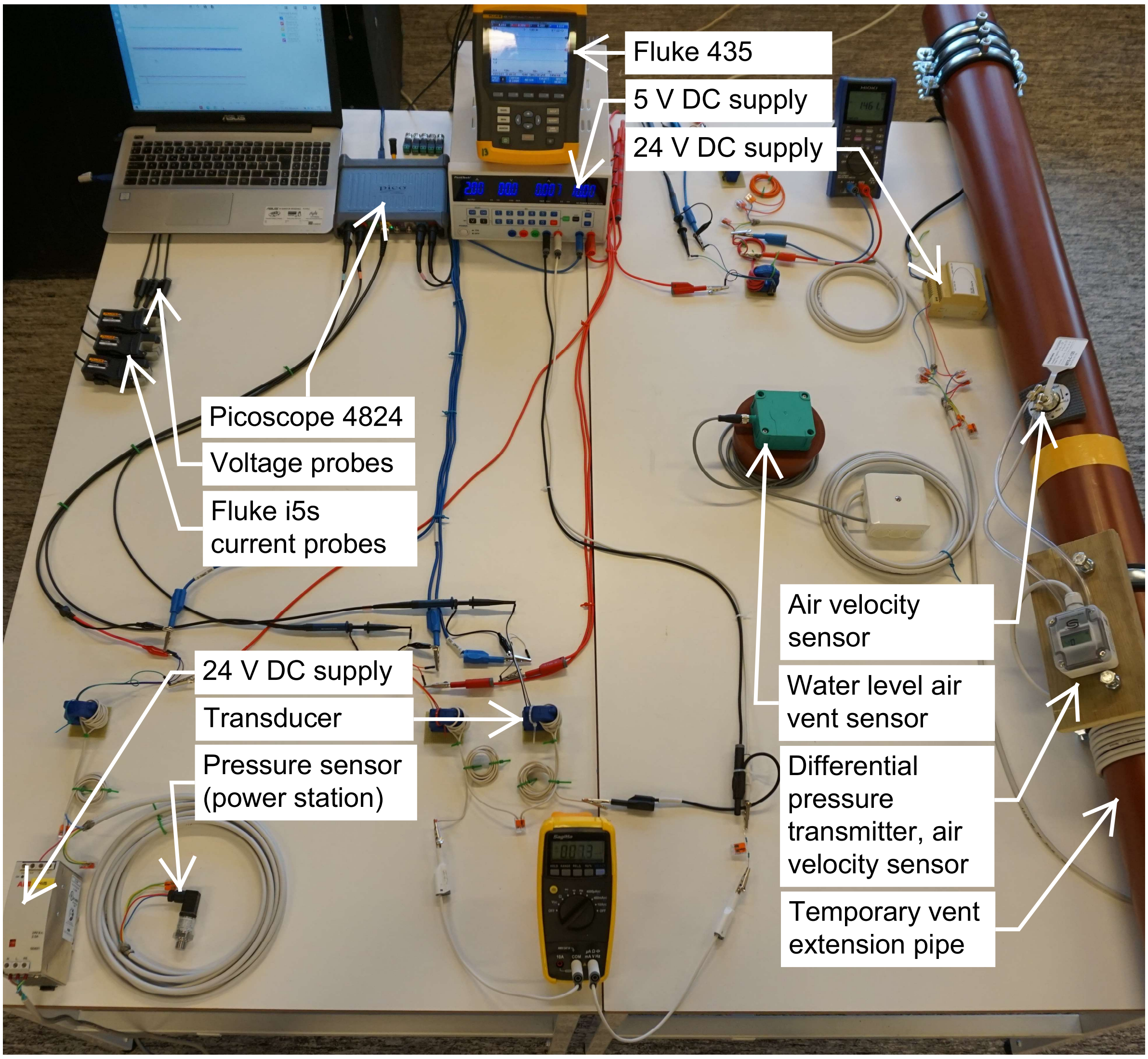


Figure 3.6: *Overview of component and circuit assembly at electro power laboratory at HVL November 2021*

3.4 Test setup at Grønhaug plant

3.4.1 Test setup at intake dam

At the intake dam, four parameters have been measured;

- air velocity in intake air vent for air flow through new and obsolete intake air vent
- water level in intake dam (existing operational parameter in plant)
- water level in intake obsolete air vent

  November 2021: ultrasonic sensor

  April 2022: submerged pressure sensor

Test setup at intake for test performed in November 2021, with temporary pipes, hoses and measurement setup, is presented in figure 3.7. The intake have two different air vents, one new and one obsolete air vent. To capture the main volume of air through the vents, both are connected together by temporary drain pipes and hoses to a common measured air input.

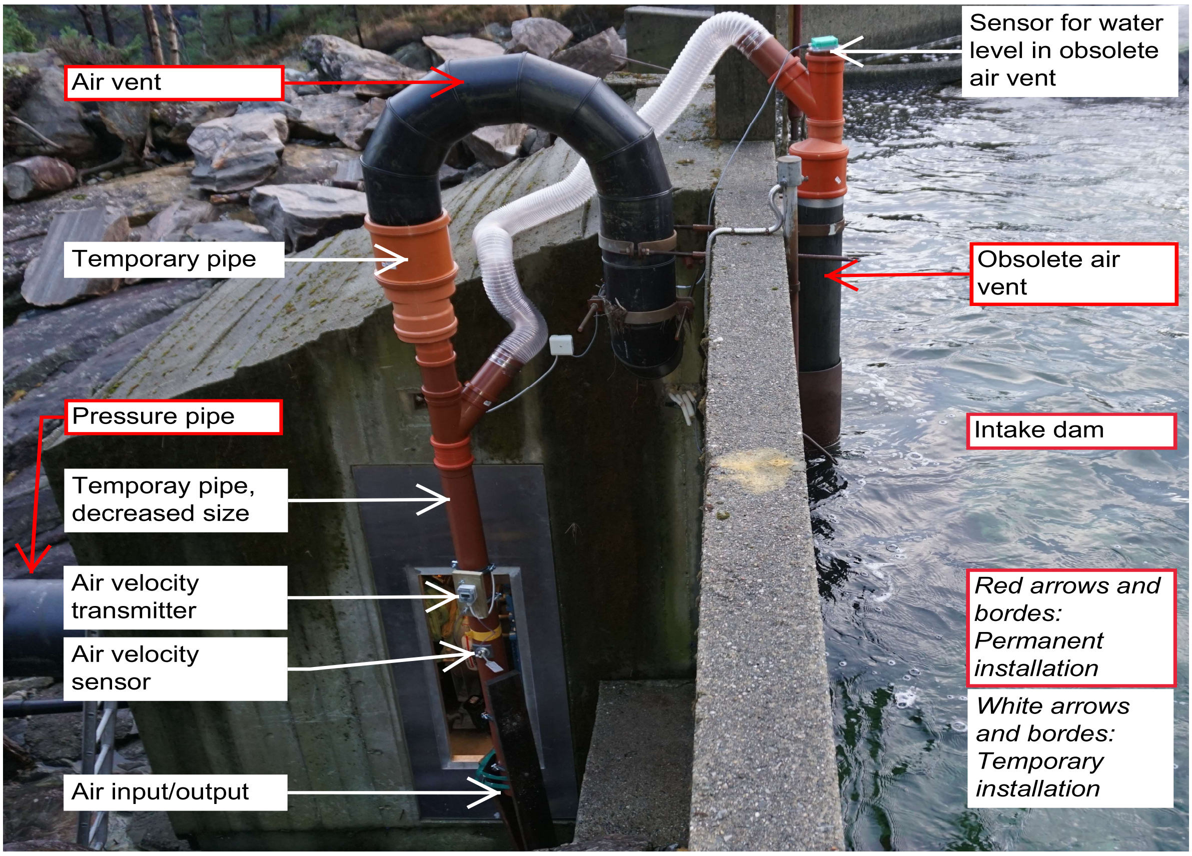


Figure 3.7: *Grønhaug plant intake area with temporary pipes and sensors at field tests November 2021. Red arrows indicate permanent equipment, white arrows is temporary installations.*

The temporary pipe diameter are largely reduced to get higher air speed, and by that higher accuracy for the air velocity sensor based on average pitot tube principle, as presented in figure 3.7, based on theory chapter 2.3.1 and 2.4.2. To obtain reasonable undisturbed flow environment for the sensor, the vendor recommendations are followed with respect to straight pipe without flow disturbance elements at least 7 times sensor length (125 mm) [45] upfront the sensor.

Water level in intake dam is an existing signal, and no action was therefore needed at the intake dam. For the water level inside the intake obsolete air vent, calibration towards intake construction drawings and water level measurements in intake dam have been necessary. Figure 3.7 indicate the given position for the ultrasonic sensor on top of the obsolete air vent, used at the test in November 2021. At the test in April 2022, the same setup is used, but an submerged pressure sensor is routed inside the obsolete vent for measurements. To protect the submerged pressure sensor a 32 mm plastic pipe is used. Covering of intake trash rack during testing is done by lowering rectangular plates step by step outside the bars at the trash rack. See figure 3.8 which present the plates used during testing. Signals from measurements at the intake is transferred to the Grønhaug station by use of existing loops and spare pairs in signal multicore cable between intake house and power station.

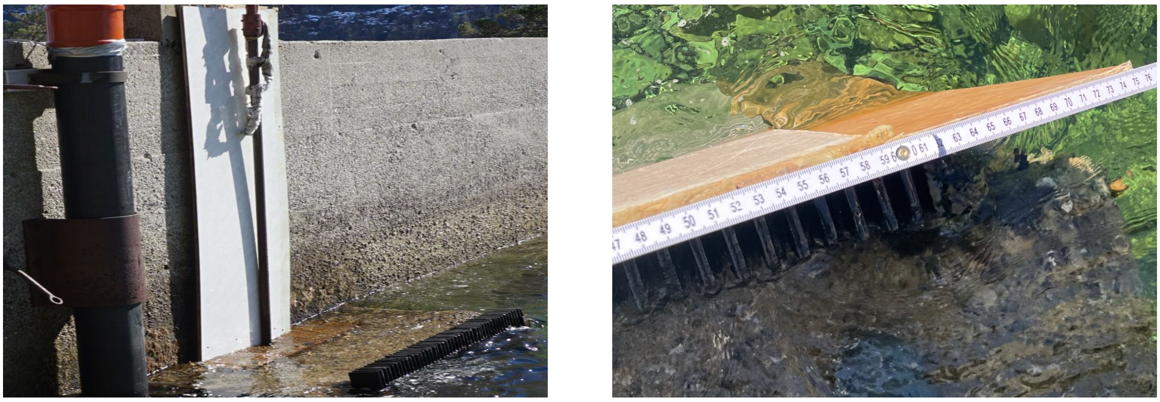


Figure 3.8: *Top of Grønhaug plant intake hood with rectangular plates used to cover intake trash rack*

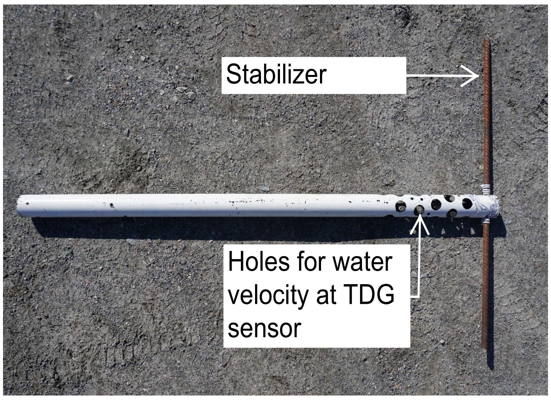
3.4.2 Test setup at Grønhaug power station

At the Grønhaug power station, the following parameters have been measured:

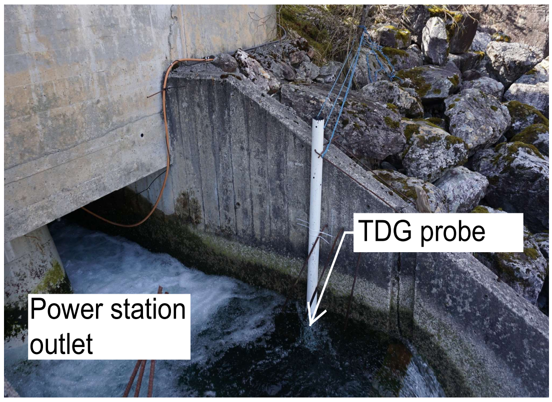
- Level of TDG downstream Grønhaug plant outlet
- Pressure head upstream turbine in station
- Turbine guide vane position
- Generator voltage and current (only in November 2021)

In additional, PicoScope 4824 (see figure 3.5) and a laptop with the software "PicoLog" from Pico Technology and "Power Log Classic" from Fluke where placed in the power station for monitoring.

Level of TDG for the test performed in November 2021, was monitored visually and documented by pictures and video (see theory chapter 2.1). At the test performed in April 2022, the TDG sensor was installed in the outlet water from the plant as given in figure 3.9. Since the water depth are limited, and the water river basin downstream the plant have low water velocity towards the Mofjord, the probe needed to be installed in the outlet flow from the plant to avoid disturbing air bobbles on the probe (see chapter 3.2.2 and theory chapter 2.1). It is also important to secure that measurements only monitoring water from the power plant outlet, not other contribution in the downstream river.



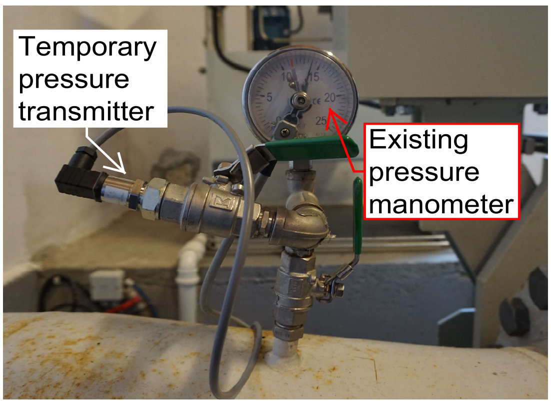
(a) Pipe for protection of TDG sensor



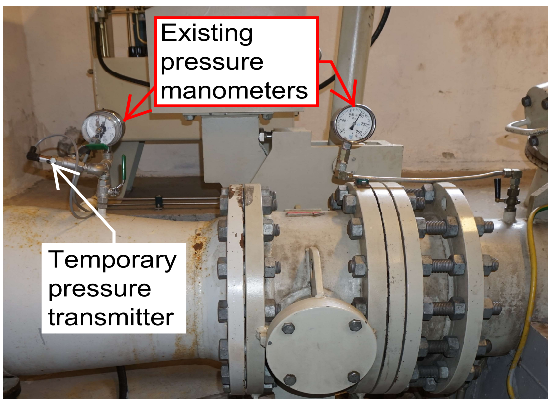
(b) Location of TDG sensor

Figure 3.9: *Location of TDG sensor downstream Grønhaug power station outlet*

The pressure head sensor is connected to the pressure pipe close to the turbine inside the power station. See figure 3.10. The local manometers, preferable the manometer on the same pipe outage with the same velocity head present, can be used for calibration purposes.



(a) Pressure transmitter in power station



(b) Pressure transmitter in power station

Figure 3.10: *Location of pressure transmitter in Grønhaug power station*

For the turbine guide vane position, the existing 4 – 20 mA signal loop are extended into one of the transducers introduced by this thesis, no more actions were needed except calibration of range at site. The generator current and voltage are measured in the power station control panel at the terminals for CT and VT circuits, into the fluke 435 power quality analyser.

3.5 Test method

The overall method chosen to initiate and observe the increased level of artificial TDG supersaturation downstream Grønhaug plant at field tests can be summarized as:

1. Hydropower plant in normal operation
2. Intake trash rack covered step by step up to 90 % coverage
3. Level of TDG, air entrainment and other relevant parameters observed
4. Intake trash rack coverage removed step by step
5. Hydropower plant operation normalized

During all steps, all relevant parameters are observed (i.e. level of TDG, air entrainment, pressure head at power station, turbine guide vane position). ≈ 90 % coverage of trash rack at intake is used as maximum.

An different approach was used at field tests in November 2021 and in April 2022. At the field tests in November 2021, moderate flow in Stølselvi (the river upstream Grønhaug plant intake area) was an prerequisite for this first attempt of forced air entrainment on a hydropower plant in operation. Moderate flow is defined as approximately 0.4-0.5 m^3/s in the river, half the plants capacity. This enables easier control of intake dam water level and production during testing, and also reduced the energy present with risk of damage when introducing air in the pressure pipe. For field tests performed in April 2022, higher river flow and water velocity was needed, as a lesson learned from the first field tests, to achieve normal operation conditions during testing. Strict requirements for river conditions during testing dramatically restrict the number of feasible field test days in the time frame of this thesis.

During testing, the water level in the intake magazine, close to the intake hood, should not be too low to avoid air leading vortex at intake trash. See theory chapter 2.3.4. Based on equation 2.12 and 2.13, diameter of pipe at 0.6 m, and given discharge at the different tests, recommended minimum submerged intake to reduce risk of air leading vortexes during testing calculated, see appendix C.1. In November 2021, approximately 0.5 m^3/s was present, given water level in intake dam recommended above 1.75 m during testing. For the test in April 2022, with full production at 0.93 m^3/s, the intake dam depth is recommended to 2.1 m.

3.6 Safety during testing

With regards to safety during testing, three main topics have been assessed: personnel safety, prevent damage of power plant, and consequence for artificial supersaturation downstream the power plant outlet.

3.6.1 Personnel and plant safety

During field tests, air are introduces to the pressure pipe. As described in theory chapter 2.3.5, a consequence of air entrainment is blow outs, and by that, awareness for the energy release direction from the pressure pipe is important [7]. In addition, hydraulic transient because of rapid change in flow, as activation of emergency stop during testing if the hydropower plant enter operation conditions outside its limitations, can result in pressure shock waves [28], also known as water hammer [48]. Grønhaug plant owners informs that the intake area have experienced destructive powerful blowout / water hammer effect after introduction of air into the system in combination with automatic shut down of the plant. Both release of large volumes of trapped air as blow outs, and pressure shock waves, needs to be avoid during testing, for personal safety and damaging the power plant. To reduce the probability for personal injuries and damage of the plant, following mitigation actions are planned:

- Have respect for the energy release points at the intake, the pressure pipe length direction at the intake, in the most critical phases of testing
- Reduce the total period of air entrainment and hydropower plant abnormal operation
- Controlled normalizing of plant after air entrainment

3.6.2 Consequence by introduction of artificial supersaturation

The river downstream Grønhaug plant have been exposed to supersaturated water from the plant during testing. Possible consequences for biological life in the downstream river are therefore briefly assessed.

As a basis, the essential mitigation actions will be to reduce the duration and volume of released supersaturated water to an needed minimum, since the consequence for fish depend on duration and level of TDG supersaturation [1]. During field tests, only short periods with air entrainment will be present. The consequences for this short time testing are assessed to be small. There have not been observed fish in the river downstream Grønhaug plant. The river are short, just above 100 m, and ends up in the fjord Mofjorden. The supersaturated water will be thinned out in the large water volume in the fjord [1], compared to the relatively small volume from the power plant (≈ 0.5 – 1.0 m^3/s over a short time). In addition, the water depth in the fjord close to Grønhaug decrease quickly to above 70 m, and as explained in theory chapter 2.1, increased pressure at higher water depths reduce the supersaturation, and fish can by that compensate for the supersaturation by deeper position in the water [1]. Aeration of supersaturated water will be a process that can continue over several kilometres [1]. Rough river bottom conditions and aerating edges/jump in the river is possible factors that can increase the aeration process to reduce supersaturation. The river downstream Grønhaug station have a diagonal and limited threshold and partly rough river bottom conditions in part of the river (depended on tide level). It is assumed that this will to some degree reduce the supersaturation reaching Mofjord [1].

4 Results

This chapter presents the results obtained from the field tests performed at Grønhaug plant, based on methods described in chapter 3. The results are presented in two sections. Section 4.1 present the result from field tests performed at Grønhaug plant in November 2021. At this test, TDG level was not confirmed with measurements, only visual observation, and abnormal operational conditions with low discharge were present. Then, section 4.2 present the results from field tests performed at Grønhaug plant in April 2022, where the level of TDG was measured in the plants outlet during tests. At this test, operation conditions were as in normal operation with higher discharge.

4.1 Field test at Grønhaug plant November 2021

4.1.1 Introduction

Result from field test performed at Grønhaug plant the 26th of November 2021 is presented in this chapter, based on the test method described in chapter 3.5. The river flow rate upstream Grønhaug plant intake dam are estimated to approximately 0.5 m/s during the test day, and an outside temperature between 0 °C to 1 °C.

Covering of the intake trash rack was performed three times to observe if the different measured parameters was behaving similarly at all tests. Between each test the plant were set back to normal operation conditions without covering of intake trash rack.

Data presented in graphs are obtained from voltage input signals to PicoScope 4824 and Power Log Classic, given by setup presented in topology drawing 3.5. Relevant parameters are extracted to Microsoft excel, followed by noise filtering in Matlab and import to LaTex plot module. Appendix A present additional figures, not included in this chapter. Appendix D includes exported data from PicoScope and Power Log Classic, and the main Microsoft excel file with data imported into latex.

4.1.2 First covering of trash rack

Air flow measurements from the first intake trash rack covering are given in figure 4.1, based on equation 3.2, where air density is adjusted for temperature (1 °C) and atmospheric pressure at intake dam (estimated to 994 hPa) field test date. The air velocity sensor clearly indicate air entrance in to the intake air vents during performed tests. Figure 4.1 also indicate air leaving the air vents, understood that air flow in reverse direction have higher measurement error then at designed forward direction as described in chapter 3.2.1. The grey area in figure 4.1 indicates the time period where the intake trash rack was ≈ 90 % covered (maximum coverage during test). After removing the trash rack covering, normalizing of the power plant was performed to be ready for the next test.

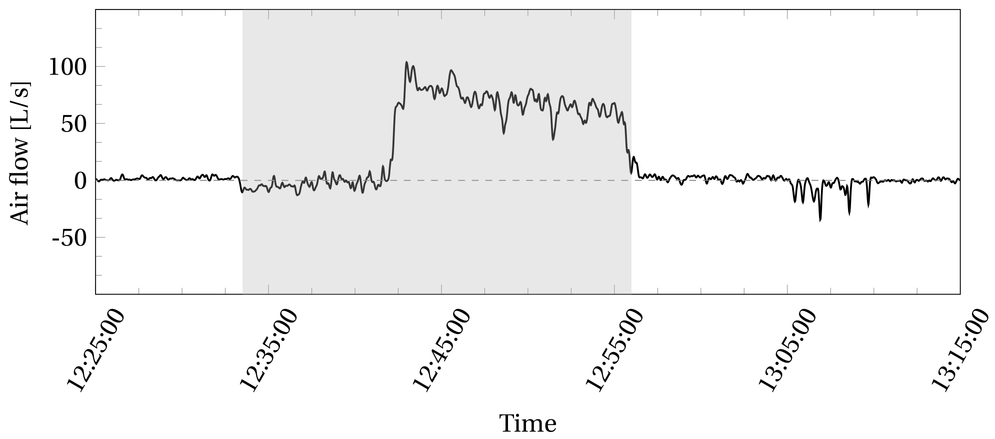


Figure 4.1: *Air flow through intake air vents, before, during and after the first covering of the intake trash rack at field tests in November 2021. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %)*

The air velocity transmitter 4−20 mA signal range was set to reflect the measure range of -300 Pa to 300 Pa. During the test, local transmitter display indicated short time peak differential pressure up to 1000 Pa which then not are included in the result. The intake dam water level was mostly below 1.9 m as indicated in 4.3b, 4.5b and 4.7b. No vortexes were observed at water surface into the trash rack, only surface swirl, defined as vortex type 1 in [37], and no air was observed (audible) to enter through the trash rack.

In addition to the air flow measurements, other parameters monitored during the first covering are included in figure 4.3 and A.1, where the most important are level of TDG downstream Grønhaug plant station presented in figure 4.2. Air flow through air vents are included in figure 4.3 to relate the different parameters to air entrance measurements.

Figure 4.3e are indicating TDG supersaturation above visible levels in the test period, documented by video and pictures during the first coverage of trash rack. The TDG level 120 % in 4.3e are defined in presented result as the first indirect visible sign of supersaturation [27] by

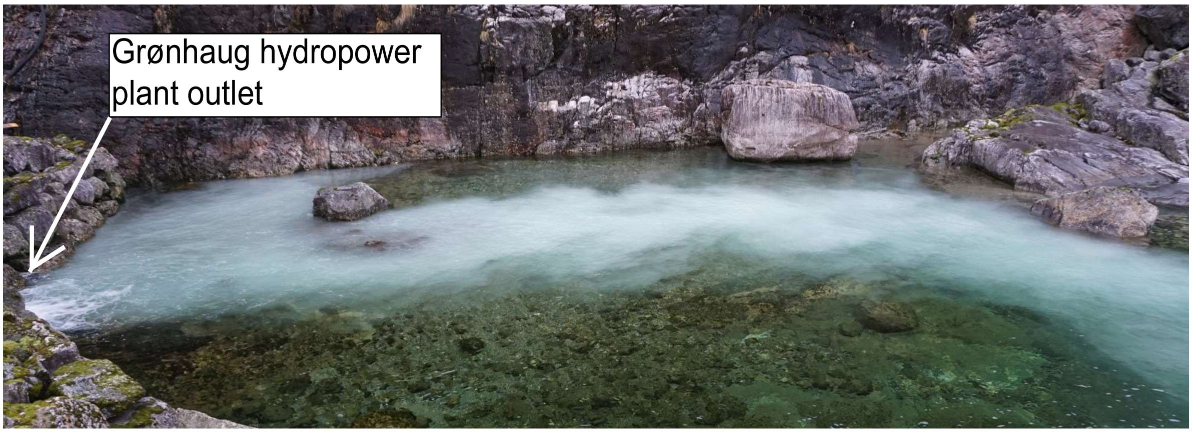
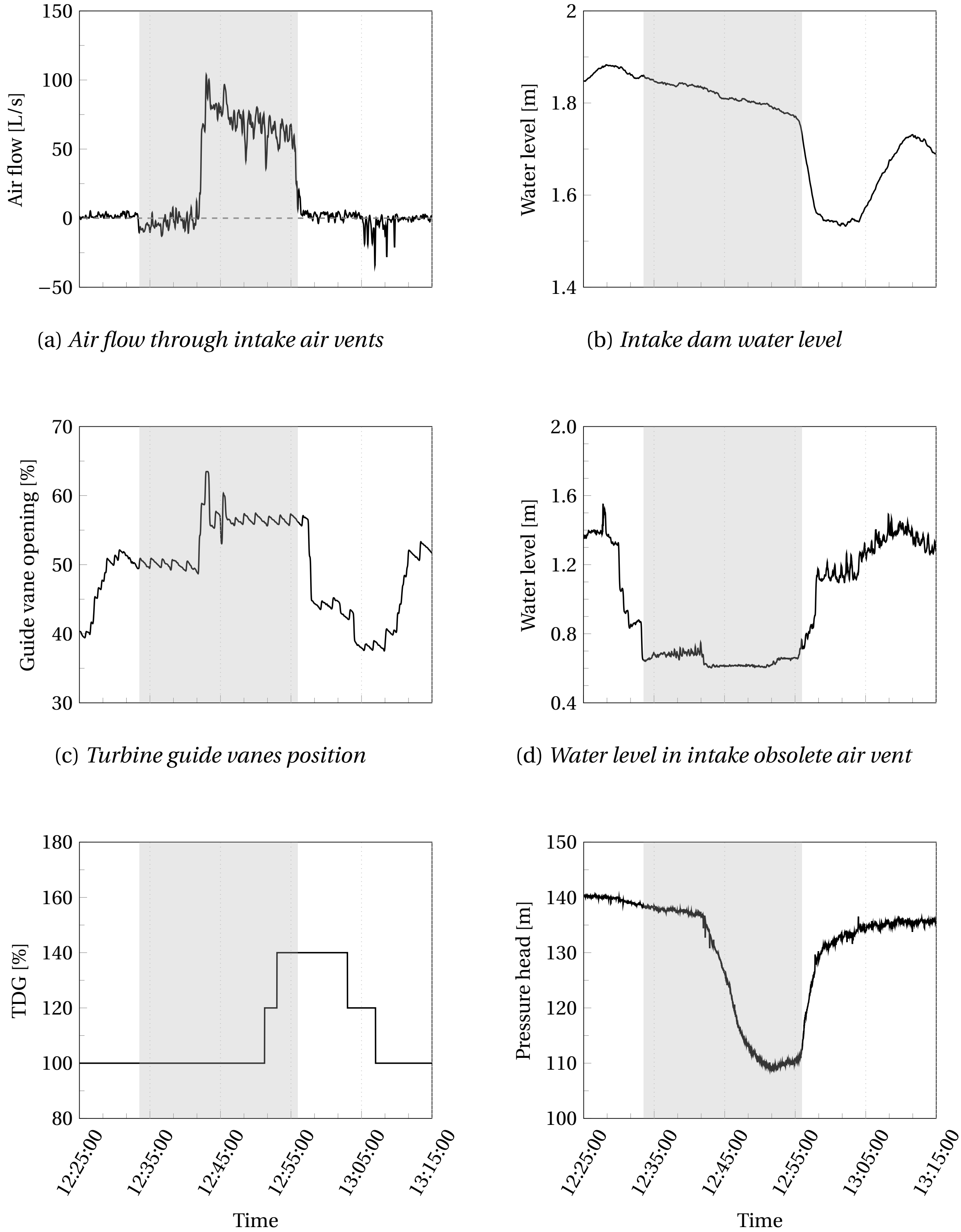


Figure 4.2: *River downstream Grønhaug plant during first covering of trash rack during field test in November 2021, with visible sign of TDG supersaturation in the outlet river*

small air bubbles visible in water, where 140 % are indicated the period of high visible sign of TDG supersaturation. See theory chapter 2.1. Figure 4.2 present periods with strongly visible sign of high level of TDG supersaturation in the plant outlet river.

The presented data from pressure head measurements in Grønhaug power station, see figure 4.3f, is based on equation 3.3 given in method chapter 3.2.4. The accurate range of transducer was not found during field test, and the result have therefore been calibrated against one of the local pressure head manometers given in figure 3.10b. Based on the manometer calibration, a general factor of 6 m is added to the result with respect to the calculated pressure head in unit meter from the pressure sensor. The manometer is installed on a slightly smaller pipe diameter then the pressure sensor, 400 mm versus 460 mm at the pressure sensor, resulting in a minor higher velocity head and lower pressure head compared to the pressure sensor position. Still, due to low discharge and the following low difference in velocity head between the different positions, discharge range approximately at 0.1 – 0.5 m^3/s during testing, this is not taken into consideration when the calibration factor of 6 m have been added.

Calibration of turbine guide vane position data was done by adjusting the position from 0 – 100 % before start of testing. The range of loop at plan control system is 0 – 104 %, presented as 0 – 100 % in result. Loop for water level in intake dam (existing loop in use by plant) were calibrated against the water level given in the plants control system. In figure 4.3d, the ultrasonic height measurement of the water level in the obsolete air vent at intake is included. Water level in obsolete air vent is presented with respect to corresponding water level in intake dam area, calibrated against the Grønhaug water level loop in intake dam. The sensor was partly unstable during testing, which is filtered from the results. Corresponding transducer faced problems during the test day. Re-check of the transducer was performed after the test day to valid the used range.



(a) *Air flow through intake air vents*

(b) *Intake dam water level*

(c) *Turbine guide vanes position*

(d) *Water level in intake obsolete air vent*

(e) *Visible sign of TDG supersaturation at outlet*

(f) *Pressure head upstream turbine*

Figure 4.3: *Main parameters measured during second covering of intake trash rack at field tests in November 2021. Grey area indicates the period with maximum coverage of trash rack at (≈ 90 %).*

4.1.3 Second covering of trash rack

Air measurements from the second intake trash rack coverage are given in figure 4.4. Other parameters monitored during the second covering are included in figure 4.5 and A.2. The plant response by the covering of intake trash rack are similarly as for the first covering of trash rack, except for more air released *out* of the intake air vents during testing. The high peaks of air release out from ventilation pipe are experienced as minor not destructive blow outs. Exact time for 90 % covering and removal are not noted during test and therefore not included in the result for the second covering.

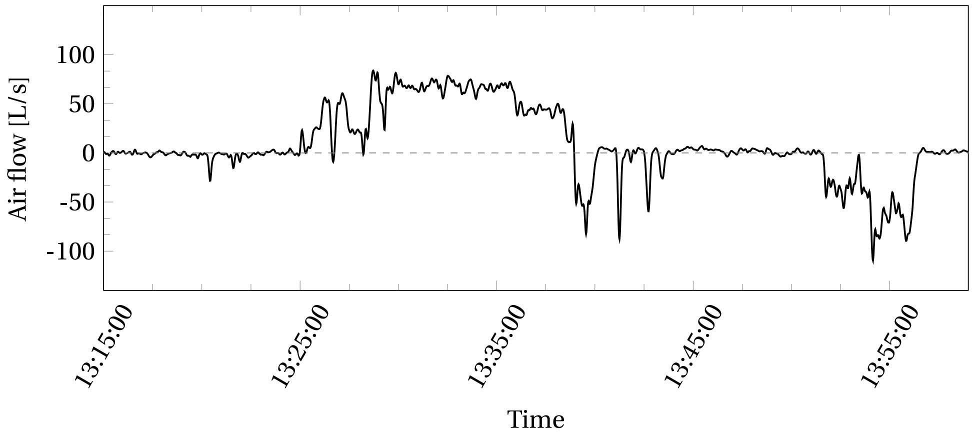
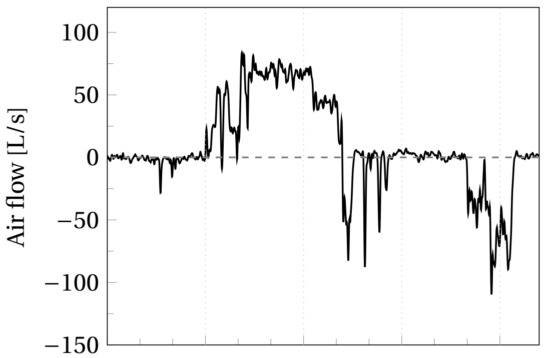
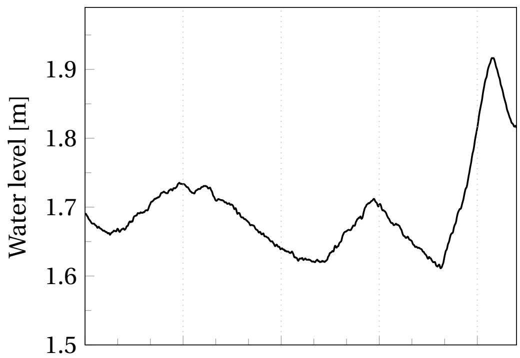


Figure 4.4: *Air flow through intake air vents, before, during and after the second covering of the intake trash rack at field tests in November 2021.*

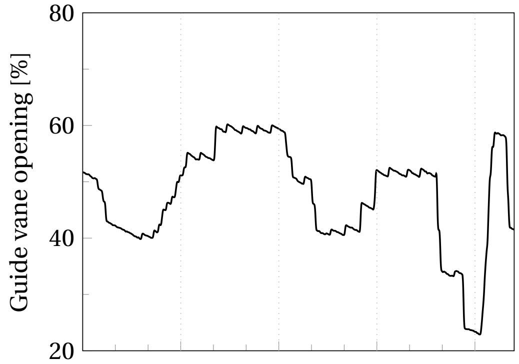
Level of TDG supersaturation downstream Grønhaug plant was visually followed during the second covering of intake trash rack, and the same clear sign of high level of TDG supersaturation was observed as for the first coverage of the intake trash rack. The period of visible sign of TDG supersaturation is not documented as good as for the first covering with pictures and videos, figure 4.5e are therefore only indicated with dashed lines the approximately period of visual sign of TDG supersaturation downstream the hydropower plant outlet.



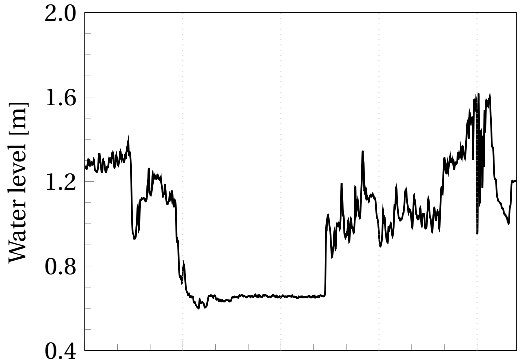
(a) *Air flow through intake air vents*



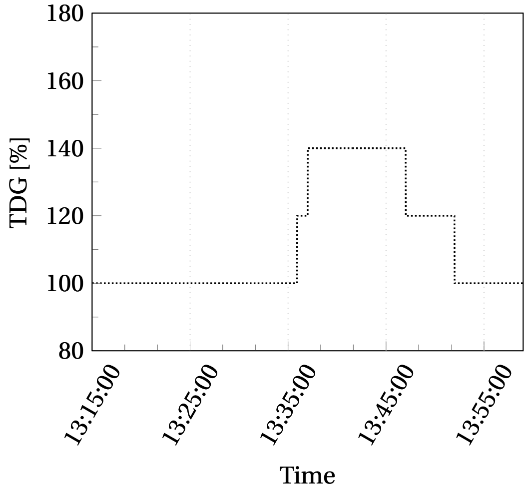
(b) *Intake dam water level*



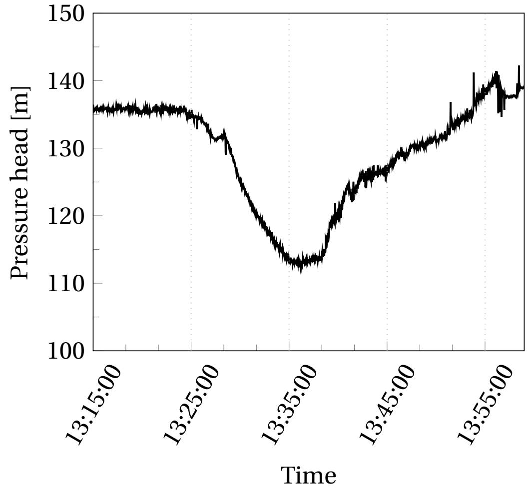
(c) *Turbine guide vanes position*



(d) *Water level in intake obsolete air vent*



(e) *Visible sign of TDG supersaturation at outlet*



(f) *Pressure head upstream turbine*

Figure 4.5: *Main parameters measured during second covering of intake trash rack at field tests in November 2021.*

4.1.4 Third covering of trash rack

Air measurements from the third intake trash rack coverage are given in figure 4.6. Other parameters monitored during the third covering are included in figure 4.7 and A.3. The plant response by the covering of intake trash rack are similarly as for the first and second covering of trash rack. The high peaks of air release out from ventilation pipe are experienced as minor not destructive blow outs. The last blow out, short time after 14:45:00 in figure 4.7, was observed to be more powerful at the intake dam. Exact time for 90 % covering and removal are not noted during test and therefore not included in the result for the third covering.

Level of TDG supersaturation downstream Grønhaug plant was visually followed during the third covering of intake trash rack, and the same clear sign of high level of TDG supersaturation was observed as for the first and second coverage of the intake trash rack. The period of visible sign of TDG supersaturation are not documented as good as for the first covering with pictures and videos, figure 4.7e are therefore only indicated with dashed lines the approximately period of visual sign of TDG supersaturation downstream the hydropower plant outlet.

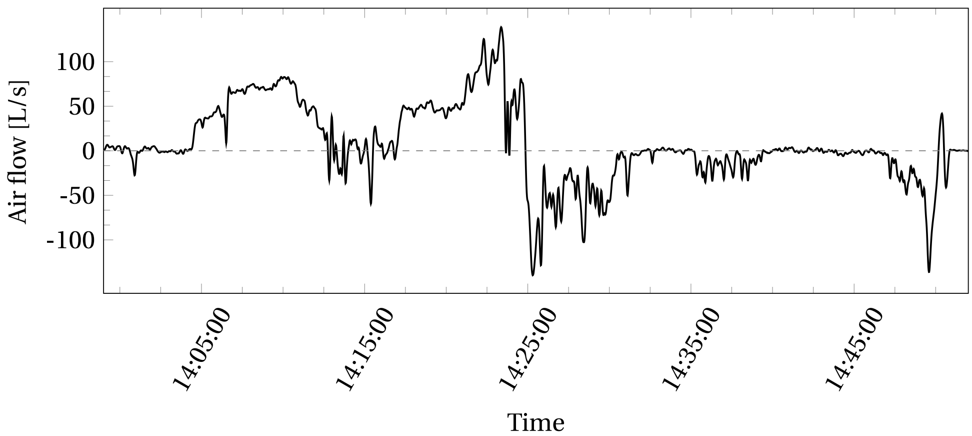
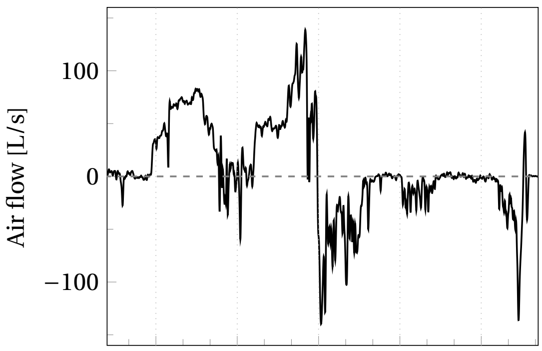
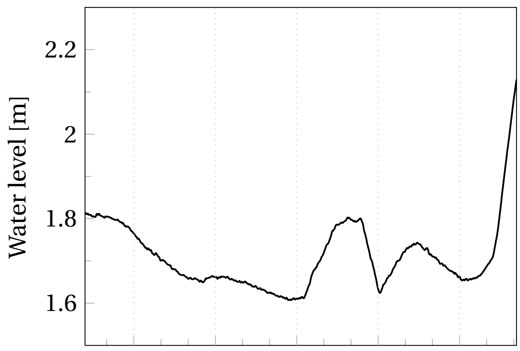


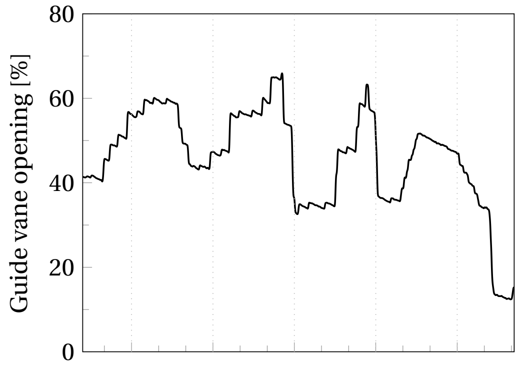
Figure 4.6: *Air flow through intake air vents, before, during and after the third covering of the intake trash rack at field tests in November 2021.*



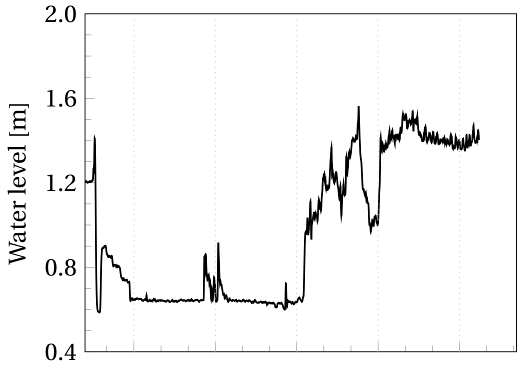
(a) *Air flow through intake air vents*



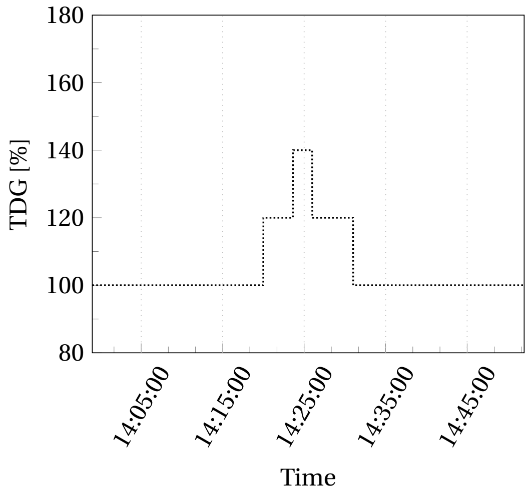
(b) *Intake dam water level*



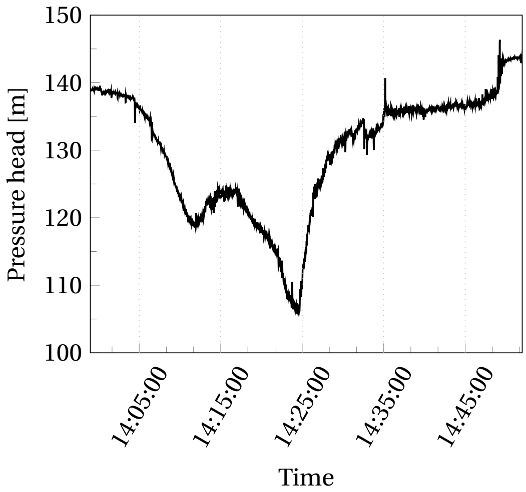
(c) *Turbine guide vanes position*



(d) *Water level in intake obsolete air vent*



(e) *Visible sign of TDG supersaturation at outlet*

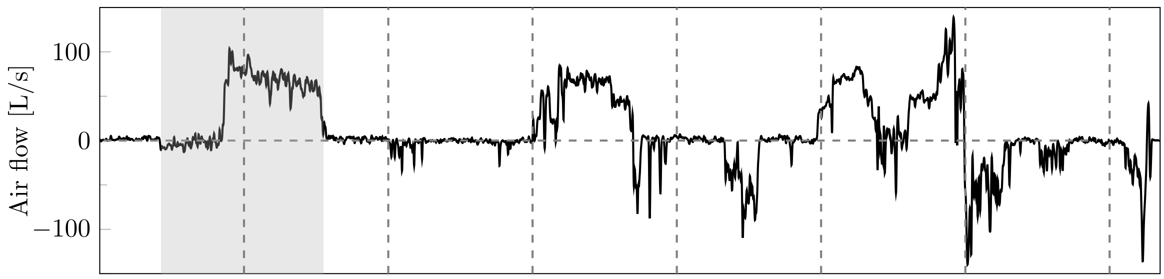


(f) *Pressure head upstream turbine*

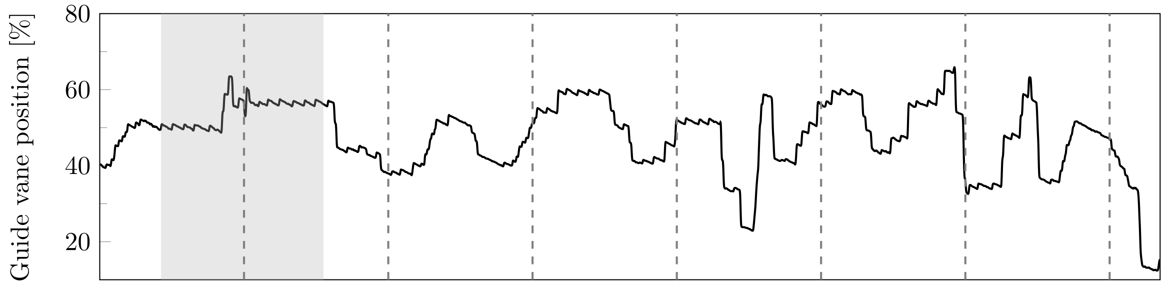
Figure 4.7: *Main parameters measured during third covering of intake trash rack.*

4.1.5 Summarized data from November 2021

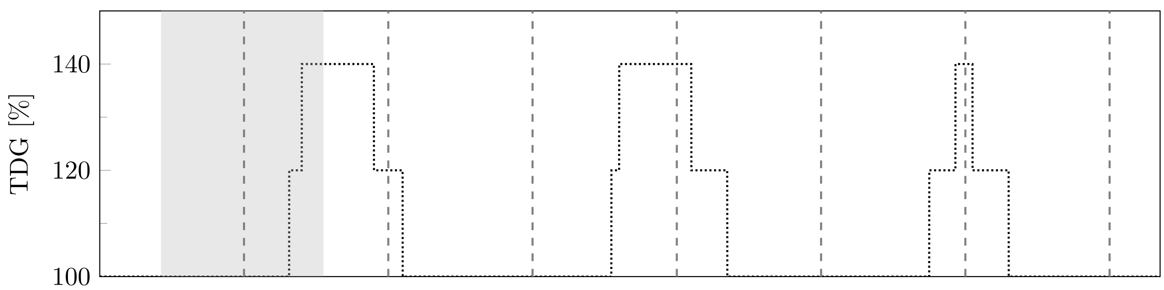
Figure 4.8 present air entrance, pressure head, observed level of TDG and guide vane position as a summary from tests performed in November 2021 at Grønhaug plant.



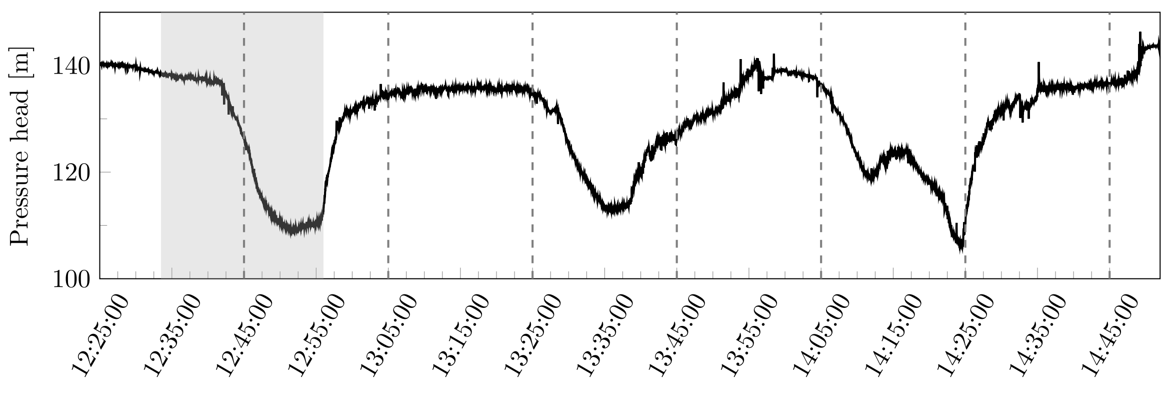
(a) *Air flow through intake air vents*



(b) *Guide vane position in Grønhaug power station*



(c) *Visible sign of TDG supersaturation at plant outlet*



(d) *Pressure head upstream turbine in Grønhaug plant station*

Figure 4.8: *Overview of main parameters during all tests performed November 2021 at Grønhaug plant. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %), which is only defined for the first covering*

4.2 Field test at Grønhaug plant April 2022

4.2.1 Introduction

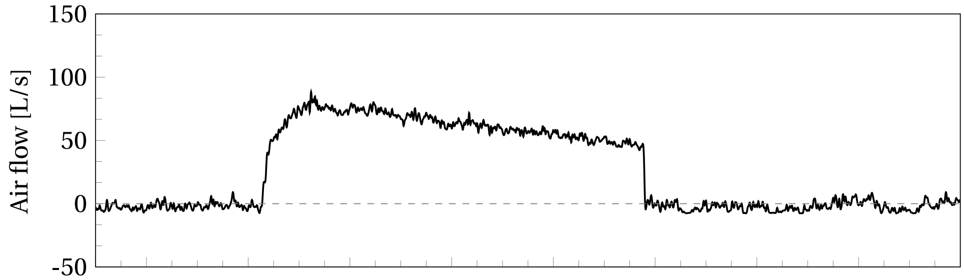
Result from the field test performed at Grønhaug plant the 18th of April 2022 is presented in this chapter, based on the test method described in chapter 3.5. The river flow upstream Grønhaug plant intake dam was increasing rapidly during the test day due to snow melting, from to approximately 0.6 m^3/s during preparation to above 1.0 m^3/s in the last test activities. The outside temperature started close to 0 °C, but was about 15 °C in the most relevant test period. Since the river started with too low flow for the planned test, and increased rapidly during the test day to above intake dam maximum operational level, only one main covering of intake trash rack was performed with needed river flow. During the period with coverage of the trash rack, normal operational plant and river discharge conditions were present, opposite to the abnormal operational conditions present during tests in November 2021.

Data presented in graphs are obtained from voltage input signals to PicoScope 4824, given by setup presented in topology drawing 3.5. Relevant parameters are extracted to Microsoft excel, followed by noise filtering in Matlab and import to LaTex plot module. TDG sensor raw data is received from Norce. Appendix D includes raw data from PicoScope, TDG sensor raw data and the main excel file used to calibrate and prepare data for import to latex.

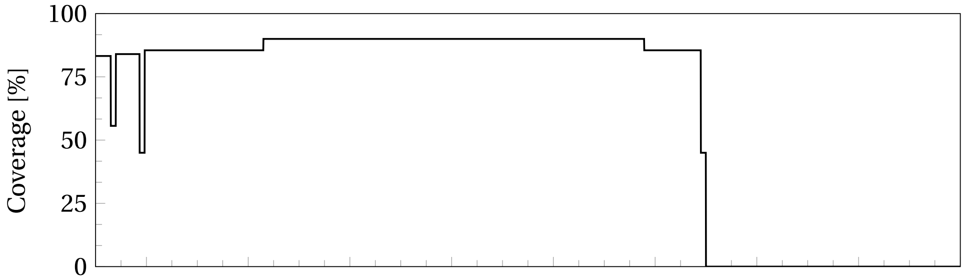
4.2.2 Air entrainment and level of TDG

Figure 4.9 present air flow through intake vent (figure 4.9a), included coverage of trash rack (figure 4.9b) and detected level of TDG (figure 4.9c) at the plants outlet. Air flow through intake air is based on equation 3.2, where air density is adjusted for temperature (15 °C) and atmospheric pressure at intake dam (estimated to 999 hPa) field test date. The air velocity transmitter $4-20$ mA signal output range was set to reflect the differential pressure measure range of -300 Pa to 300 Pa.

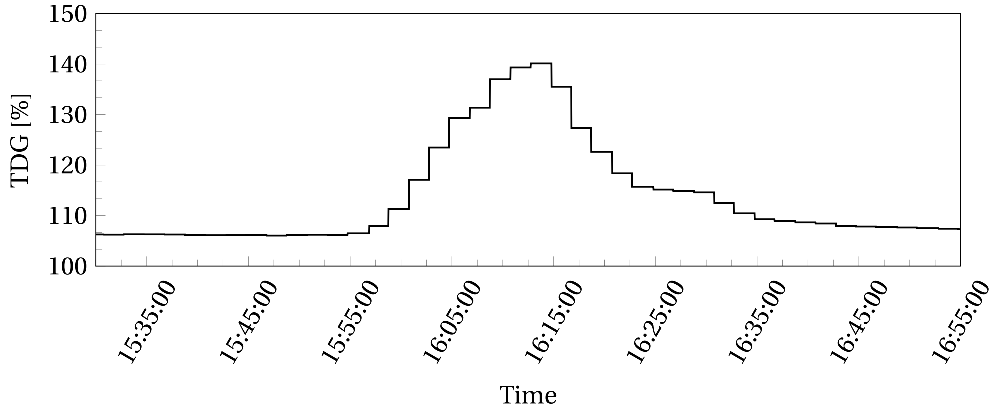
As also observed during field tests in November 2021, air entrainment is clearly identified through intake air vents during tests. No air of significance is observed to *leave* the intake vents during or after the test, only air entering the pressure pipe from vents is identified. Covering of intake trash rack have been performed up to $\approx$ 90 % as maximum coverage. Figure 4.9b present the approximately coverage in percentage before, during and after the main air entrainment period. Data is obtained from time lapse camera with 30 s interval and gives an approximately degree of coverage.



(a) *Air flow through intake air vents*



(b) *Intake trash rack temporary coverage*



(c) *Measured TDG in Grønhaug plants outlet*

Figure 4.9: *Air entrainment, TDG and coverage of intake trash rack during essential period of field tests April 2022 at Grønhaug plant*

Figure 4.12 in chapter 4.2.3 present all data gathered at the field tests in April 2022, and sub figures of 4.12 will be used throughout the rest of chapter 4.2.2 and 4.2.3. The intake hood submerged depth was high compared to field tests in November 2021, giving enough margin to the calculated critical submerged depth at 2.1 m, as can be seen in figure 4.12b. During air entrainment periods, no vortex is observed at trash rack, and no air is observed (audible) to enter through the intake hood area. Air entering into pressure pipe is observed to be from the main air vent, not the obsolete air vent. Figure 4.12d present the water column in the obsolete air vents during testing, which at all time is above zero.

Data from measured TDG level at Grønhaug outlet river is presented in figure 4.9c. As described in chapter 2.4.1, measured TGP % is presented as TDG %. The sensor was installed and set online the 8th of April 2022, with data sent to Norce every 30 min. During test period the 22th of April, sampling time at 2 min have been chosen to capture the short peak of TDG supersaturation. Shorter sampling time is not relevant due to the slow sensor reaction time to gain equilibrium as described in theory chapter 2.4.1. In the period with high air entrainment, figure 4.10 present the highly visible sign of TDG supersaturation released from the plants outlet. Figure 4.11 draw the measured TDG during test day, but also the day upfront, to set the measured supersaturation in relationship to levels present before air entrainment activity started. By comparing figure 4.10 and 4.11, it can be seen that highly supersaturated water is present during testing.

Figure 4.10: *Grønhaug plant outlet river during field tests April 2022*

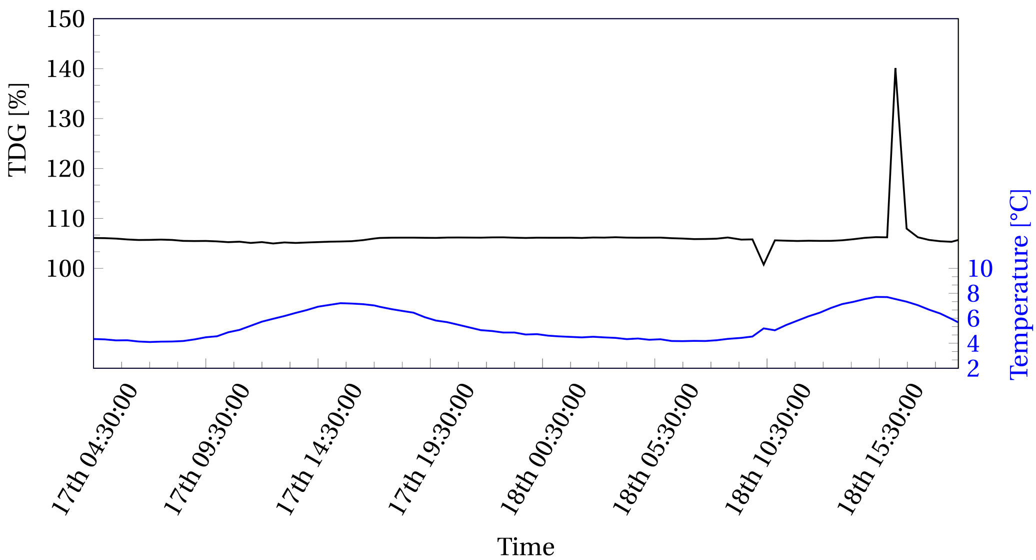


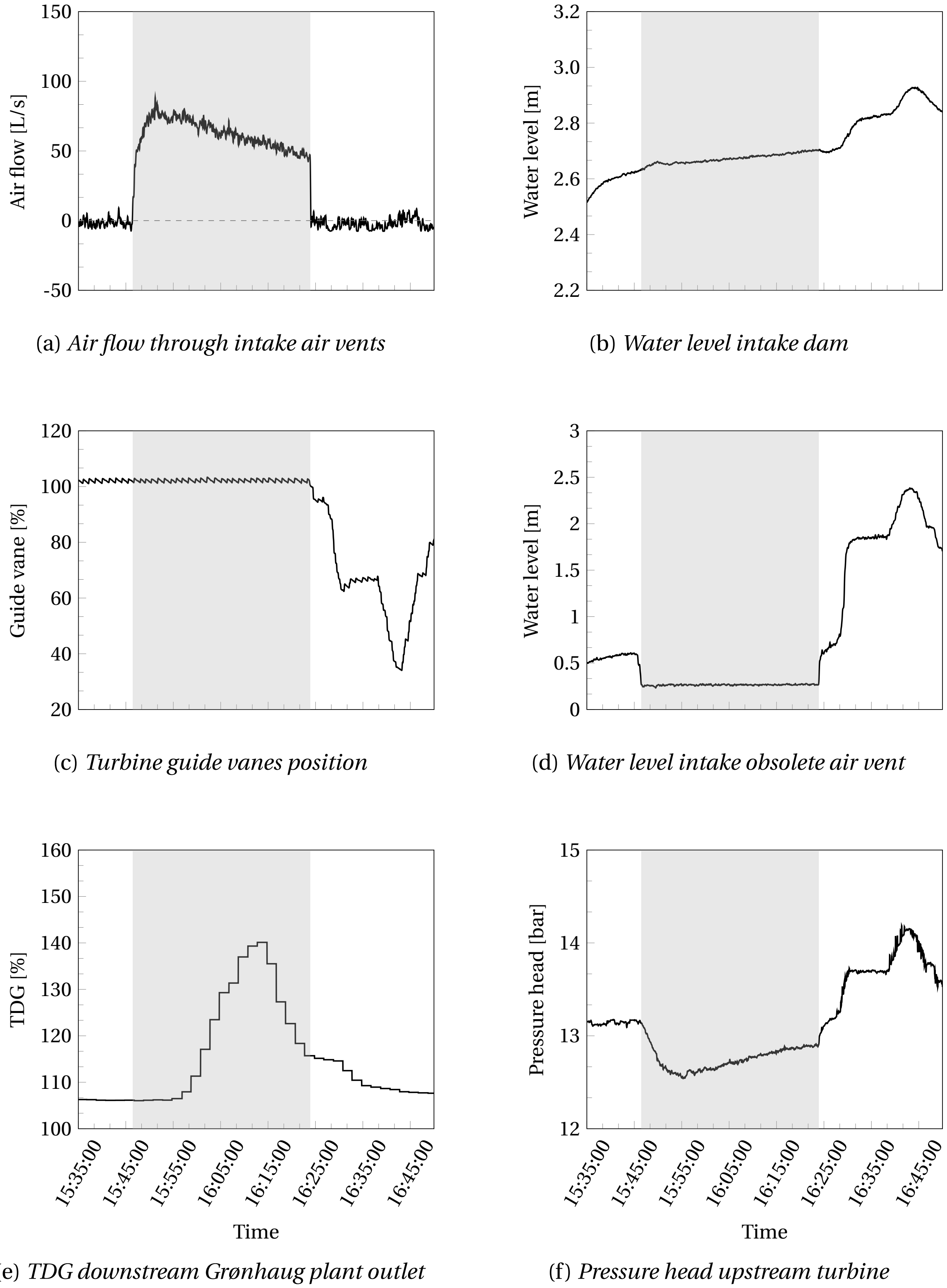
Figure 4.11: *Measured TDG at Grønhaug plant outlet for the 17th and 18th of April 2022, included water temperature through sensor*

4.2.3 Air vent, pressure head station and turbine discharge

Water level in intake obsolete air vent was gained from a submerged water level pressure sensor with higher accuracy and more robust installation then the ultrasonic sensor used at field tests in November 2021. Generator produced power was not monitored during field tests in April 2022. The grey area in figure 4.12 indicates the time period where the intake trash rack was ≈ 90 % covered (maximum coverage during test).

The presented data from pressure head measurements in Grønhaug power station, see figure 4.12f, is based on equation 3.3 given in method chapter 3.2.4. The accurate range of transducer was not found during field tests, and the result have therefore been calibrated against the local pressure head manometer on the same pipe measurement outlet manifold, given in figure 3.10a. Data is presented in unit bar and a general calibration factor of 0.1 bar is used to align the measured data to the pressure manometer readings. Visual reading is used to gain values during testing from manometer with range at 0 – 25 bar.

Calibration of turbine guide vane position data was done by adjusting the position from 0 – 100 % opening before start of testing. Plants control system indicate 104 % as maximum, which is used in calibrated range. Loop for water level in intake dam (existing loop in use by plant) was calibrated against the water level given in the control system in power station.



(a) *Air flow through intake air vents*

(b) *Water level intake dam*

(c) *Turbine guide vanes position*

(d) *Water level intake obsolete air vent*

(e) *TDG downstream Grønhaug plant outlet*

(f) *Pressure head upstream turbine*

Figure 4.12: *Main parameters measured during field tests at Grønhaug plant April 2022. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %).*

5 Discussion

This discussion chapter is divided into four parts. First, the result from field test performed in November 2021 at Grønhaug plant is discussed, based on chapter 4.1, relevant theory and methods. Secondly, results from the field test performed at Grønhaug plant in April 2022 is discussed based on chapter 4.2. Third, a common and summarized discussions is given. In this sub chapter, air vent measurement as principle is discussed and compared with measurement principle for trash rack pressure head and TDG monitoring in the plants outlet. Further, findings and recommendation given by the field tests and discussions is presented. Last, a brief discussion regards possible actions to stop ongoing air entrainment is presented.

5.1 Field test at Grønhaug plant November 2021

5.1.1 Introduction

Chapter 5.1 presents a discussion of the result from field tests performed at Grønhaug plant the 26th of November 2021. The overall observation is that coverage of intake trash rack result in air entrainment through intake air vents, with clearly indication of high level of TDG supersaturation from the hydropower plant outlet. Turbine discharge during testing was approximately at 50 %, which is an low and abnormal operation condition for the plant.

5.1.2 Air entrainment

As summarized in figure 5.1, air entrainment through intake air vents are confirmed by the measurements during all three field test the 26th of November. This is expected as coverage of submerged intake trash rack in combination with Francis turbine are already known as a possible source to TDG supersaturation from hydropower plants [1]. Figure 5.1 also indicate air leaving the ventilation pipes. As explained in chapter 3.2.1, the accuracy of reverse air speed measurements are lower but still it confirms reverse air flow through vents, which also have been confirmed locally during field testing.

The grey area in figure 5.1 are an approximately indication for the time period when trash rack coverage was at maximum (≈ 90 %) during the first test. The second and third test was not clearly time stamped for coverage at ≈ 90 %, which is important information to fully understand the behaviour and relationship for air entrainment, also related to other parameters as pressure head and TDG supersaturation.

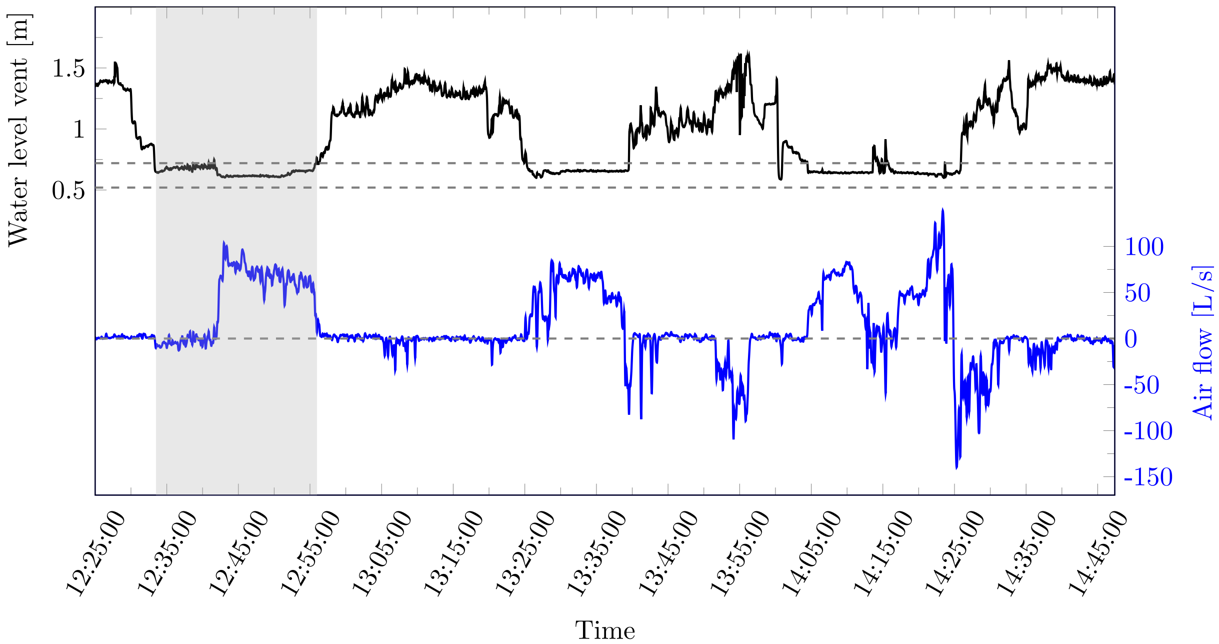


Figure 5.1: *Air entrainment at intake air vents at field test at November 2021, combined with water level in intake obsolete air vent. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %). Dotted lines for air vent water level present 0.72* m *(water level corresponding to top of pressure pipe) and 0.52* m *(water level corresponding to obsolete vent unsubmerged limit)*

The air flow measurements contains uncertainties with regards to total volume of air entrained to the pressure pipe during testing, in additional to general equipment accuracy considerations for air speed sensor, transmitter, transducer and PicoScope. Air can be transported through air leading vortexes at the intake, if intake water level are present below a critical depth [37], ref. theory chapter 2.3.4 and method chapter 3.5. The planned minimum intake water depth at ≈ 1.75 m, see appendix C.1, to avoid air vortexes and to easier monitor air entrainment at the intake trash rack was not obtained during all parts of the field tests. The water depth was between 1.6 to 1.9 m (see figure 4.3b, 4.5b and 4.7b). Still, only surface swirl [37] was observed and no audible air entrainment detected. The requirement in chapter 3.5 are conservative and observed to give too strict requirements with the given intake geometry and present flow conditions, where e.g. the intake hood roof, by prolonging of distance from free water surface to intake, can mitigate air vortex generation [37].

Air entrainment to intake hood is also possible through the top of the trash rack, between the vertical bars, when the intake dam water level is below the roof of intake hood. Especially, when the pressure pipe and intake hood experience free surface flow due to high head loss over trash rack, this source to air entrainment is relevant to consider. Still, during testing, only for minor periods the water was below the bottom of intake hood roof at approximately 1.65 m. Other sources to error are smaller leakages through the intake air vent temporary pipes system used during testing, but possible leakage volumes are considerer to be small.

An detailed fluid behaviour analysis inside the intake trash rack hood and start of pressure pipe is not relevant to include in this thesis. Still, based on the high amount of measured air entrained, and also the measurement of water level in intake obsolete air vent, free surface flow is expected at start of pressure pipe during the period of high air entrainment and ≈ 90 % coverage of intake trash rack, combined with higher turbine discharge. Relatively strong air leading vortex's is described to typically contribute to an air void fraction of $1-2$ % [37], which is much lower then the air void fraction introduced during field testing at Grønhaug. To be able to deliver the volume of air entrained during field tests, free access to air inside pressure pipe at intake, through intake air vents, are likely to be present. The measurement of water level in intake obsolete air vent is presented with respect to the same range as water level in intake dam (need in general also to consider velocity head, losses at trash rack and contraction losses at pressure pipe inlet), see figure 4.3d, 4.5d and 4.7d. ≈ 0.72 m intake dam water level correspond to water level up to the top of pressure pipe in the intake dam area, i.e. pressure pipe barely completely filled with water. Figure 5.1 present air entrainment and intake obsolete air vent water level, where the dotted lines for air vent water level present 0.72 m (top of pressure pipe) and 0.52 m (obsolete vent submerged limit). Relationship between water level in intake obsolete air vent below 0.72 m is related to high air entrainment periods according to figure 5.1. During high air entrainment periods, audible sign of free surface flow is given by sound of moving water in "new" intake air vent.

Another observation is that the water level in obsolete air vent is not below 0.6 m, which describe water filled cross section of obsolete air vent during high air entrainment periods. This is an important observation and is further discussed in chapter 5.2.2. Limit for loss of continuously water column in obsolete air vent is at 0.52 m related to intake dam water depth. See figure 5.2 for 90 % coverage of trash rack and proposed fluid flow in intake during 90 % coverage in high air entrainment periods. The measurements of obsolete intake air vent transducer faced problems at test day, but with re-check and calibration after the test, gathered data is concluded to be used in the report. To strengthen the measurements, new transducer and also a more stable sensor (submerged pressure sensor) were used at the field tests in April 2022, see discussion in chapter 5.2.2.

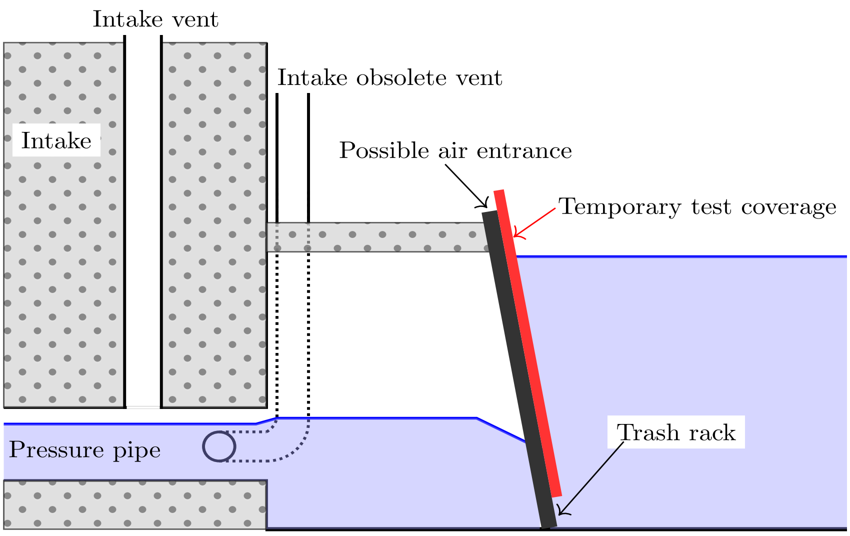


Figure 5.2: *Proposed intake flow with ≈ 90 % coverage and high turbine discharge*

Due to plant in operation, exact verification of intake dam main construction length and depth values was not possible to obtain, e.g. exact height between top of obsolete air vent in pressure pipe at intake. Values are therefore given by Grønhaug construction drawings, where error in drawings have been as far as possible confirmed by field measurements.

To summarize, air entering or leaving the trash rack is not verified during testing, and by that, the total volume of air entering and leaving the pressure pipe at intake area cannot be concluded. Still, air through intake air vents were audible and by measurements confirmed during testing, as opposite for possible air entrainment at intake trash rack. It is by then expected that the main air entrainment to the pressure pipe at intake area was introduced through the intake air vents, in periods with free surface flow in start of pressure pipe.

5.1.3 Level of total dissolved gases

Figure 5.3 relates air entrainment to observed sign of TDG supersaturation. For the three performed tests, a similarly relationship is identified, air entrainment resulted in clearly visible sign of TDG supersaturation downstream Grønhaug power station outlet. Only visual observation of indirect sign of TDG supersaturation are performed, the actually level of TDG during test is not measured or confirmed. Several suggestions of indirect visible limits for indication of TDG supersaturation have been found in literature and presented in theory chapter 2.1. The result and data given for TDG supersaturation at field test in November 2021 are based on that visible sign of supersaturated water (large volume of small air bobbles in the water) are present at 120 %, see result chapter 4.1.2. The periods of visible sign of TDG supersaturation, given in figure 5.3, can by visible detection method, only be used as an carefully indication of supersaturation levels.

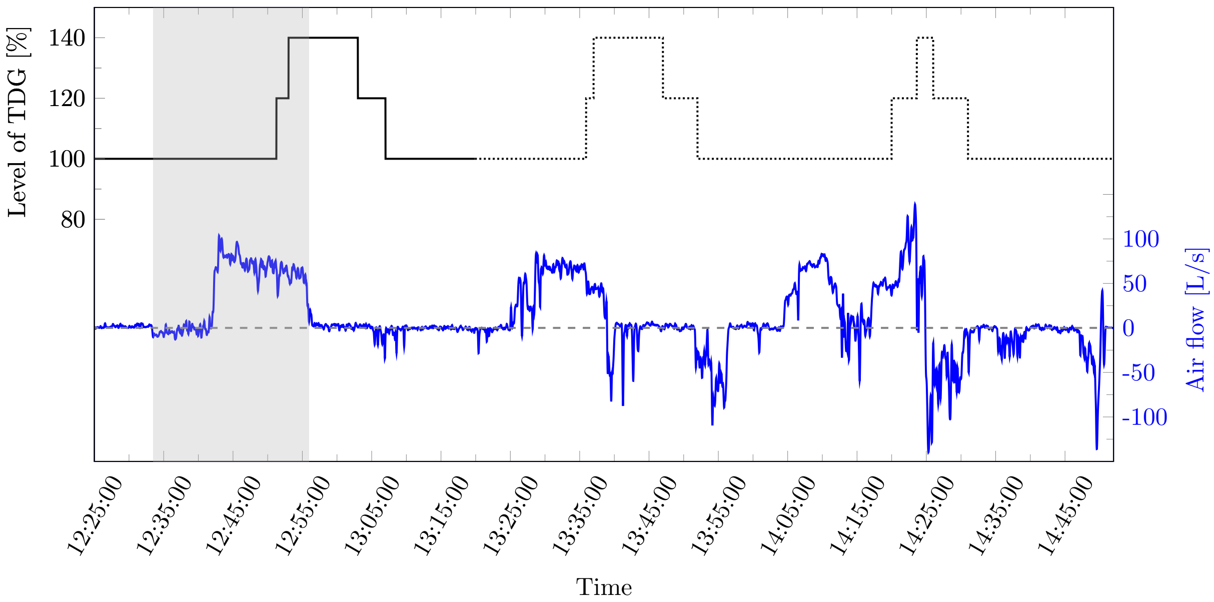


Figure 5.3: *Level of TDG related to air entrainment during field tests the 26th of November. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %)*

TDG supersaturation have probably been present during field tests before the indicated 120 % level and also after the indicated time periods with 120-140 %, but not at visible levels as invisible diffusion [7]. Low water velocity in river downstream the power station can also lead to misinterpretation of duration of visible sign of supersaturation, where it is difficult to divide between already released sign of supersaturation, and eventually ongoing or stopped release of supersaturated water. During the first test, continuously video recording of the river downstream Grønhaug station was performed to visually confirm visible sign of TDG supersaturation. At the second and third test, visual observation and pictures were used, which gives uncertainties about duration of visible levels, drawn as densely dotted lines in figure 5.3. Figure 5.4 present picture of highly visible sign of TDG supersaturation during the last air entrainment test.

Based on the visual observation and definition of TDG supersaturation, presented levels of TDG, and duration, is the parameter with highest uncertainty in the result from the field test in November 2021. Direct measurements of TDG will give a more robust result with regards to actually supersaturation, also included not visible TDG supersaturation levels that will be present before and after the visual indicated level. Even with uncertainties regarding presented level of TDG, the test confirmed a clear relationship between air entrainment and visible indication of TDG supersaturation. Field test performed in April 2022 included direct measurement of TDG by measurements. The pictures and movies obtained from field test in November 2021 is comparable in sign of supersaturation to similarly pictures gained at field test in April 2022, during confirmed high level of TDG supersaturation.

Figure 5.4: *Grønhaug plant outlet river during field third covering of intake trash rack at field tests the 26th of November*

5.1.4 Pressure head at Grønhaug power station

To better understand influence of air entrainment for the plant, also the pressure head in Grønhaug station have been measured during testing. Pressure head measurements are first summarized in figure 4.8, where figure 5.5 relate the pressure head with air entrainment directly. Dashed vertical lines in figure 5.5 indicate start and stop of high level of air entrainment for easier reading of pressure head in the same period. The repeating trend is that pressure head decrease rapidly with high air entrainment, and as soon as the air entrainment stops, the pressure head increase. This is in line with how Eviny Fornybar AS observed pressure head loss when Myster hydropower plant experienced problems with artificial TDG supersaturated water from the plant [1], and also as expected with high air entrance volume of significant less density then water [49].

During large air entrance periods, readings from a local pressure head manometer in the power station was fluctuating. In a range of up to 10 m pressure head fluctuations were observed during short time readings ($\approx$ 1 s). In normal, steady none-transient operation, Grønhaug plant owner observes measurements from the manometer at almost fixed position. The pressure sensor used for pressure head measurements in figure 5.5 do not give the same high level of fluctuation, still, during the whole test period after introduction of coverage at trash rack, more fluctuations were observed then before start of test, which are as expected with air partly present in the pressured pipe [50].

As described in result chapter 4.1.2, pressure head measurements have been calibrated against a local pressure manometer in the power station during testing with a simple constant calibration factor, not considering the minor difference in pipe diameter and the following different flow velocity at given measurement point. The turbine have an internal leakage, which give difficulties in specifying the fluid flow without measurements.

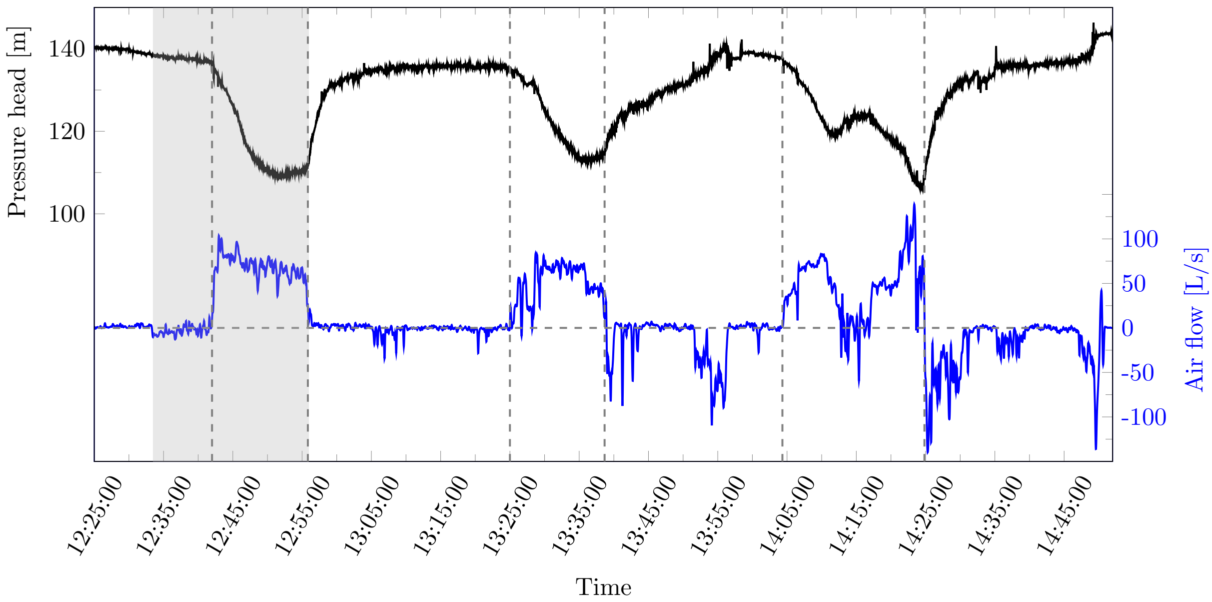


Figure 5.5: *Pressure head related to air entrainment during field tests the 26th of November. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %). Dashed vertical lines indicate start and stop of high level of air entrainment.*

The velocity head difference between the calibration point and field test pressure sensor will be minor due to the general limited velocity head contribution at the discussed measure points, pipe diameter magnitudes and fluid velocity, and is therefore neglected. During air entrainment periods, where large volume of air are dissolved or mixed as two-phase flow of water and air, density of water will be different than in normal operations. The density deviation is not taken into account when calculating pressure head in unit meter presented in this report. The intention for the pressure measurements is to observe main changes in pressure head during air entrainment, not the accurate pressure head at a given measure points. The level of accuracy are therefore accepted without further tuning of the pressure sensor calibration and measurements.

5.1.5 Turbine guide vanes position

Another relevant parameter to consider is the guide vane position for the Francis turbine in the power station to understand the discharge and fluid velocity during testing. The guide vane position can be regulated from 0 % (closed) to 100 % (fully open). Figure 5.6 presents guide vane position related to air entrainment.

During the first test, when ≈ 90 % coverage was established, indicated as point 1 in figure 5.6, only minor fluctuating air volumes was entering or leaving the intake air vents. When the guide vane position was increased to above 50 %, large air entrainment starts, indicated by point 2 in figure 5.6. This is as expected, a certain discharge is needed to give high enough head losses in the intake area to initiate air entrainment. Point 3 in figure 5.6 indicate when coverage at trash rack was removed, with end of air entrainment independent of guide vane position, since the large head loss over the trash rack are removed. No exact time stamping have been done for the second and third coverage, which then is the reason for missing relationship between guide vane, air entrance and coverage for these tests in figure 5.6.

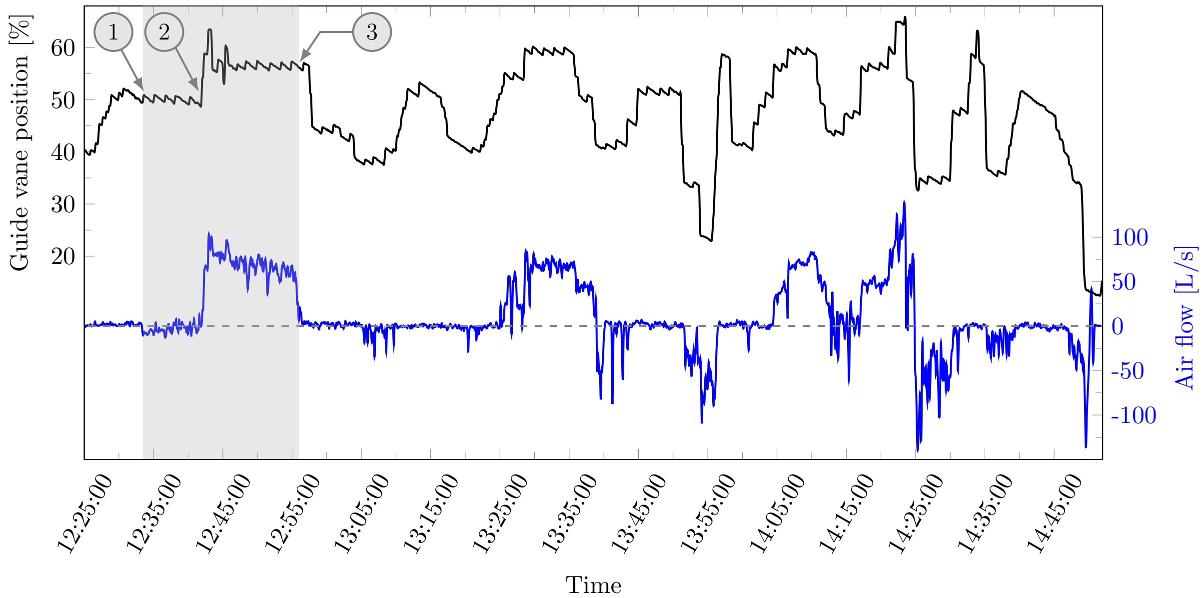


Figure 5.6: *Turbine guide vane position related to air entrainment during tests the 26th of November. Point 1 indicate start of period with ≈ 90 % coverage, point 2 star of air entrainment and point 3 when air entrainment stops. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %)*

Another observation that can be extracted from figure 5.6 is the indicated relationship between low guide vane position and air leaving the intake air vents. Lower guide vane positions results in air leaving the intake air vents, several of these experienced as limited and not-destructive blowouts. The air-water flow properties and behaviour during testing will be a function of several parameters, e.g. geometry, speed of flow and turbulence [50], and not relevant to investigate in detail. Still, water speed is described to be an essential parameter for air entrainment [7] [50], as also observed to be a relationship during testing. At 13:55:00 in figure 5.6, the guide vane position is below 30 %, which allows release of trapped air in the pressure pipe, several minutes after coverage are removed and in an time period with no air flow present i intake air vents. In figure 5.5, the pressure profile indicate lower pressure fluctuating after the air release at ≈ 13:55:00, which also support the understanding of air trapped in the pressure pipe which need low water speed to release [50]. See theory chapter 2.3.5. The same is observed in the end of the field tests where the guide vane was below 20 %, resulting in a the test days largest blow-out (none-destructive), and afterwards, a more stable pressure head reading in figure 5.5. To stabilize the plant after air entrainment and coverage of trash rack, the observations gives that not only stop of air entrainment and removal of coverage at intake trash rack can stabilize the hydropower plant, but also removal of possible trapped air in the pressure pipe is needed.

Figure 5.7 present guide vane position, pressure head at power station and air entrainment at intake air vents. Pressure head reduction was significant during high air entrainment periods and clearly indicate an abnormal relationship between guide vane position and pressure head at given discharge. I.e., in normal operation, a certain pressure head is expected based on given turbine discharge, which during high air entrainment periods largely deviate from normal values. Based on the given test results, deviation between pressure and discharge can be used as an indication of air entrainment.

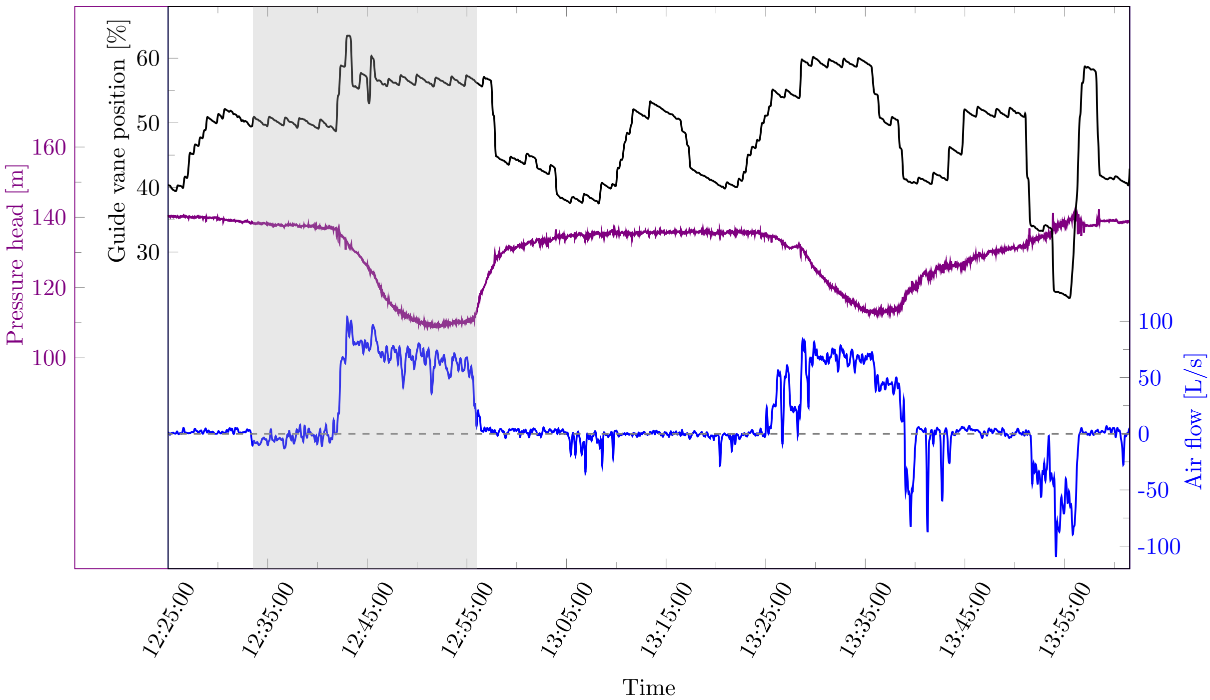


Figure 5.7: *Air entrainment related to turbine guide vane position and pressure head during the two first tests performed the 26th of November. Grey area indicates the period with maximum coverage of trash rack (≈ 90 %)*

5.2 Field test at Grønhaug plant April 2022

5.2.1 Introduction

Sub chapters of 5.2 present a discussion of the result obtained during the field test performed at Grønhaug plant the 18th of April 2022. In addition, when relevant, result from the field test in November 2021 is compared with the test results from April 2022. The overall observation is that coverage of trash rack result in air entrainment through intake air vents, with the following confirmed TDG supersaturated water from the plant outlet, as also indicated during the field test in November 2022. The same interesting design observations have been found with regards to obsolete and "new" intake air vent pressure pipe entrance location and distribution of air supply to pressure pipe, which will be presented more in detail chapter 5.2.2.

Based on experience from field test performed in November 2021, several improvements were prepared for the field test in April 2022. The most important improvement is direct measurements of level of TDG at the plants outlet, which by then have confirmed the level of TDG during testing. Other main improvements is higher turbine discharge during testing to see the plants reaction of trash rack coverage at normal plant operation conditions. An more robust and accurate measurements of water level inside intake obsolete air vent is implemented, and higher degree of documented covering of intake trash rack was performed.

5.2.2 Air entrainment

As for the field tests in November 2021, the field test in April 2022 detected large air entrainment through intake air vents. The sources of measurement error is lower due to higher degree of submerged intake, which in practice eliminate possible air entering at intake hood area. Also, during testing, higher focus have been given to observe the intake hood area during air entrance periods. Plant operational and river discharge conditions were similarly to normal operation during testing, as opposite to the abnormal and low discharge conditions during testing in November 2021. Result from April 2022 will therefore be closer what normally can be expected for operating hydropower plants with regards air entrainment.

During high air entrainment periods, a minimum water level of ≈ 0.25 m is measured inside the obsolete air vent. Obsolete air vent outer diameter is ≈ 0.2 m and the water level sensor is installed ≈ 5 cm above the air vent pipe horizontal bottom, giving obsolete air vent pipe pressure pipe entrance to be submerged at measured water level inside obsolete vent above ≈ 0.15 m with given sensor location. Based on the measurements, in general, obsolete air vent is submerged during all testing and not contributing to air entrainment, still expected to be shortly not completely submerged during osculations of the water column in air vent.

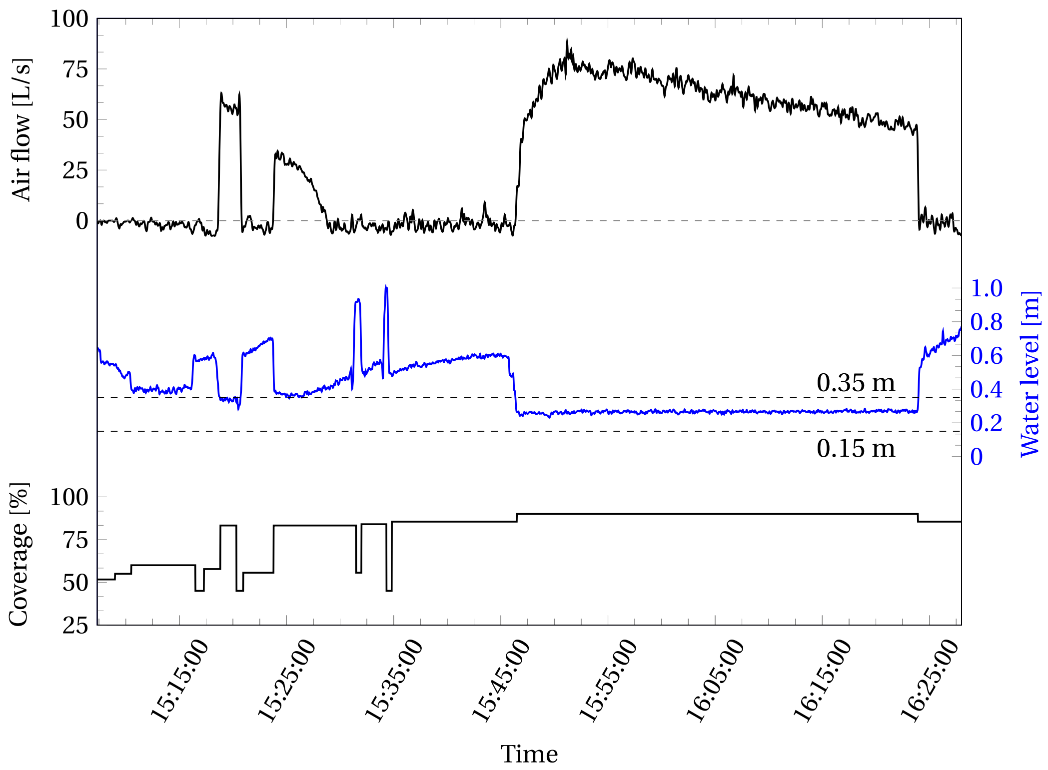


Figure 5.8: *Air flow through air vents, presented with water level in intake obsolete and coverage during air entrainment periods at field tests in April 2022. Dotted lines at the water level graph, marked with 0.35 m and 0.15 m indicate water level in obsolete air vent related to top of pressure pipe in intake area and limit for unsubmerged obsolete air vent.*

The new air vent pressure pipe entrance is not submerged during high air entrainment periods. Limit is calculated to ≈ 0.35 m based on water level in obsolete air vent. The two limits ≈ 0.15 m and ≈ 0.35 m is indicated as dotted lines in figure 5.8. At high air entrainment periods, water level in obsolete air vent is between 0.25 and 0.35 m, see figure 5.8, and by that results in large air entrainment through the new air vent at the given high discharge. Figure 5.9 indicate the water level in intake obsolete air vents during high air entrainment periods.

Visual observations coincides with the water level measurements in obsolete air vent. It is not observed air volume to enter pressure pipe through obsolete air vent, only "new" air vent is observed to contribute with air. This is also in line with the observation and measurements done for field tests in November 2021, see figure 5.1, where presented water level in obsolete air vent is aligned with intake dam water level, and by that have 0.72 m as pressure pipe free surface limit. Water level in obsolete air vent have been measured with two completely different measurement principles at November and April, ultrasonic length measurement and submerged pressure sensor, but the same result is obtained, which is a strength with regards to the conclusion.

Water level in intake dam is increasing during the time span given in figure 5.8 and will influence the given water level measurements in obsolete air vent. E.g., between 15:35:00 and 15:45:00 in figure 5.8, the coverage and discharge is relatively stable, but water level in intake dam increase which gives increasing water level in obsolete air vent.

High head loss at trash rack with extreme coverage, contraction losses for pressure pipe entry, air vent pressure pipe entrance and valve will give a turbulent water flow at the discussed area of pressure pipe in the intake area, and the behaviour of fluid, losses and air mix in water is not investigated in detail. Exact measurements of obsolete air vent sensor location with regards to pressure pipe and existing intake dam water level datum was not obtained due to plant in operation. Values is based on construction drawings from Grønhaug plant, with observed errors, tuned by field measurements. As an additional verification, an calculation to verify the measurements and calibration is presented in appendix C.2 with a 4 cm calculated deviation above used datum level. The calculation is based on a period with low discharge and equation 2.7, 2.8 and 2.11 is used. Pipe friction losses is not included. Based on plant drawings, field measurements, result from field test in November and April, datum level calculated (appendix C.2) and also audible observations during test, the common indicators is that obsolete air vent have had submerged entrance towards pressure pipe during high air entrainment periods, where the new air vent faces free surface flow at top of pressure pipe and distribute main part of air inn/out of pressure pipe in the same periods.

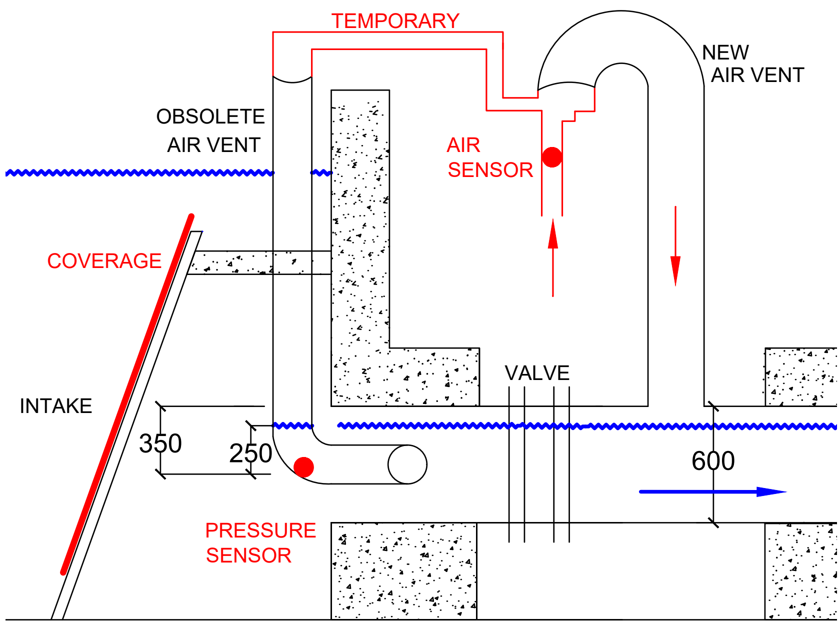


Figure 5.9: *Grønhaug plant intake during high air entrainment periods*

The total outcome from the field tests with regards to air vents is that air vent entrance at top of pressure pipe is not ideal with regards to high discharge, covered intake trash rack and the possible air entrainment to pressure pipe. Opposite, design used for the obsolete air vent, with entry vertically centred at pressure pipe, is observed by field testing to significantly reduce the probability for air entrainment through air vents. The essential difference in location of intake air vent entrance into to pressure pipe is an important observation. Existing hydropower plants experience challenges with air entrainment, and for new hydropower plants, location of intake air vent entrance at pressure pipe is recommended to be included in design considerations with regards to air entrainment. Figure 5.9 outline the different intake air vents, included temporary installations, used during testing. The given design recommendation should be verified preferable by model analysis as Computational Fluid Dynamics (CFD), and also independent additional field tests to strengthen the conclusion gained by this thesis.

During field testing in November 2021, large volume of air were released out of air vents when coverage have been removed, and the turbine discharge was at low levels. Even minutes after removal of coverage, low discharge were needed to release from the pressure pipe. At the field test in April 2022, no air of significance is detected to be released out from the pressure pipe, even in periods with low discharge. This is expected with larger water velocity and by then increased capacity to transport air in the water flow [7].

5.2.3 Level of total dissolved gases

The data gained from field test in April 2022 presented in figure 4.12 and 5.10, confirms the assumed relationship from field tests in November 2021, high degree of coverage of intake trash rack and air entrainment at intake air vents result in supersaturated water released from the plants outlet. In general, TDG at ≈ 106 % is measured in periods without air entrainment, increasing rapidly during air entrainment periods to 140 % TDG. The short reduction to 100 % TDG close to 10:30:00 the 18th of April in figure 4.11 is related to a short stop of the plant to connect transducers into the plants 4 – 20 mA loops for guide vane position and intake water dam level, which confirms the sensors validity.

Due to the relatively short time period with air entrainment, and by that need for short sample interval for the TDG sensor, most likely the TDG sensor do not reach completely equilibrium between each sampling interval in the periods with air entrainment and rapid changing level of supersaturation. See theory chapter 2.4.1. At the chosen two minutes sampling time, exact level of TDG can not be expected, but enough accuracy to confirm the high level of supersaturation.

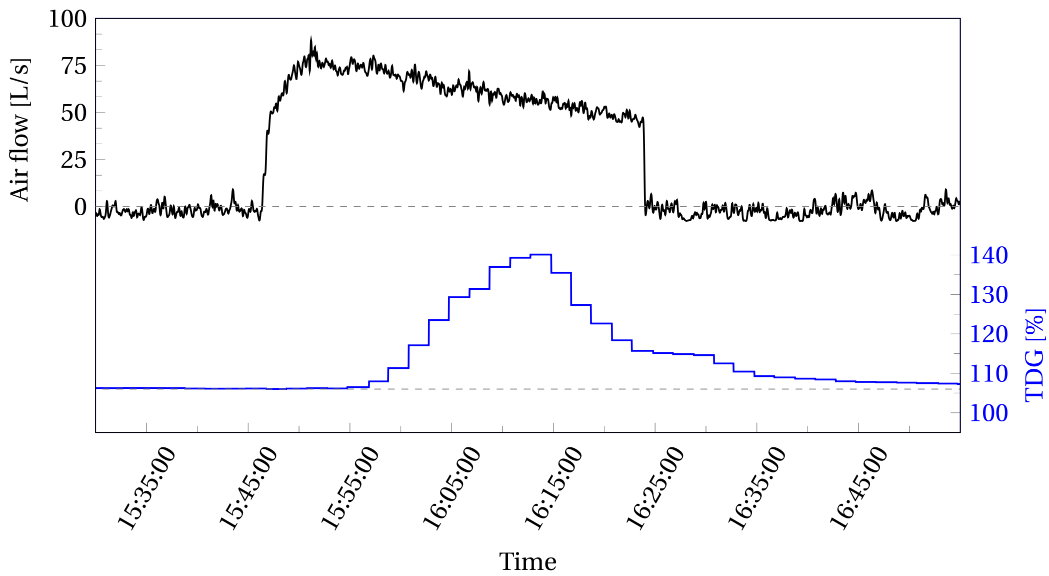


Figure 5.10: *Air through intake vents, presented with measured level of TDG at Grønhaug plant outlet April 2022*

Figure 5.11 present picture from plant outlet during high level of visible sign of TDG for both field test in November and April. In field, the milky visible sign of supersaturation is experienced to be the same both in November and April. In April, larger discharge, almost double, is present during testing and volume of supersaturated water will therefore be more visible in the outlet area. It also need to be noted the distribution of visible sign of supersaturated water in the outlet area, giving that location of the TDG sensor in general need to consider the flow distribution behaviour in the outlet river.

In figure 5.10, the relationship between air entrainment and TDG is presented. In the start, the relationship is expected with regards to a certain delay. Air is entrained at intake vent, transported and dissolved in water, and released from plants outlet as supersaturated water, where sensor need time to obtain the new equilibrium [25]. Air entrainment is gradually reduced from ≈ 75 L/s to below 50 L/s, and a relative high reduction in level of TDG is observed, still measured 115 % TDG at air entrainment stop. Since air is only entering, not leaving at the intake vents, air can either be dissolved or transported by the water as bobbles [7], and it cannot be proved if all air is dissolved or also unsolved air bobbles is transported through pressure pipe in the relatively high water speed.

(a) *Visible sign of TDG supersaturation during field tests November 2021*

(b) *Visible sign of TDG supersaturation during field tests April 2022*

Figure 5.11: *River downstream Grønhaug plant outlet (outlet at left in figures) during high air entrainment periods at field tests in November and April.*

The Norce logger used to calculate TDG based on TDG sensor in outlet water, consist of a atmospheric pressure sensor. Since the logger is located ≈ 4 m above water surface, a general measurement error of 0.5 hPa is present. This error is small and neglected in the result. Location of TDG sensor have been done with regards to isolate plants contribution to supersaturation, needed water velocity and water depth, location which facilitate easy robust fastening and also easy access, with goal to propose a common location that can be used in similarly Francis small hydropower plants. Sensor location is discussed in more detail in chapter 5.3.2

The turbine in Grønhaug plant have an internal leakage due to normal wear and tear after several years in operation. This results in higher water consumption and operation outside specifications, which can influence the normal operation level of released supersaturation. In addition, the natural level of saturation in the river upstream Grønhaug plant intake is not measured, and will influence the TDG level at the plants outlet.

5.2.4 Pressure head Grønhaug power station

The main difference between pressure head measurement readings from tests in April 2022, compared to November 2021, is lower deviation from expected pressure head. Less pressure fluctuation in readings is also observed. As described in chapter 5.2.2, more normal plant operational and river discharge conditions were obtained during tests in April 2022 compared to November 2021, which gives results that normally can be expected for operating hydropower plants. Even if the deviation is not as significant as during field tests in November, pressure reduction at given guide vane position is a clear sign of an abnormal situation. In figure 5.12, air flow, station pressure head and guide vane position is presented. Circle marked with 1 indicate turbine guide vane relation with station pressure head at high trash rack coverage but no air entrainment. Circle marked with 2 indicate the same relationship, but in addition, high air entrainment is present. The reduction in pressure is significant, given constant turbine discharge. Circle marked with 3 indicate normal operation conditions and still the same discharge. This abnormal pressure loss readings at air entrainment, as illustrated also in figure 5.7, can be utilize to indicate ongoing air entrainment.

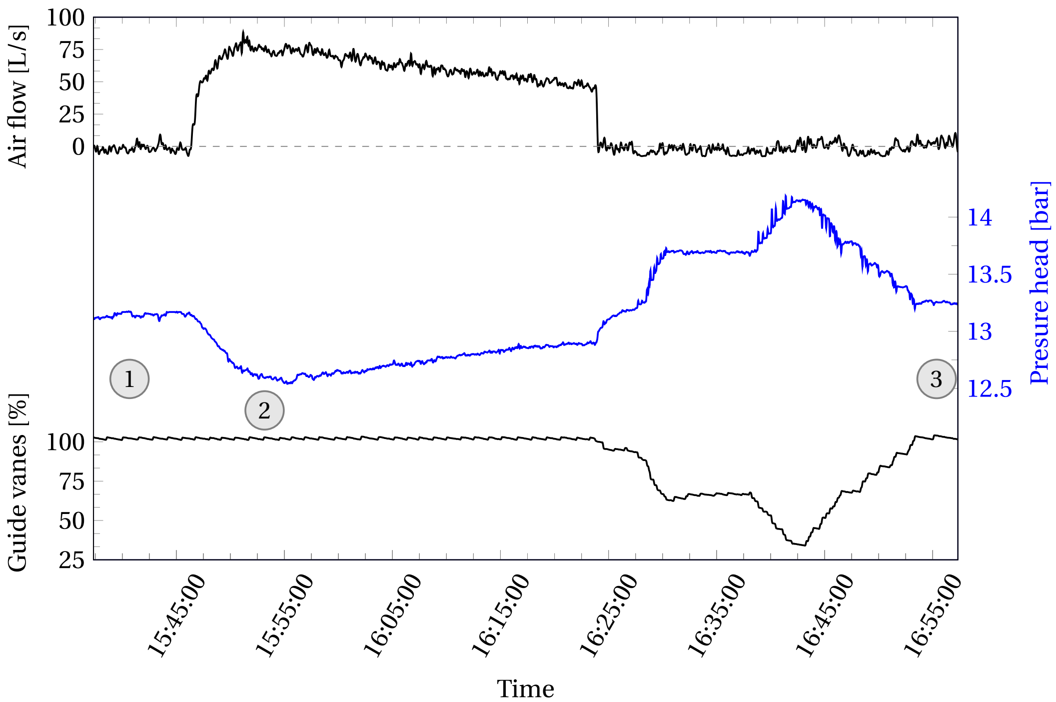


Figure 5.12: *Pressure head related to turbine guide vane position during high air entrainment periods at field test April 2022. The three numbered circles indicate periods with 1: high pressure loss at trash rack, no air entrainment, 2: high pressure loss and air entrainment, 3: normal operation of plant.*

5.3 General discussions

5.3.1 Air entrainment and artificial gas supersaturation

The first main objective for this thesis have been to investigate the relationship between air entrainment at intake air vent and release of artificial supersaturated water from the plants outlet. Air vent entrainment measurement, to indicate air volume entrained in water flow, is not a new principle for defining air entrainment into air-water flow [50], but have not been found to be related to release of artificial TDG supersaturation from hydropower plants.

During the two field tests performed at Grønhaug plant in November 2021 and April 2022, artificial TDG supersaturation in the plants outlet river is observed to be related to air entrainment through intake air vents. The initial factor is head loss at intake trash rack in order of magnitude to give free surface flow in pressure pipe in the intake area, given by the extent of intake trash rack coverage, turbine discharge and water level in intake dam. Free surface flow is observed to give pressure pipe access to consume air from air vent located on top of the pressure pipe. At field tests, large entrained air volumes is both measured and audible observed. Details is given in chapter 5.2.2. A prerequisite for the present method is submerged intake to avoid air entrainment directly through trash rack, or as air leading vortexes at intake.

The field tests have been executed only at some hours duration. To strengthen the conclusion, continuous measurement of air entrance at intake vents and TDG supersaturation downstream the plants outlet is needed. Continuously measurements can discover other possible parameters influencing the conclusion, which might not be found during short time testing. E.g., as discovered at Hellandsfoss hydropower plant, brook intakes were expected to be the source of TDG supersaturation from the plant. After long time monitoring of TDG in river, it was revealed that not only the brook intakes, but also aeration of the plants Francis turbine contributed to supersaturation, present at start/stop and low turbine discharge [1].

As described in chapter 2.3.5, air entrainment in pressure pipe can have other unwanted effects, e.g. as destructive blow-outs and reduced production [7], besides risk of developing artificial TDG supersaturated water [1]. The proposed setup with intake air vent velocity measurements will detect air entrainment in general, if intake is sufficient submerged, and by that also give the plant operator possibility to detect and prevent air entrainment in general, in additional to avoid supersaturated water release. In Grønhaug plant, destructive blow-out have been experienced due to air entrainment, the following low pressure pipe sensor initiated emergency stop and resulting pressure waves, which could have been avoided with intake air vent sensor.

The air speed measurement principle used, average pitot tube with the sub category Annubar, is at short time use experienced to be suitable for the given application and environmental conditions. Temporary reduced air vent diameter have given higher air velocity and by that higher accuracy during testing, which need to be noticed. Both air at high velocity, and water, can be present in intake air vents, which gives need for mechanical and environmentally robust sensors at continuous measurements. Still, other measurement principles can be more suited for the given application, which can be investigated further. For the test setup in Grønhaug, vane anemometers is assessed to be not robust enough [33]. Hot wire principle have high accuracy at low air velocities [33] but not expected to be robust enough for vent conditions. Permanently installed air speed sensor should be tested for long duration to ensure robustness for the present environment conditions.

Air entrainment at submerged intake is described in research to be related to TDG supersaturation [1]. The field tests in this thesis have observed that at sufficient submerged intake, air entrainment can be directly detected and monitored through intake air vents, and by that give the plant possibility to quickly avoid air entrainment of importance. With regards to the research needs given in chapter 1.2, based on reference [1], new and cost friendly methods is generally described. Results gained from field testing confirms that air velocity sensor can be a simple alternative to detect artificial supersaturation released from small Francis hydropower plants with submerged intake. Cost is limited, and the output can be chosen to a e.g. simple and standard 4 – 20 mA signal as other plant parameters as water level at intake dam. The level of accuracy is not considered important due to no need for accurate air entrainment volumes, the purpose is to detect ongoing air entrainment, which simplify the installation with regards to type and location of air sensor in a small air vent. For existing plants, available pairs in signal cables between intake area and power station can be challenging if signal is planned to be implemented in the plants control system.

5.3.2 Comparison of discussed measurements principles

For the chosen setup, hydropower plants with submerged intake and Francis turbine, the recently (Nov. 2018) published knowledge summarizing [1], proposes measurements of differential pressure on intake trash rack in combination with TDG in downstream river, with alarm system, as method to detect release of supersaturation from the plant. Result gained from field tests at Grønhaug plant indicate that both air flow through intake air vents, pressure loss at intake trash rack and measurement of TDG in plants outlet, can be used to detect artificial supersaturation induced by operation of the plant. In the following paragraphs, these three methods is compared and discussed.

Trash rack head loss measurements is well known principle and not complicated to implement in new hydropower plants, normally feasible to install at existing intakes, and is experienced comparable to the air velocity sensor with regards to cost and installation complexity. It is also installed in many hydropower plants today, e.g., the large operator of small hydropower plants in Norway, Småkraft AS, trash rack head loss measurements with alarm/stop is commonly used [51]. Only snow/is through the winter and Grønhaug plant in operation restricted installation of pressure sensor in intake hood for differential measurement at trash rack, which instead was installed in the obsolete intake air vent.

Detection of TDG supersaturation in rivers is in literature often described to be done with Weiss-saturometer [1] [6] [52] [53]. Still, no information or guidelines is found to be distributed to hydropower plants operators with information about e.g. installation advices, equipment and alarm criteria for monitoring of TDG, e.g. where other hydropower plant relevant topics is included in informative guidelines published by NVE, as reference [19] and [22]. This type of measurement is therefore understand to be unknown for most of hydropower plants operators. The experience from measurement of TDG with Weiss Saturometer during field tests at Grønhaug plant, is that this type of measurement, with some essential principle guidelines and the right equipment, is of low complexity and feasible to implement for not-trained personnel. Reference [17] describes TDG measurement as not complicated, and reference [1] present need for knowledge to perform measurement, which confirms the need for a guideline. As described in theory chapter 2.4.1, water velocity to avoid disturbing air bobbles when the sensor is installed above the compensation depth is important [25]. If the sensor is installed in a moving water, and by that more vulnerable to damage, mechanical protection of sensor is important to reduce probability of frequently damage. Experience in reference [1] is that sensor parts needs to be replaced after 1-2 years, which is frequent compared to other plant sensors as e.g. submerged water level sensor.

When comparing the different methods and sensors, total duration with possibility to avoid or quickly reduce release of supersaturated water is essential:

- **Head loss at intake trash rack:** Head loss at trash rack will increase (not linearly, ref. equation 2.10) as the degree of coverage increase, and can indicate high head losses before air entrainment starts. Air entrainment, with the following release of supersaturated water from plant, can therefore in general be avoided, if correct calibration and action is taken before head loss is above a certain level. The limit for reduction/stop of production should be calibrated with head losses that gives pressure pipe at air vent entrance free surface flow, with a needed margin. According to findings given by field tests at Grønhaug plant, see chapter 5.2.2, this will generally avoid air entrance and release of supersaturated water from the plant.

- **Air velocity sensor at air vent:** Air vent monitoring detects start of air entrainment, and can by that quickly initiate actions to reduce/stop plant production and largely reduce the air entrainment duration and volume to an minimum. A prerequisite is submerged intake to avoid direct air entrainment through trash rack or air leading vortexes. As seen in figure 4.11 and 5.8, short periods of air entrainment is only detected by air sensor, not TDG sensor, or visually. Still, a short initial time delay should be implemented to avoid unwanted stop of plant.

- **TDG sensor in plants outlet:** TDG sensor will confirm if supersaturation is present or not. A certain delay is present, first air entrainment need to be initiated at intake, water and air need to be transported through pressure pipe to plant outlet, and then TDG sensor need time to gain equilibrium [25] with the increased total gas pressure in water. This method as stand alone method will probably release the highest volume of supersaturated water from plant before action is taken.

To summarize, trash rack head loss measurements can avoid air entrainment at intake, sensor in air vent can quickly stop initiated air entrainment, and TDG sensor will confirm supersaturation present in plants outlet river after a certain delay.

Both air flow through intake air vents and pressure loss at intake will have additional benefits for the plant by detecting high head losses (production losses), and also with regards to safety and possible blow outs [7]. In addition, these methods will isolate and detect only plants contribution to air entrainment and the following supersaturation. Naturally supersaturated water can be present in the river upstream intake due to e.g. solar heating during daytime or naturally as a result of water falls [6]. If natural supersaturation is present upstream the plant intake, TDG sensor installed at the plants outlet can initiate mitigating actions in plant as shut down of plant based on conditions not caused by the plants operation. Alternatively, TDG sensors can be installed both upstream intake and downstream the plant outlet which will increase cost and maintenance. In the plant outlet TDG sensor can be installed with purpose to isolate present supersaturation in downstream river by correct position of TDG sensor (ref. chapter 5.3.3) If the plant decision is to continue operation with high head losses at intake trash rack, air sensor or calibrated trash rack head loss measurement can be the final limit for reduction/stop of production to remove trash rack coverage. On the other hand, if only level of TDG is the goal for the measurements, the TDG sensor will measure supersaturation directly, not indirectly, and by that confirm when the supersaturation is present.

The choice of method, or an combination of these, will be an assessment of several factors for each plant as e.g. plant design, installation cost, need for external competence, maintenance interval and cost, intake/station access and operator personnel availability. Also the intention of the measurement is important to consider: to avoid supersaturation (trash rack head loss and/or air vent sensor), or to detect/monitor and confirm if supersaturation is present by TDG sensor. TDG sensor in combination with trash rack head losses, recommended in reference [1], is experienced by field tests to both avoid and detect supersaturation, in line with reference [1].

For small hydropower plants, no guidelines or general information is know to be present for installation and operation of TDG sensor. It is not observed standard setup/equipment to include TDG sensor directly to plants control system for fast response, to avoid stand alone systems, and a relatively frequent maintenance follow up is expected. Head loss measurements at intake trash racks is in common use in several small hydropower plants already, e.g., the large operator of small hydropower plants in Norway, Småkraft AS, commonly use trash rack head loss measurements with alarm/stop criteria [51]. If trash rack head loss measurements is properly calibrated, e.g. against air entrainment limit, and proper actions implemented by the plant when head loss approaching the limit, the general observation in this thesis is that this will avoid initiation of air entrainment from the plant. Given Francis turbine small hydropower plant with submerged intake, calibrated pressure head measurements at trash rack is recommended as the most effective, simple, technology mature and low cost measure to avoid air entrainment, and by that avoid TDG supersaturation to be initiated and released. In addition, production losses can be reduced by early indicating of pressure losses at trash rack, before risk of air entrainment is present.

5.3.3 Findings and recommendations

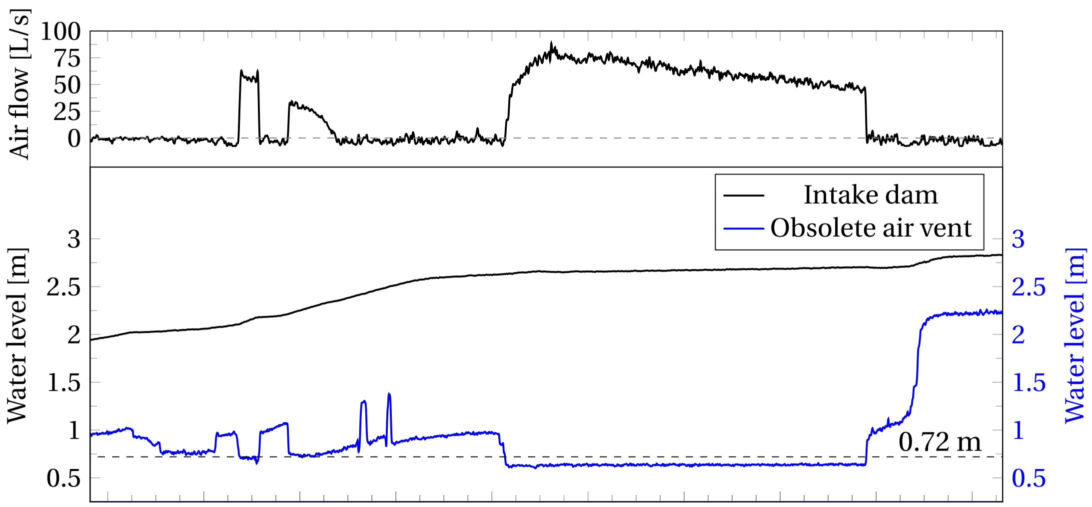
This subchapter summarize proposed small hydropower plants design improvements and general recommendations based on obtained result and discussions. The proposed principle with air velocity sensor in intake air vent is described in detail at chapter 5.2.2 and 5.3.1, and will not be repeated in this sub chapter.

Intake air vent entrance at pressure pipe

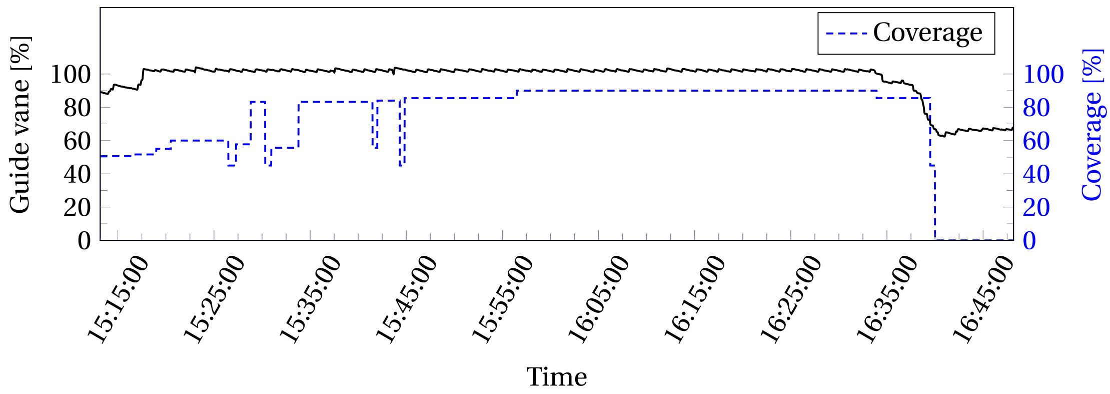
Grønhaug plant is equipped with two intake air vents, where the obsolete air vent entrance pressure pipe at the vertical center of pipe, and the "new" air vent entrance is at the top of pressure pipe. With regards to air entrainment at intake, results from field tests at Grønhaug plant gives that obsolete air vent vertical center entrance, towards pressure pipe, is highly favourable. Opposite, the new air vent, with top entry towards pressure pipe, supply large volume of air if trash rack coverage and discharge is at an certain level. This is an important observation which at large extent permanently can remove the source of air entrainment by design choice. Chapter 5.2.2 includes an detailed technical description of the air vent entrance observations.

Trash rack pressure loss alarm calibration

Intake trash rack pressure loss monitoring with alarm system is recommended in reference [1] as method to avoid or detect artificial supersaturation, combined with TDG sensor in plants outlet river [1]. Based on results from field tests at Grønhaug plant, high trash rack pressure loss giving free surface flow at the start of pressure pipe at the intake, is essential for start of air entrainment. Specially with air vent entrance at top of pressure pipe. Trash rack pressure loss sensors guidelines can be more specific with regards to limits for alarm or reduced/stopped production. Alarm is naturally to be given at partly covered trash rack to be able to reduce production losses. If access is limited, as can be relevant for small hydropower plants during e.g. snow melting, a final limit should be implemented to ensure that high coverage and pressure loss do not result in air entrainment. With a certain margin, this final limit for stop or reduce production is recommended to be calibrated against top of pressure pipe to avoid the air entrainment situations, as obtained during field testing at Grønhaug plant. Local losses, e.g. pressure pipe entrance and datum path, between trash rack and air vent need to be included in the calibration. Figure 5.13 present water level in obsolete air vent, calibrated against the range of water level in intake dam, combined with air entrainment at intake vent, intake dam water level, turbine discharge and degree of coverage. The relationship between water level in pressure pipe and air entrainment is indicated, giving that pressure loss at intake area it self only gives part of the needed information. Lower intake water level can give air entrainment at lower degree of coverage then higher intake water level with higher degree of coverage and pressure loss. The initial parameter is experienced to be intake air vent access to free surface flow in pressure pipe, and if e.g. an limit of 0.8 m with action to largely reduce turbine discharge had been implemented during testing at Grønhaug plant, no air entrainment should be initiated (see figure 5.13). Plants with automatic trash rack cleaner is expected to normally be able to remove debris with god margin before the air entrainment limit is reached if no personnel access is needed.



(a) *Obsolete air vent water level, calibrated to intake dam water level, presented with intake dam water level and air entrainment*



(b) *Turbine discharge related combined with trash rack coverage*

Figure 5.13: *Water level in obsolete air vent calibrated to intake water level, intake water level, air entrainment, trash rack coverage and turbine guide vane position*

Common location of TDG sensor

Location of TDG sensor used during field tests at Grønhaug plant, is proposed as a common location for TDG sensors at other similarly small hydropower plant with Francis turbine. The main focus at selection of sensor location have been:

- Location that facilitate robust and easy fastening of the sensor for years in operation
- Enough water velocity and water depth to avoid measure error due to air bobbles [25]
- Easy access for inspection and maintenance
- Measure the plants contribution to possible supersaturation in outlet river, isolated from natural causes to supersaturation that can be present in the outlet river
- Common location, possible for small Francis hydropower plants in general

The location chosen at field tests in Grønhaug plant is in the draft tube outlet basin, see figure 5.14. In this area, concrete walls gives possibility to easy and robust fastening of sensor. The sensor need to be protected by e.g. highly perforated [1] [53] pipe (steal) secured with pipe clamps. The water velocity in this area is not only horizontal, but it is understood that the direction of flow is not essential. Easy access is expected to be present at this location, and also availability to utility power and plant station if relevant to include the sensor directly in the plants control system (highly recommended). Other possible locations have been considered, but these gives more challenges with regards to robust fastening and easy access for follow up during measurements, and is less standardised for the different plants. It is also observed that the (visible sign of) supersaturated water is not present in the complete cross section of the outlet river, and the sensor therefore needed to be installed based on predicted outlet river flow distribution, see figure 5.11. By the proposed sensor location, other causes to supersaturation in outlet river area is isolated from the plants contribution, see figure 4.10. Sensor location given in figure 5.14, can be a possible recommended common sensor location, if long term tested and verified at the given positions for eventually not observed challenges during the short time testing at Grønhaug plant.

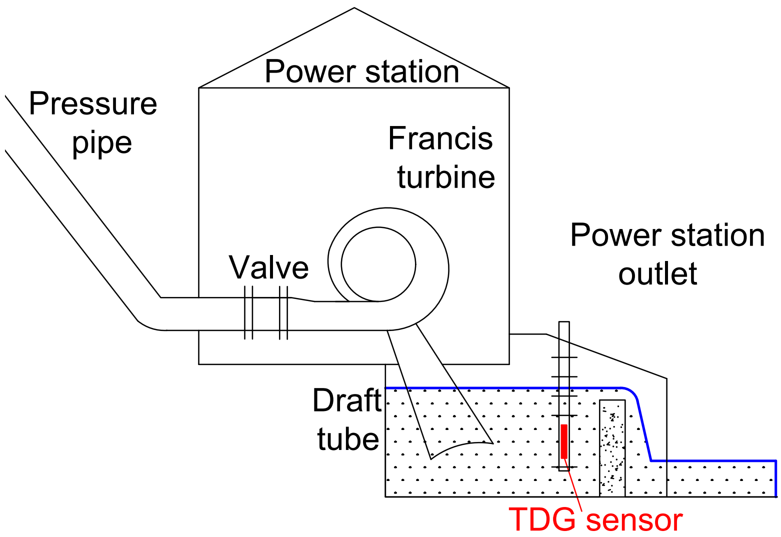


Figure 5.14: *Proposed general location of TDG sensor in small Francis hydropower plants*

To help small hydropower plant operators to perform direct measurements of TDG where this is necessarydistribution of a simple guideline with needed knowledge is recommended. Installation recommendations, feasible locations and type of equipment with interfaces can be relevant topics to lower the threshold for small plants operators to install and maintenance TDG sensors, and also avoid frequently damage of sensors. Also development of standard solutions to implement sensor in the plants control system is important. This can be in specially relevant for small hydropower plants, where the total turnover is less and the economical robustness for use external competence can be lower.

5.3.4 Test setup and reuse for further research

The test method developed at Grønhaug plant by coverage of trash rack with plates until air entrainment start, can also be utilized for further research with regards to air entrainment and TDG supersaturation release. The test method advantages is that air entrainment can be initiated in controlled manner, air entrainment monitored by intake vent measurements, and adjusted according to test objectives. This give possibility to perform tests of specific equipments, plant behaviour or effect of supersaturation for aquatic organism in real situations.

The utilized measurement setup can be upgraded by easier converting of 4 – 20 mA signals in to a logging device. Used setup involved large numbers of connections, power supplies, loose items, and improvements with regards to simplification and mechanical robustness is present. Current clamps with Bayonet Neill–Concelman (BNC) connectors for mA signals, which can be used to directly connect to e.g. PicoScope, is experienced to be expensive. Operational amplifier or implementing of signal directly into a Programmable Logic Controller (PLC), is alternatives which could have simplified the field setup.

5.3.5 Alternative methods to indicate gas supersaturation

This thesis have focused on air entrainment at intake air vent to indirect detect TDG supersaturation from small hydropower plant, as alternative method to the already described trash rack head loss measurement and direct monitoring of supersaturation [1]. Throughout the thesis period, both based on the different plant parameters measured at field tests but also discussions and literature review, other alternative parameters that possibly can indirectly identify supersaturation have been briefly assessed:

- Turbine guide vane position related to station pressure head measurements
- Turbine guide vane position related to generator output power
- Water level at intake air vents
- Image processing of river downstream power station

Station pressure head measurements, upstream turbine, is clearly influenced by air entrainment at lower turbine discharge, see figure 5.7 and 5.12. The pressure head deviation is less with air entrainment at full turbine discharge (figure 5.2.4), but still outside expected losses at given turbine guide vane position and pressure head. Grønhaug plant have already implemented stop of plant at too low pressure head in pressure pipe, which will firstly protect the plant but also prevent long duration of large air entrainment with possible artificial TDG supersaturation. The large operator of small hydropower plants in Norway, Småkraft AS, commonly use alarm and stop of plant at too low pressure in station [51]. Deviation from expected relationship between turbine guide vane position and generated power is in the same way found during testing to be a measure for large air entrainment and possible TDG supersaturation at plants outlet (see figure A.1), which is expected when the total pressure is largely decreased. Both pressure and generated power, related to turbine discharge, need proper calibration for both unnecessary stop of plant, plant safety and supersaturation levels, but can reveal if large air volumes entering the pressure pipe.

At high level of air entrainment, free surface flow is expected at top of pressure pipe, see chapter 5.1.2, to be able to deliver the order of magnitude of air volume drawn into the system. An simple water level sensor in intake air vents can also indicate when free surface level is present, and by that, high pressure head at intake area and the following risk of air entrainment as presented in chapter 5.2.2. The same sensor will in general be an alternative to intake trash rack pressure head measurements, in combination with intake dam water level, but will also include contraction head losses in the intake area. See figure 5.9. Large air leading vortexes in air vent can be an source to measurement error.

Image processing of hydropower plant outlet river can also be a possible method to detect high level of TDG supersaturated water. This method is expected to be depended on the outlet river flow and river conditions, and will probably only detect supersaturation at levels which gives visible sign of TDG supersaturation (see theory chapter 2.1) with release of small air bobbles, not periods with invisible diffusion [7]. Still, based on the plant configuration used during field tests at Grønhaug plant, the air entrainment volume flow is large when first initiated, and by then quickly resulted in visible sign of supersaturation. Image processing may be too far from the principle about robust, simple and cost-efficient solutions to detect TDG supersaturation.

5.3.6 Grønhaug kraftverk AS approach to obtained test results

The coverage of intake trash rack performed at field tests in Grønhaug plant is extreme and extensive by use of large plates, almost completely covering the trash rack. Still, based on the result and findings from field tests performed at Grønhaug, the owner of Grønhaug Kraftverk AS plan to install differential pressure measurements at intake trash rack, and also install TDG sensor in the plants outlet (thesis recommended location) to avoid future possible extreme coverage of trash rack and risk of release of artificial TDG supersaturation from the plants outlet. For Grønhaug, these mitigation actions is most relevant at large river flows during snow melting or autumn high rain periods, where access to the trash rack is limited.

The plants turbine have an internal leakage due to normal wear and tear which results in higher water consumption and operation outside specifications. New tests and continuously measurements is recommended with TDG sensor when upgrade of the turbine is performed to observe TDG during normal operation. Measurements can also include TDG sensor upstream the intake dam to reveal the natural TDG level entering the pressure pipe intake, and downstream in a certain distance from the plants outlet to see the final level of TDG in the outlet river.

5.4 Simple actions to stop initiated air entrainment

The main principle in a hydropower plant will be to avoid air entrance where entranced air can be pressurized [1]. Still, if air entrainment are present, quick actions needs to be taken to stop the source of air entrainment and by that the risk of release of TDG supersaturated water. A brief discussion with methods to reduce present air entrainment is given in this section, based on the described hydropower plant configuration with submerged intake trash rack and Francis turbine.

Results from field testing gives that head loss in intake area above a certain level is needed to initiate air entrainment and the following risk of release of artificial TDG supersaturated water from the plants outlet. In the opposite way, field tests indicate that stop of air entrainment need to be done by reducing head losses in intake area under a certain level. This can be done with the following measures:

- Reduce turbine discharge (guide vane position)
- Remove coverage from trash rack

During field testing, both decrease of turbine discharge and removal of coverage have been used to stop air entrainment. By use of these two measures, the plant have been continuously in operation during all field tests. Both in figure 5.1 and e.g. 5.13, the limit for stop of air entrainment can be found. This limit is observed to be the same as start of air entrainment, just in the opposite direction. If water level in intake obsolete air vent is observed to be above "new" air vent pressure pipe entrance at top of pressure pipe, air entrainment stops. By this, with regards to air entrainment, the most important measure is to reduce the head loss in intake area below the air entrainment limit described in chapter 5.3.3.

During manned field testing, removal of coverage on trash rack is easy to perform. In normal operation, at an not manned small hydropower plant, automatic trash rack cleaner can be preferable, which is expected to be expensive for small hydropower plants [1] [20]. Still, the relevance depend on frequency of debris coverage and access/cost for operation personnel.

Systems to clean trash rack can also be design with pressured air which blow away debris through openings in trash rack bars [38] during stop of production. Removal of debris is not only motivated with supersaturation reduction, but will obviously be important for plants income due to head losses.

During field tests in November 2021, air seems to be trapped in the pressure pipe after the coverage of the trash rack was removed. The pressure head gives fluctuating measurements until the guide vane position (discharge) was low enough to remove all trapped air, see point marked as number 1 in figure 5.15. This aspect needs to be considered to ensure all trapped air are removed from pressure pipe before normal operation is obtained. At field tests in April 2022, with normal operation conditions and higher discharge, higher pressure head were present in station during air entrainment, and no air seems to be trapped in the pressure pipe system after removal of temporary coverage.

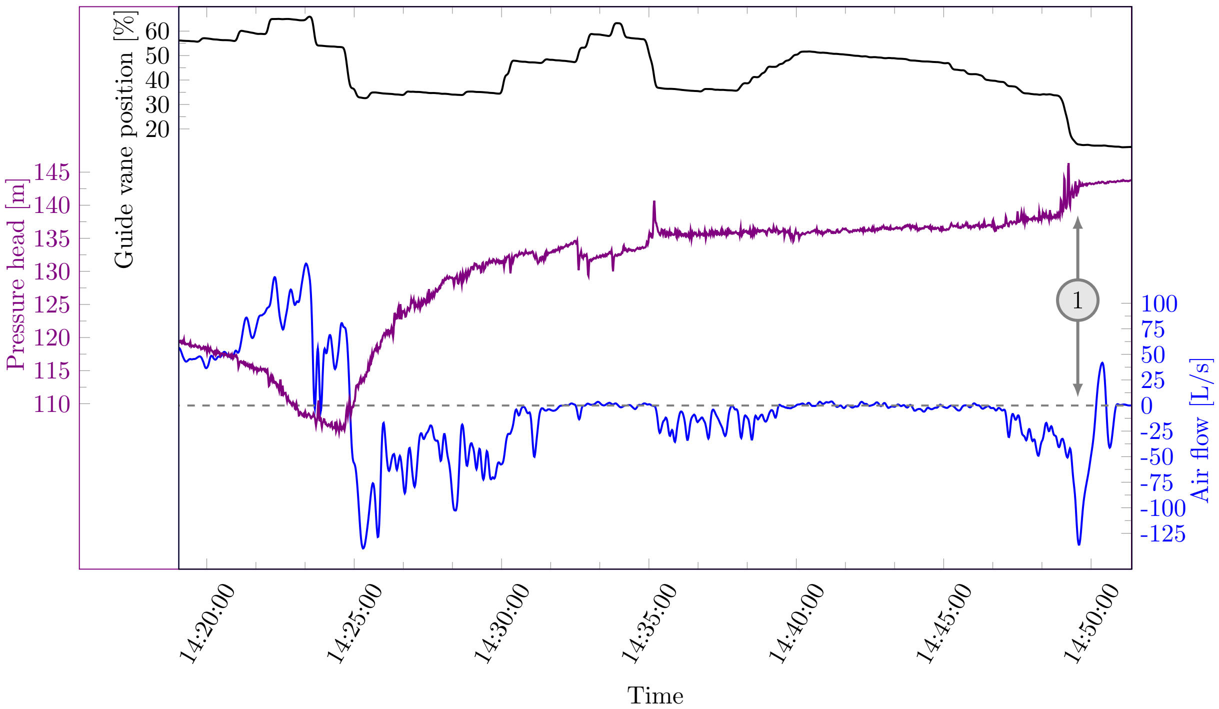


Figure 5.15: *Air entrainment related to turbine guide vane position and pressure head during last test performed November 2021 at Grønhaug plant, and until stabilized plant. Circle with number 1 indicate the non-destructive blow out of trapped air at low discharge.*

6 Conclusion

The relationship between covered trash rack, air entrainment at intake air vents in small hydropower plants, and artificial Total Dissolved Gas (TDG) supersaturated water from the plants outlet have been investigated. Two field tests have been performed at Grønhaug Kraftverk AS to expose the relationship, where also measurement at air vents have been compared against head loss at trash rack and TDG supersaturation in the plants outlet river. The main conclusions, relevant for small Francis hydropower plants with submerged intake, can be summarized as:

- Field test results relate air entrainment at intake air vents with artificial TDG supersaturation from the plants outlet, given submerged intake as a prerequisite: air vent monitoring can be an alternative method to detect air entrainment and largely avoid release of TDG supersaturation.
- Based on result from field tests, the low cost and simple trash rack head loss monitoring method is recommended to mitigate TDG supersaturation release. If properly calibrated and integrated in the hydropower plant control system, air entrainment and initiation of supersaturation in general can be avoided.
- Design improvement proposal is given for intake air vent entrance at pressure pipe: avoid top entry air vent on pressure pipe to largely limit air entrainment. Intake head losses of magnitude to give free surface flow, at air vent entry in pressure pipe, is identified as initial parameter for air entrainment.
- Common and standardized location of TDG sensor in Francis small hydropower plants outlet basin is proposed.

Future Work

Further work is needed to strengthen the air vent measurement principle identified in this thesis, as also for the design recommendation with air vents entrance at pressure pipe. The recommended general TDG sensor location in outlet need long term testing to reveal other factors not found at short term testing. Further work is identified as:

- Identify air sensors with robustness for years in operation at hydropower plants intake air vents.
- Strengthen the concluded relationship between air entrainment at intake air vent and artificial supersaturation from plants outlet by long duration testing, to reveal if other parameters is influencing the conclusion.
- With additional field tests and model testing as Computational Fluid Dynamics (CFD) analysis, strengthen the design recommendation given with regards to location of air vent pressure pipe entrance and air entrainment due to free surface flow at start of pressure pipe.
- Long term test of recommended TDG sensor location to reveal potential challenges not observed during short time testing at Grønhaug plant.
- Develop a standardised solution for implementing of TDG sensors directly into the hydropower plant control system.

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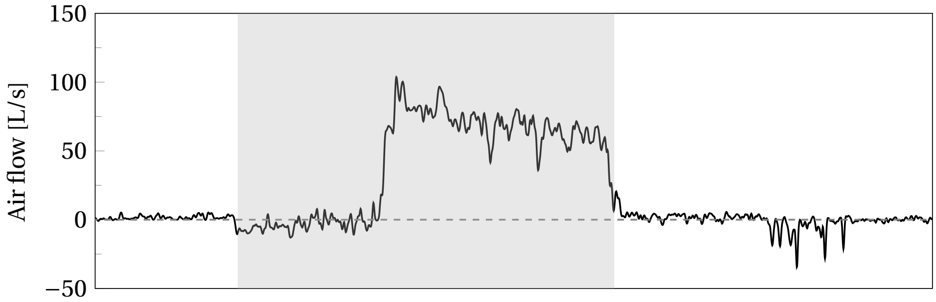
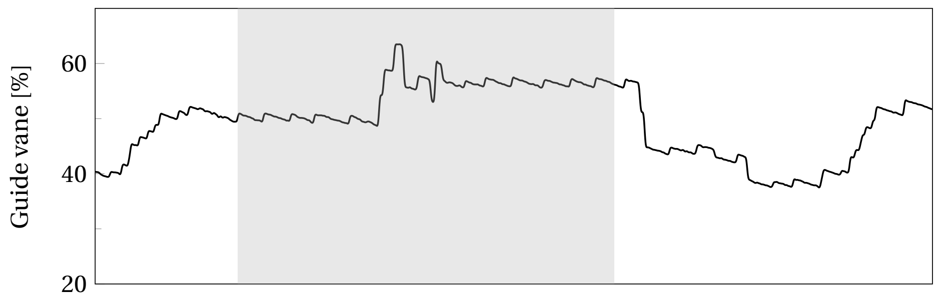
A Additional result from field tests

A.1 Field test at Grønhaug plant November 2021

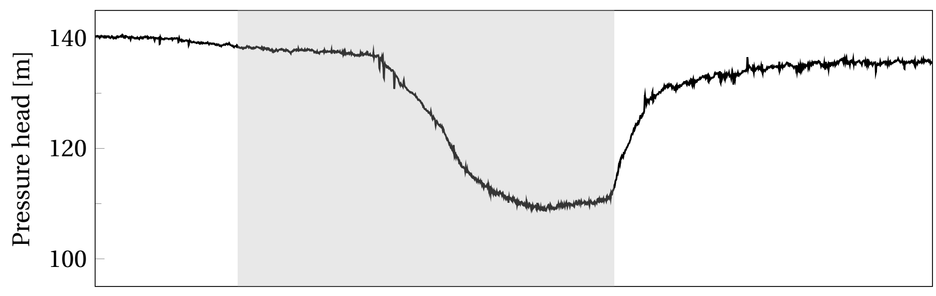
A.1.1 First covering



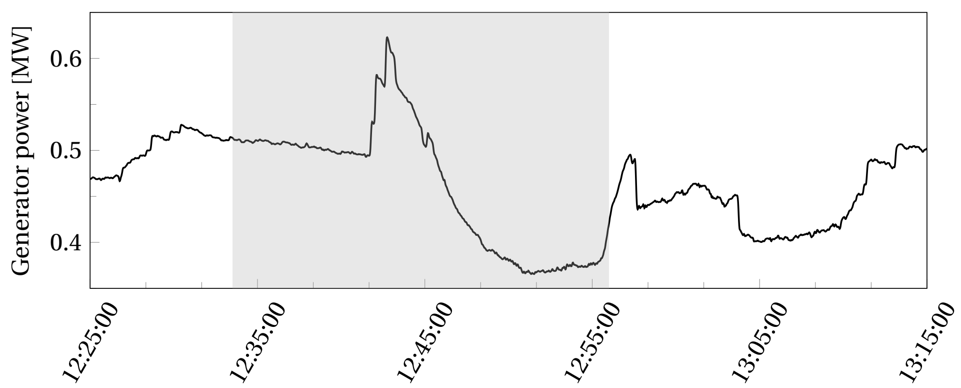
(a) *Air flow through pressure pipe ventilation at intake dam*



(b) *Turbine guide vanes position.*



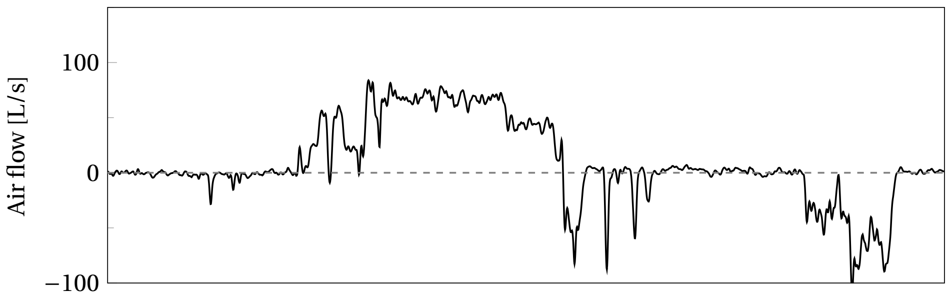
(c) *Pressure head at Grønhaug power station*



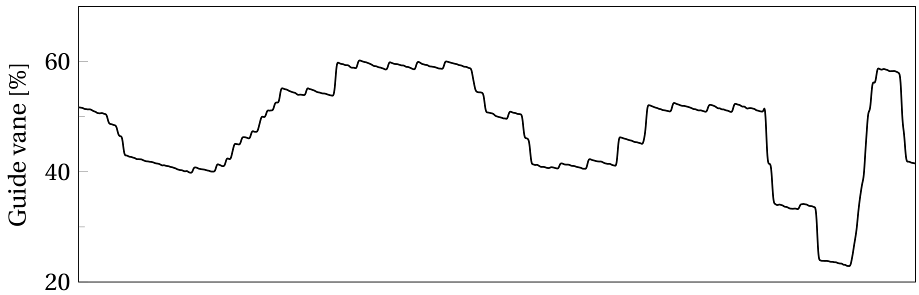
(d) *Power produced by generator*

Figure A.1: *Result from first covering of intake trash rack the 26th of November 2021. Grey area indicates the period when trash rack was ≈ 90 % covered. Power produced by the power station generator are included.*

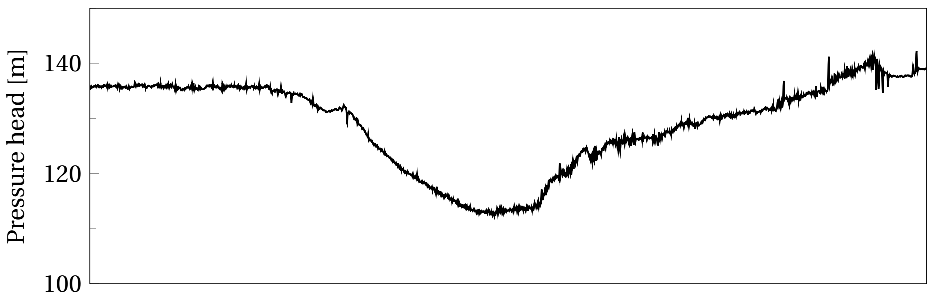
A.1.2 Second covering



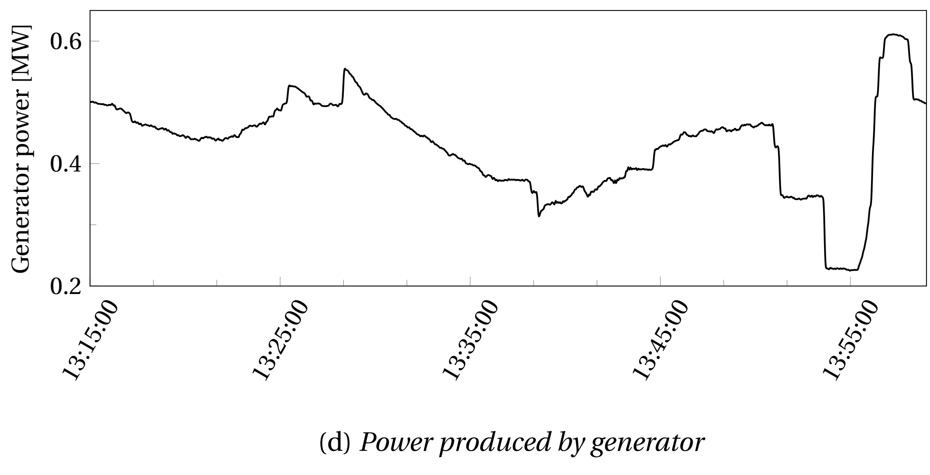
(a) *Air flow through pressure pipe ventilation at intake dam*



(b) *Turbine guide vanes position.*



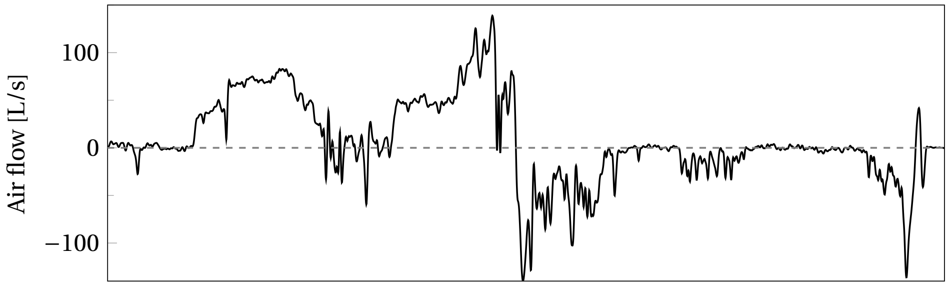
(c) *Pressure head at Grønhaug power station*



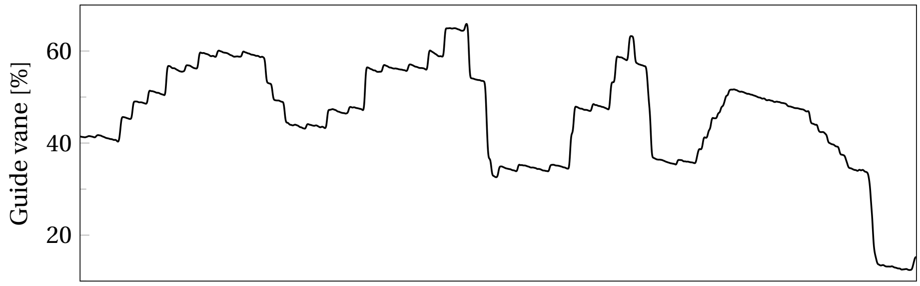
(d) *Power produced by generator*

Figure A.2: *Result from the second covering of intake trash rack the 26th of November 2021. Power produced by the power station generator are included.*

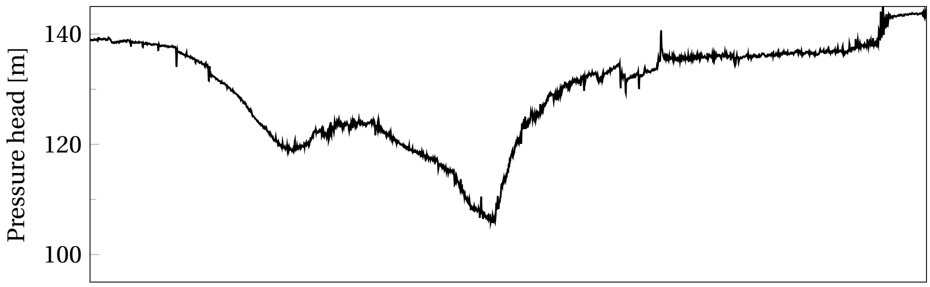
A.1.3 Third covering



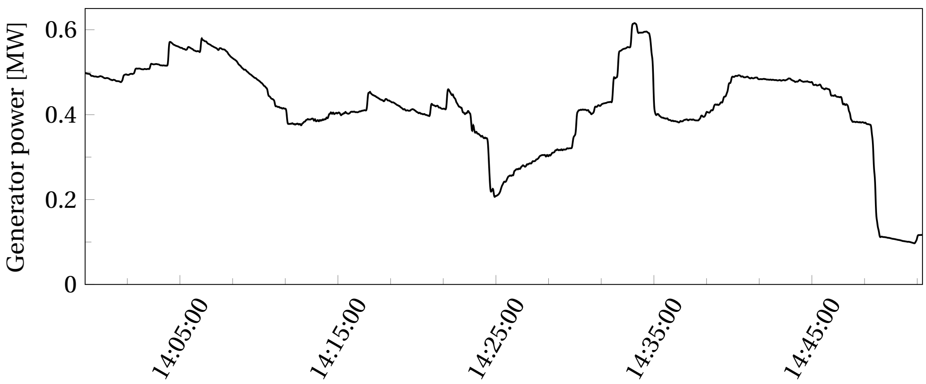
(a) *Air flow through pressure pipe ventilation at intake dam*



(b) *Turbine guide vanes position.*



(c) *Pressure head at Grønhaug power station*



(d) *Power produced by generator*

Figure A.3: *Result from the third covering of intake trash rack the 26th of November 2021. Power produced by the power station generator are included.*

B Equipment documentation

B.1 Equipment used during field tests

This appendix gives additional information about equipment and sensors used during site tests at Grønhaug plant. Air velocity, TDG and method for differential pressure measurement over trash rack is described in detail in main report chapter 3.1. Other parameters and sensors is described at same level of details in this appendix. Table B.1 gives an total overview of all main equipment and sensors used during testing. Details as temporary hoses, temporary coverage and similarly are not described in detail.

Parameter	Location	Equipment	Model	Manu-facturer	Range	Output	Accuracy
Air velocity	intake dam vent	Air velocity sensor	MFS-C-125	Micatrone SE	1 – 50 m/s	4 – 20 mA	Undisturbed flow - ± 2 %, recommended 3 – 5 %
Air velocity	intake dam station	Pressure differential transmitter	PREMASGARD 1121-I LCD	S+S Regeltechnik	± 1000 Pa, adjustable	4 – 20 mA	± 10 Pa
TDG	Power station outlet	Weiss Saturometer	High pressure saturometer	Fisch und Wassertechnik	80-200 TDG	4 – 20 mA	± 1 % TDG
TDG	Power station	Logger junction box	Norce ver.7	Norce	Unknown	SD card / GSM	Unknown
Pressure head	Power station - pressure pipe upstream turbine	Pressure transmitter	3100-B00-16G01-B000	GEM Sensors & Controls	0 – 16 bar	4 – 20 mA	0.25 % Full Scale (FS)
Water level	Intake dam	Pressure sensor	PTX 1830	Druck	0 - 350 mbar	4 – 20 mA	± 0.1 % FS
Water level	Intake dam obsolete vent	Ultrasonic sensor	UB4000-F42-I-V15	Pepperl + Fuchs	0.2 – 4.0 m	4 – 20 mA	± 1 % FS
Water level	Intake dam obsolete vent	Pressure sensor	LMP 305	BD SENSORS	0 - 350 mbar	4 – 20 mA	± 0.50 % Full Scale Output (FSO)
Guide vane position	Turbine	position sensor	Unknown	Temposonic	0 – 100 %	4 – 20 mA	Unknown
Generator current	Generator Current Transformer (CT)	Energy analyzer with current clamp	Fluke 435 & Fluke i5s	Fluke	0 - 5 A	NA	Fluke 435: ± 0.5% i5s: 1 % + 5 mA
Generator voltage	Generator Voltage Transformer (VT)	Energy analyzer	Fluke 435	Fluke	1- 1000 V_{rms}	NA	± 0.1 % of nominal voltage
NA	Power station	DAQ	Picoscope 4824	Pico Technology	NA	USB	DC accuracy ± 1 % of FS ± 300 µV
NA	Power station	Current transducer	CTSR 0.3 P	LEM	± 500 mA	2.5 V ±2.5 V	1.90 %

Table B.1: *Sensors, transmitters and main equipment used during field testing at Grønhaug plant*

B.1.1 Water level in intake dam

As described in chapter 3.2.3, an Druck pressure sensor PTX-1830 is used by Grønhaug plant in operation. To capture the information given by the plant 4 – 20 mA signal loop, the water level loop are extended (serial connection) through one of the prepared project transducers, giving voltage input to the PicoScope. No calculation have been necessary, but site calibration of voltage range of transducer compared to 4 – 20 mA loop signal was needed.

B.1.2 Turbine guide vane position

The Francis turbine in Grønhaug plant have adjustable guide vanes, which can be adjusted from 0 – 100 % position. To capture the information given by the plant 4 – 20 mA signal loop for turbine guide vane position, the loop are extended (serial connection) through one of the prepared project transducers, giving voltage input to the PicoScope. No calculation have been necessary, but site calibration of voltage range of transducer compared to 4 – 20 mA loop signal was needed. The turbine have a leakage which result in not constant position from guide vane, but frequently adjusting to gain the given setpoint.

B.1.3 Generator current and voltage measurements

Measurement of generator current and voltage is done by use of the CT and VT circuit from the plants generator in the plant station.

The CTs is installed between the generator breaker and the step-up transformer in the plant station. CT ratio is 1200:5 A, and the Fluke 435 is connected to the secondary side of the CT circuit. Ratio in Fluke 435 is set to 720:3 to reflect the CT ratio directly in the Fluke 435. Measurements are done by current clamps 5is from Fluke, directly connected to Fluke 435.

The VTs utilized is installed between the generator and the generator breaker in the plant station. VT ratio is 660:110 V, and the Fluke 435 is connected to the secondary side of the VT circuit. Fluke 435 measure the VT secondary side voltage directly at VT reduced voltages, which after the monitoring are calculated to real generator voltages.

After the recordings, data is imported into the Fluke software Fluke "Power Log Classic" for analysis and export to excel-format for further calculations to presented total produced power (MW) in appendix A in this report.

B.1.4 Water level intake obsolete air vent - ultrasonic sensor

The ultrasonic sensor UB4000-F42-I-V15 from Pepperl+Fuchs have been used during the first field test. The sensor range was adjusted to utilize the full scale up to 4 m and gives signal in the standard range 4 – 20 mA as output. The sensor was calibrated, tested, and settings adjusted at the electric power laboratory at Høgskulen på Vestlandet (HVL). The sensor need 24 V DC supply, and gives directly the parametrized measure range as 4 – 20 mA output without need for calculations or equations. The 4 – 20 mA signal is converted into voltage signal by one of the transducers for implementing to the PicoScope.

The water level measured by the intake obsolete air vent pipe have been related to the water level in intake dam. This is done by subtracting the water level measured by the sensor in intake obsolete air vent, from the physical installed height of the sensor position, related to water level in intake dam.

B.1.5 Logger device with transducers

As described in chapter 3.3, PicoScope 4824 with software PicoLog were chosen as the logger device for field tests in Grønhaug plant. PicoScope 4824 have 8 voltage inputs that can be used to capture measurements. During planing, focus have been to obtain a similarly setup for all the different 4 – 20 mA signals in use, and this have been done by use of current transducers of type CTSR 0.3 P, from manufacturer LEM.

The current measure range are between -500 to 500 mA. Measured signals loops introduce between 4 – 20 mA signal current, which are low compared to the range of transducers. To reduce the influence of no-load energized transducer output signal error, the primary current through the transducers was routed 15 turn through the transducer. The order of magnitude of error are the same, but with 15 times larger range, the error are lower relative to the measured range. In additional, to remove high frequency noise, a simple low pass filter is wired for each voltage input signal to the PicoScope 4824, close to the input ports at the PicoScope 4824. The chosen low pass filter consist of a capacitor C_f of 1.53 μF and a resistor R_f of 3.15 kΩ, giving a cutoff frequency of 33 Hz. The transducers is soldered to circuit boards, and mechanical protected for more robust approach for field work.

For each energizing transducers with 5 V DC supply, the range of output signal from transducer changes by mV order of magnitude. Before field test, calibration with 4 – 20 mA after energizing are needed if accurate measurements are important to reveal the transducers range for the measurement signals at the given field tests. The 5 V DC supply used is not adjustable (fixed). At zero primary current, the output signal voltage is approximately 2.5 V.

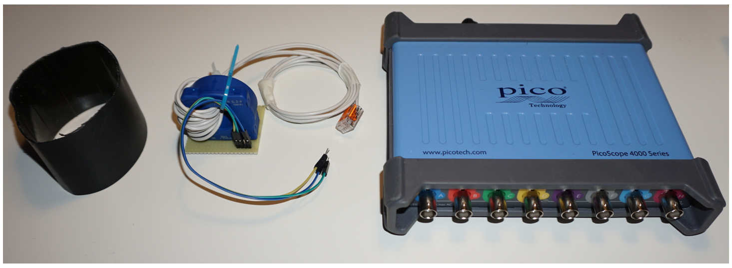


Figure B.1: *PicoScope and one of the transducer with 15 turns and black mechanical protection cover*

C Calculations

C.1 Critical depth - submerged intake during field tests

Intake dam critical depth is calculated with both equation 2.12 and 2.13, where the most conservative depth limit is used. See also figure 2.4.

Input data for recommended submerged intake during tests at Grønhaug hydropower plant

```
clear all
clc

Q_test_nov=0.5;                                  %m^3/s
Q_test_april=0.95;                               %m^3/s
d_pipe=0.6;                                      %m
A_pipe=(pi*((d_pipe/2)^2));                      %m^2
v_pipe_nov=Q_test_nov/A_pipe;                    %m^2/s
v_pipe_april=Q_test_april/A_pipe;                %m^2/s
g=9.81;                                          %m/s^2
rho_vann=1000;                                   %kg/m^3
Fr_nov=v_pipe_nov/(g*d_pipe)                     %Froude number
```

```
Fr_nov = 0.3004
```

```
Fr_april=v_pipe_april/(g*d_pipe)                 %Froude number
```

```
Fr_april = 0.5708
```

```
kinematisk_visk=1.5*10^-6;                       %m^2/s
Re_nov=(d_pipe*v_pipe_nov)/kinematisk_visk       %Reynolds tall
```

```
Re_nov = 7.0736e+05
```

```
Re_april=(d_pipe*v_pipe_april)/kinematisk_visk   %Reynolds tall
```

```
Re_april = 1.3440e+06
```

$\left(\frac{h_1}{d}\right)_{cr} = 0.5 + 2\mathrm{Fr}$, as gives: $h_{1cr} = d * (0.5 + 2.0\mathrm{Fr})$ (min h/d=1.5)

$\left(\frac{h_2}{d}\right)_{cr} = 1.0 + 2.3\mathrm{Fr}$, as gives: $h_{2cr} = d * (1.0 + 2.3\mathrm{Fr})$

$h_1 =$ height between water surface and senter of pressure pipe

$h_2 =$ height between water surface and top of pressure pipe

$d =$ diametre of pressure pipe

November 2021:

```
h_1_d_nov=(0.5+2.0*Fr_nov)                      %[-] (h1/d)critical
```

```
h_1_d_nov = 1.1009
```

```
h_1cr1_nov=d_pipe*(0.5+2.0*Fr_nov)              %[m] calculated
```

```
h_1cr1_nov = 0.6605
```

```
h_1cr2_nov=d_pipe*1.5                          %[m] based on min. val. 1.5 f (h1/d)cr.
```

```
h_1cr2_nov = 0.9000
```

```
h_2_d_nov=(1.0+2.3*Fr_nov)                     %[-] (h2/d)critical
```

```
h_2_d_nov = 1.6910
```

```
h_2cr_nov=d_pipe*(1.0+2.3*Fr_nov)              %[m]
```

```
h_2cr_nov = 1.0146
```

```
h_dam_min_nov= 1.75                            %[m] Resulting water level at plant HMI
```

```
h_dam_min_nov = 1.7500
```

April 2022:

```
h_1_d_april=(0.5+2.0*Fr_april)                 %[-] (h1/d)critical
```

```
h_1_d_april = 1.6417
```

```
h_1cr1_april=d_pipe*(0.5+2.0*Fr_april)         %[m] calculated
```

```
h_1cr1_april = 0.9850
```

```
h_1cr2_april=d_pipe*1.5                        %[m] based on min. val. 1.5 f (h1/d)cr.
```

```
h_1cr2_april = 0.9000
```

```
h_2_d_april=(1.0+2.3*Fr_april)                 %[-] (h2/d)critical
```

```
h_2_d_april = 2.3129
```

```
h_2cr_april=d_pipe*(1.0+2.3*Fr_april)          %[m]
```

```
h_2cr_april = 1.3878
```

```
h_dam_min_april= 2.1                           %[m] Resulting water level at plant HMI
```

```
h_dam_min_april = 2.1000
```

C.2 Datum calibration of water level in obsolete intake vent

This chapter present the Matlab calculations performed to calibrate the intake obsolete air vent water level sensor level above datum for existing water level in intake dam, valid for the field test performed in April 2022. Equation 2.7 is used as basis for the calculations, together with equation 2.8.

Calculations to calibrate the intake obsolete air vent water level

This calculations is used to be able to define the datum level position of the water level sensor (pressure) installed in the obsolete air vent at intake during test performed the 18th of April 2022 at Grønhaug hydropower plant, relatively to the water level measured in the intake dam.

Initial parameters:

```
clear all
clc

%Pressure pipe flow:
Q=0.37;                                 %[m^3/] during calibartion situation

%General parameters:
g=9.81;                                 %[m/s^2]
rho_water=1000;                         %[kg/m^3]
Z_intake_dam=0;                         %[m] height above datum in intake dam water
%level measurement location
V_intake_dam=0;                         %[m/s] water speed at intake dam water level
% measurement location

%trashrack parameters:
L0_trashrack=1.2;                       %[m] lenght(width)
H0_trashrack=1.5;                       %[m] height
A0_trashrack=L0_trashrack*H0_trashrack; %[m^2] Area of trash rack
v0_trashrack=Q/A0_trashrack             %[m/s]
```

```
v0_trashrack = 0.2056
```

```
a_trashrack=0.020;                      %[m] width between vertical bars trash rack
b_trashrack=0.010;                      %[m] width of vertical trash rack bars.
betta_skjevstromning=20;                %[degrees] skjevstrømning to intake trashrack
theta_trashrack=80;                     %[degrees] inclination angle from horizontal
% (Kirschmer-Mosonyi)
Kf=1.67;                                %[-] Kirschmers trashrack bar shape.
% "Inntakshåndbok" page 86, Kf are named K1 in Vassdragsteknikk page 49
Kdelta_kirschmer=1.26;                  %[-] Degree perpendic. flow appr., from graph.

%pressure pipe parameters:
L_pressurepipe=378;                     %[m] Lenght of pressure pipe
D_pressurepipe=0.6;                     %[m] Diameter of pressure pipe
A_pressurepipe=(pi*((D_pressurepipe/2)^2)); %[m^2] Area of pressure pipe
v_pressurepipe=Q/A_pressurepipe         %[m/s]
```

```
v_pressurepipe = 1.3086
```

```

%measured parameters during test 18 april, as input to the calibration
h_intake_dam=2.927                      %[m] water level intake dam measured during
```

```
h_intake_dam = 2.9270
```

```
% calibration situation
h_obsolete_air_vent=2.379                          %[m] water level obsolete intake air vent,
```

```
h_obsolete_air_vent = 2.3790
```

```
% based on measured hydrostatic pressure
```

Calculated head loss trash rack (Kirschmers equation):

$$h_{\text{loss}}\,[m] = K_F * K_\delta * \sin\alpha * \left(\frac{b}{a}\right)^{\left(\frac{4}{3}\right)} * \frac{V_0^2}{2g}$$

Head loss over trashrack with no blokking of trashrack area given below:

```
v=(((v0_trashrack)^2)/(2*g))     %v introdused due to print margins
```

```
v = 0.0022
```

```
h_loss_trashrack=Kf*Kdelta_kirschmer*(sind(theta_trashrack))*(b_trashrack/a_trashrack)^(4/3)*v
```

```
h_loss_trashrack = 0.0018
```

Contration/entrance losses

$$h_{\text{con-loss}}\left[m\right] = 0.5 * \frac{V_{\text{pipe}}^2}{2g}$$

```
h_loss_contraction=0.5*((v_pressurepipe^2)/(2*g))
```

```
h_loss_contraction = 0.0436
```

Velocty head inside pressure pipe

$$h_{\text{vel.-haed}}\left[m\right] = \frac{V_{\text{pipe}}^2}{2g}$$

```
h_velocity_head=((v_pressurepipe^2)/(2*g))
```

```
h_velocity_head = 0.0873
```

Calculation of datum height for obsolete air vent water level sensor

$$z_{\text{intake-dam}} + h_{\text{intake-dam}} + \frac{V_{\text{intakedam}}^2}{2g} = z_{\text{air-vent}} + h_{\text{air-vent}} + \frac{V_{\text{pipe}}^2}{2g} + h_{\text{losses}}$$

$$z_{\text{air-vent}} = z_{\text{intake-dam}} + h_{\text{intake-dam}} + \frac{V_{\text{intakedam}}^2}{2g} - \left(h_{\text{air-vent}} + \frac{V_{\text{pipe}}^2}{2g} + h_{\text{losses}}\right)$$

Calibrated at discharge at 0.37 m3/s, water level in intake area at 2.927m, water level in obsolete air vent at 2.379m and concider the water speed at intake dam area to zero. This gives the datum difference between intake dam water level sensor and obsolete air vent water level sensor at:

```
z_air_vent=Z_intake_dam+h_intake_dam+0-(h_obsolete_air_vent+ ...
    ((v_pressurepipe^2)/(2*g))+(h_loss_contraction+h_loss_trashrack))
```

```
z_air_vent = 0.4153
```

D Data from field tests

D.1 Data from field test in November 2021

Appendix includes PicoLog export file, Power Log Classic export file, and Microsoft excel file with all gathered data for import to Latex from field tests at Grønhaug plant the 18th of April 2022. Data files is not included directly to the report but delivered as separate files.

D.2 Data from field test in April 2022

Appendix includes PicoLog export file, TDG data export from Norce TDG sensor database, and master Microsoft excel file used for processing data gathered at field tests at Grønhaug plant the 18th of April 2022. Since the test performed in April 2022 is the most relevant with respect to normal operation conditions in plant, only these data is included directly in the report, see files attached below:

Master excel file:

TDG data export file:

PicoLog export file:

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