Implementation of pressurized air injection system in a Kaplan prototype for the reduction of vibration caused by tip vortex cavitation

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Abstract. Blade tip cavitation is a well-known phenomenon that affects the performance of large-diameter Kaplan turbines and induces structural vibration. Injection of pressurized air has been found to yield promising results in reducing those damaging effects. In this work, the results of an experimental test of air injection on a 9.5-m-diameter Kaplan turbine are reported. Experiments were performed for several load conditions and for two different net heads. Accelerations, pressure pulsation and noise emission were monitored for every tested condition.
Results show that, at the expense of a maximum efficiency drop of 0.2%, air injection induces a decrease on the level of vibration from 57% up to 84%, depending on the load condition. Such decrease is seen to be proportional to the air flow rate, in the range from 0.06 to 0.8‰ (respect to the discharge at the best efficiency point).

1. Introduction

Large-diameter Kaplan turbines may undergo vibration and erosion at the discharge ring due to the development of tip vortex cavitation phenomena. Severe erosion problems can compromise the lifetime of the machine or cause expensive repair stops. As such issues are difficult to foresee at the design stage, even with the help of CFD simulations and model tests, mitigation strategies have become an important subject.
Air injection can be of help in these cases. On the one hand, the reduction of cavitation damage is due to the fact that the presence of a non-condensable gas inside a single cavitation bubble reduces the rate of collapse and increases the minimum bubble volume [1]. On the other hand, it was found recently [2] that miniscule amounts of non-condensable gas (air) into the shear layer of a partial cavity on a wedge could reduce the void fraction (i.e., the ratio of gas to water volumes), thus reducing the potential energy available for noise, vibration and erosion.
Air injection has indeed shown potential in preventing erosion due to cavitation in such cases as the chute of spillways of hydroelectric dams [3]. Nevertheless, its application to hydro-turbines remains relatively unexplored and has been mainly confined to the prevention of flow instabilities in Francis turbines due to vortex rope development [4]. Arndt et al. [5] examined the effect of air injection on NACA profiles for the mitigation of cloud cavitation, and found that it was an effective method of minimizing the erosion potential. Consistent results were reported in [6] for an oscillating hydrofoil, where it was also noted that small amounts of air produce a large reduction in noise emission due to

cloud cavitation. Rivetti et al. [7, 8] performed air injection experiments for tip cavitation mitigation on a model scale Kaplan turbine, reaching a reduction of vibration levels at stationary parts of about 50%.

In this work, air injection experiments were performed on a prototype Kaplan turbine for which previous tests (at a model scale) were successful. Firstly, the case study and the experiment setup are presented. Then, the main results related to vibration reduction and pressure air injection are summarized. Finally, a deterministic expression for the injection pressure as a function of the air flow rate and the operational point of the turbine rate is given and a qualitative analysis of the physical mechanism of vibration reduction is discussed.

The study introduced herein was carried out under the framework of a project focused on the dynamic behavior of Kaplan turbines that combines prototype measurements, model tests and CFD simulations, and is supported by the Yacyretá Binational Entity (EBY), the National University of La Plata, Argentina (UNLP) and the National University of Misiones, Argentina (UNAM).

2. Materials and methods

2.1. Case study

This study concerns the hydro-power station of Yacyretá, which is located on the Parana River, at the border between Paraguay and Argentina. It is equipped with twenty Kaplan turbines of 9.5 meters of diameter. The specific speed is ns = 614, the maximum electric power is P_e = 155 MW and the rated head is H_n = 22.7 m (Fig. 1). The discharge ring is made of stainless steel and presents a pattern of erosion due to cavitation that consists in 24 patches in coincidence with the number of guide vanes [9]. The runner has five blades (Z_b = 5) and 24 guide vanes and stay vanes (Z_0 = 24). The tip of the runner blades has an anti-cavitation lip covering the 60% of the blade chord.

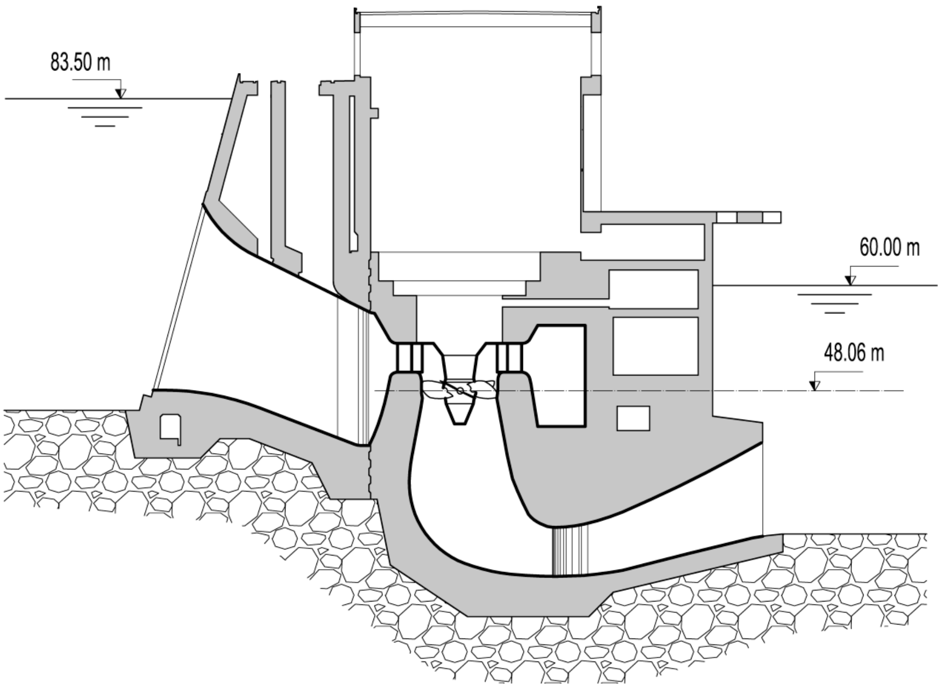

Figure 1. Kaplan hydro-power station layout of Yacyretá.

2.2. Turbine instrumentation

Two accelerometers Wilcoxin Research model 793L, a pressure transducer Keller series 21Y (PAA-21Y) a sound level meter Bruel & Kjaer model 2270 BZ-7222 and a synchronization sensor were installed on the prototype turbine (Fig. 2).

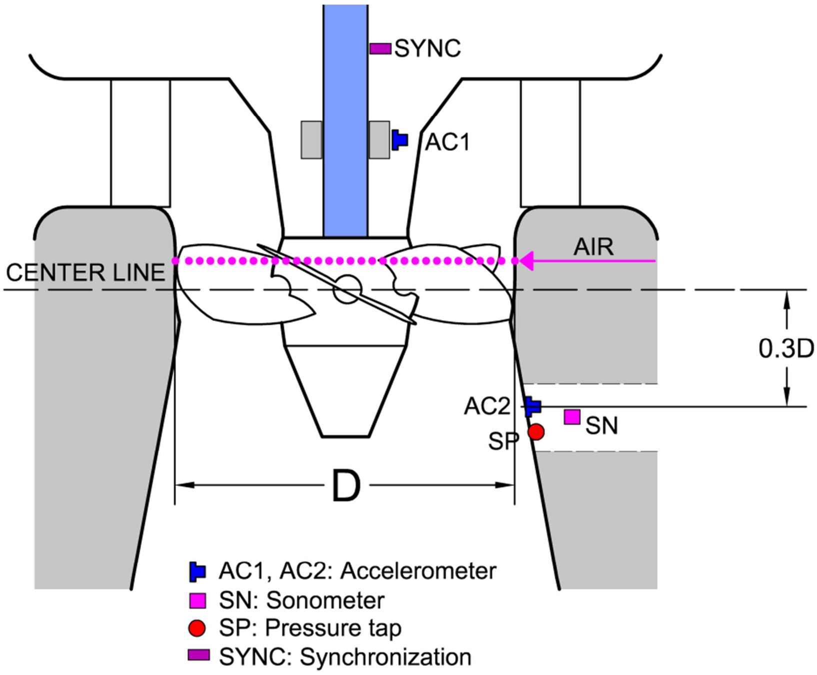

Figure 2. Cross-section of the turbine with location of the sensors.

2.3. Air injection and acquisition system

Air was injected through 60 evenly-spaced holes of 6 mm of diameter performed at the discharge ring, on a horizontal plane above the runner centerline (Fig. 3). The holes connect the flow passage with a manifold of triangular cross-section that surrounds the ring completely. The size of the holes was defined in order to have a homogeneous pressure along the manifold, thus guaranteeing a constant distribution of the injected air. A four-inch pipe connects the manifold with the high pressure line located at the electromechanic gallery.

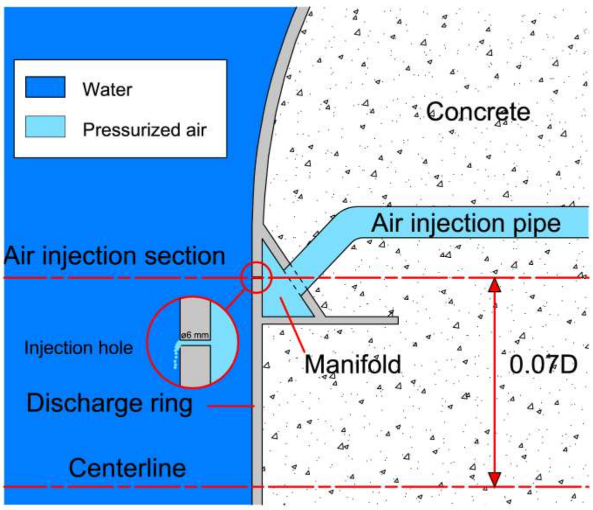

Figure 3. Cross-section of the discharge ring with the location of the air injection.

The goal of the injection system (Fig. 4) is to control and measure the desired air flow rate Q_a^* at every step of the test. A pressurized air tank of 8.5 m^3 (2) was capable of handling pressures higher than 6 bar during 2 minutes. After that, a constant pressure system (5) assured a constant air flow rate during the test. Three globe valves (6) with different diameters allowed for a high sensitive air flow rate regulation. Two pressure transducers (3) were located in order to record the injection and feeding pressure (P_i and P_t). All the variables were recorded by an acquisition card (11) and downloaded into a hard disk (12). The state signals, H_n = net head, Q = discharge, P_e, α = distributor opening, β = blade tilt angle and T = temperature were acquired with a frequency of 120 Hz. The dynamic signals (AC1, AC2, SN, SP and SYCN), and the air injection variables (P_t, P_i, and Q_a^*) were acquired at 4200 Hz. For the measurement of the air flow rate a TESTO® 6446 flowmeter was used.

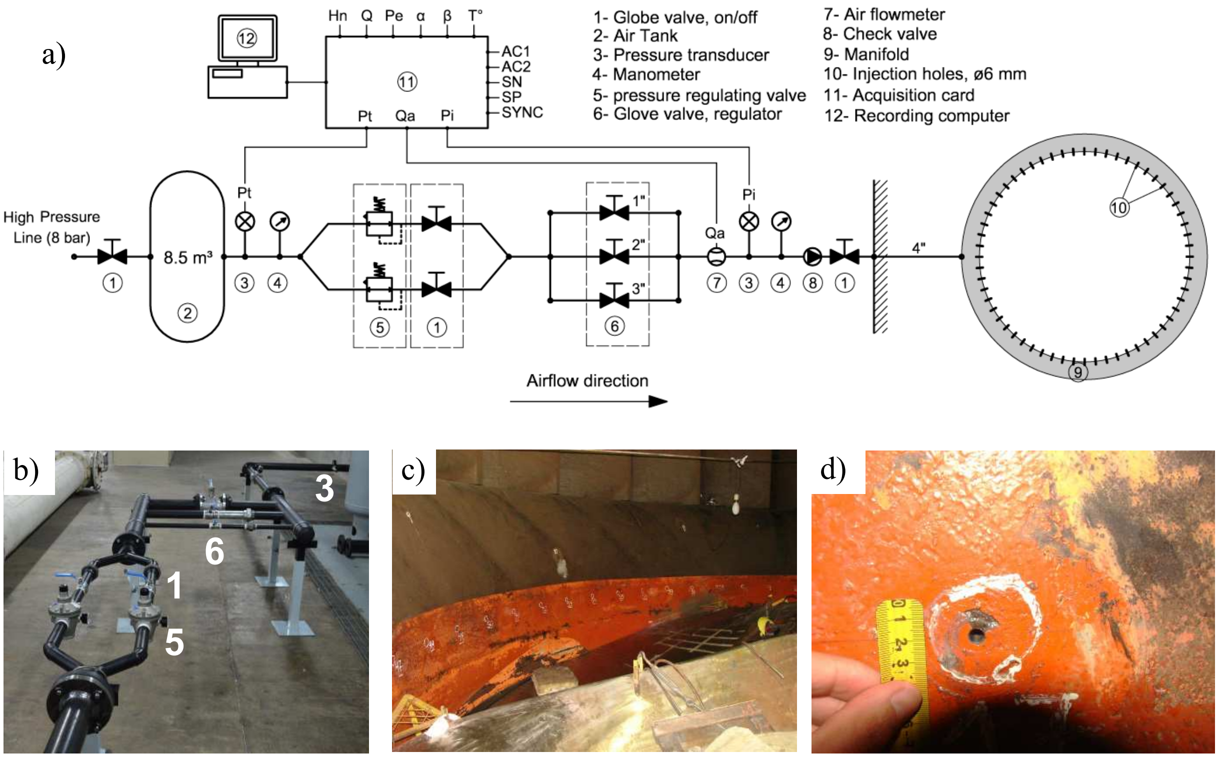

Figure 4. Air injection system a) system layout b) picture of the air regulation device installed in the electromechanic gallery c) injection holes at the discharge ring d) detailed picture of an injection hole.

2.4. Test procedure

Air was injected at constant load P_e from 0.65 to 1.0 of $P_{e\,max}$. For each load step the turbine regulator was switched off in order to keep the blade tilt angle β and the distributor position α unchanged. This feature was essential in order to detect the variation in efficiency as a drop in power generation.

Air flow rates varied from $Q_a^* = 0.06$ to 0.8‰, expressed as a fraction of the prototype flow rate at the best efficiency point Q_{BEP}. The test sequence can be listed as follows: 1) A small Q_a^* of 0.01‰ was injected to drain water off the air injection device. 2) The desired Q_a^* was established with the regulating valve arrangement. 3) Once a steady Q_a^* is reached, all the signals were recorded during 40s. 4) If the air tank pressure P_t was bigger than the minimum working pressure, point 2 was repeated with the following Q_a^* step. Otherwise, valves were closed in order to allow the pressure recovery. This sequence was repeated until the test was completed.

3. Results

3.1. Injection pressure

A rise of the injection pressure was observed as the air flow rate is increased (Fig. 5). For every load step, the pressure samples were fitted with a quadratic function (Eq.1). As the load and the specific energy increases, less injection pressure is needed for the same amount of air.

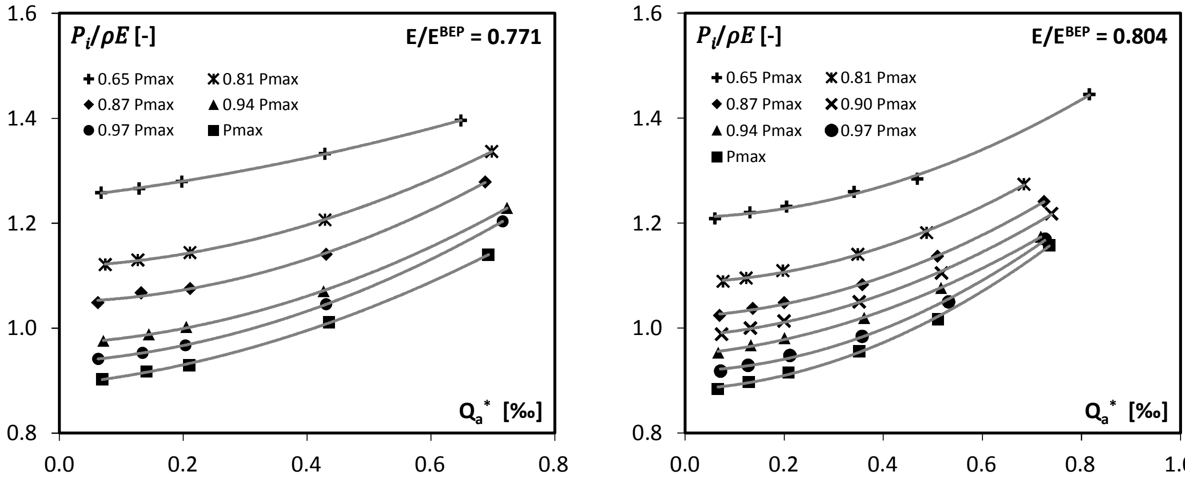

Figure 5. Dimensionless air injection pressure P_i , where ρ is the density of water and E is the specific hydraulic energy coefficient as a function of the air flow rate Q_a^* for different loads condition. The grey lines correspond to quadratic regression for every load step.

3.2. Vibrations, pressure pulsation and sound emission.

Fig.6 shows the variation of the magnitude of the dynamic variables in terms of the air injected Q_a^* for every load step. The black curve represents the typical response in function of the load without air. The behavior is the same for all the cases, flat up at to a load of 0.93 $P_{e\,max}$ and then a strong increase until reach the maximum value for $P_{e\,max}$.

Both accelerometers show a decrease in the magnitude of vibration when air is injected. The efficiency of the air injection for reducing vibration is greater at the discharge ring location than at the guide bearing, as can be seen comparing AC1 and AC2. For low loads, AC2 registers a strong drop of vibrations for a Q_a^* smaller than 0.2‰. Higher amounts of air do not produce any further attenuation. As the load increases, the slope of the attenuation curve becomes more constant. Noise emission at the man-door, SN, shows a similar pattern of attenuation but the reduction of the noise level is more effective for low loads. At high loads there is a small rise of the noise level for Q_a^* = 0.06‰. Then it is followed by a constant drop up to the maximum air flow rate. The pressure pulsation, SP, does not display a clear behavior for the maximum loads, 0.97 and 1.0 of $P_{e\,max}$. For lower loads, the shape of the attenuation curves is similar to that of vibrations. Table 1 summarized the ratio of mitigation for each variable.

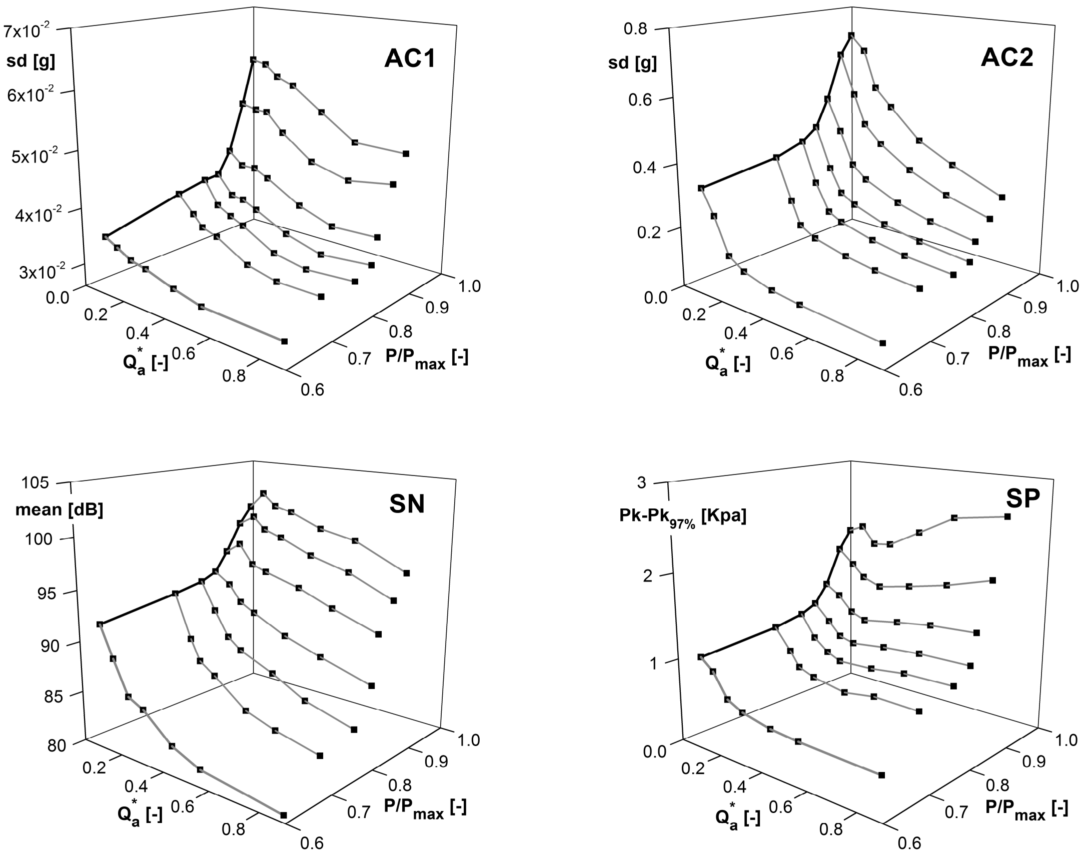

Figure 6. Magnitude of the dynamic signals for E/E$_{BEP}$ = 0.804 a) standard deviation of AC1 b) standard deviation of AC2 c) Mean value of SN d) Peak to Peak amplitude of the pressure signal for the 97% percentile.

Table 1. Mitigation ratio of dynamics variables and efficiency drop between no air condition and Q_a^* = 0.2‰ and 0.8‰.

P/P$_{max}$ [-]	Q_a*[‰]	E/E$_{BEP}$= 0.771				E/E$_{BEP}$= 0.804				Eff. Drop*
		AC1 [-]	AC2 [-]	SN [-]	SP [-]	AC1 [-]	AC2 [-]	SN [-]	SP [-]	[%]
0.93	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	---
	0.2	0.86	0.32	0.93	0.54	0.91	0.47	0.98	0.73	0.00
	0.8	0.83	0.16	0.89	0.54	0.78	0.24	0.94	0.86	0.14
1.0	0.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	---
	0.2	0.99	0.82	0.98	0.83	0.93	0.67	0.99	0.95	0.06
	0.8	0.97	0.43	0.94	1.38	0.78	0.34	0.95	1.22	0.19

*The minimum efficiency drop measurable was 0.05% due to instrumentation sensitivity

4. Discussion

4.1. Effect of air injection

The dynamic magnitudes measured for the no-air condition are proportional to the load (Fig.6). This is linked with the development of blade tip cavitation, as has been observed in the physical model [10].
For the same amount of air injected, mitigation was more effective at lower loads. This could be explained by the fact that the greater the amount of cavitation, the more air is needed to neutralize it. The same could be derived when comparing the effect of air evaluated under different head conditions, as higher air flow rates are needed for lower heads for comparable levels of mitigation to be achieved. That leads to bigger tilt angles required to get the same load at lower heads, for which the tip cavitation is more likely to develop.
The most beneficial effect of air in reducing vibration was observed in the draft tube man door (AC2), as the effect of tip cavitation implosion is captured directly by the discharge ring section, where the sensor is located. On the other hand, the guide bearing accelerometer AC1 is not directly in contact with the source of vibration. The vibration then is transmitted through the rotating part up to the guide bearing.

4.2. Injection pressure

Results suggest that the dimensionless injection pressure may be expressed as a function of the dynamic and static pressures at the injection points (first and third terms of the right-hand side of Eq. 1, respectively) and the energy losses in the air conduit system (second term).

$$\frac{P_i}{\rho E} = A\varphi^2 + B{Q_a^*}^2 + C \tag{1}$$

Where P_i is expressed in bars, ρ=water density (kg/m^3), E=specific hydraulic energy coefficient (J/kg), φ =Flow Coefficient (-), (A, B, C)= dimensional regression coefficients, Q_a^* is expressed in ‰.

The required injection pressure for a desired air flow rate Q_a^* would be then a function of the operating point of the unit. Assuming that the flow coefficient φ can be written as the ratio of the electric power P_e and the net head H_n, the absolute injection pressure can then be defined as a function of the operating point of the unit P_e and H_n and the air flow rate Q_a^* to be injected (Eq. 2). Regression analysis of the measured data (Fig. 5) allows for the determination of the coefficients $\tilde{A}$=0.0277 $\tilde{B}$=2.58 and $\tilde{C}$=3.24. This expression could be of practical use in the power plant for a permanent injection system, as P_e and H_n are parts of the permanent monitoring system of the unit.

$$P_i = \tilde{A}\left(\frac{P_e}{H_n}\right)^2 + \tilde{B}{Q_a^*}^2 + \tilde{C} \tag{2}$$

Where P_e is expressed in MW and H_n is expressed in m, $(\tilde{A}, \tilde{B}, \tilde{C})$= dimensionless regression coefficients (-).

4.3. Air injection mitigation model

The potential energy contained in a cavitating flow is defined by Eq.3 [11] as a function of the cavity volume and the difference of the surrounding and vapor pressure. When the cavity collapses, this energy is released producing shock waves, micro jets and noise emission. The potential of erosion is then proportional to the amount of energy available for the collapse.
Consequently, the magnitude of these dynamic variables will be greater in relation to the amount of available potential energy E_p, or which is the same thing, the cavitation volume V_{cav} and the pressure gradient $(p_{ref} - pv)$. Then, if we could control some of these two parameters, we would be able to mitigate the undesirable effects of cavitation. As shown by Mäkiharju et al. [2], the injection of a non-

condensable gas on a partial cavity produces a decrease in the void fraction, meaning a reduction of V_{cav}.

$$E_p \sim V_{cav}(p_{ref} - p_v) \quad (3)$$

Where E_p= potential energy of the cavitating flow, V_{cav}= vapor volume, p_{ref}= Surrounding pressure, p_v= vapor pressure.

In addition, the minimum pressure in the tip vortex cavitating core could increase with the air entrance. Indeed, high speed visualization performed on the physical model [7,8] enabled to see that air travels from the injector to the tip vortex core merging into a unique gas volume.
The alleged reduction of V_{cav} and the increase of p_{ref} could explain the reduction of noise emission and vibration due to air injection. In Fig. 7, a model scheme summarizing the mitigation mechanism is shown. Further research is needed on this topic.

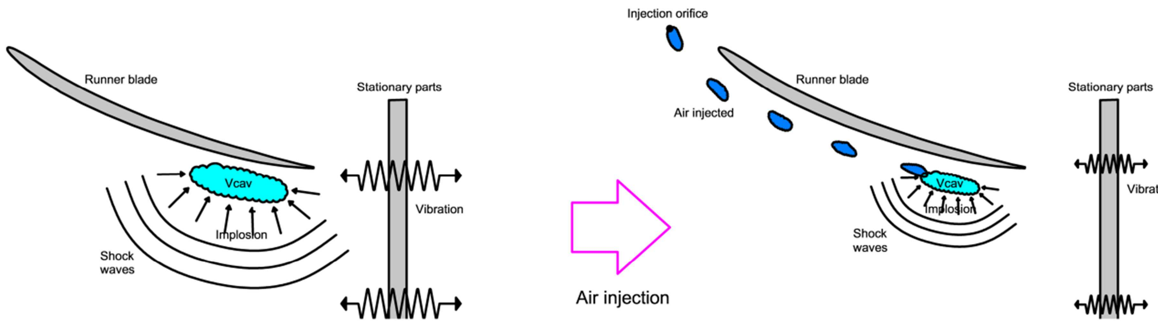

Figure 7. Vibration and noise emission model due to tip cavitation (a) under no air and (b) with air injection. The reduction of the volume of the cavity might account for the attenuation of cavitation potential energy.

5. Conclusions

In agreement with the results found on a physical scale model, air injection proved to be an effective method for the mitigation of tip blade cavitation in a Kaplan prototype turbine. The decrease in vibration level at the discharge ring was about 57-84%, depending on the load condition at the expense of a maximum efficiency drop of 0.2%. For an air flow rate smaller than 0.2‰, the drop in efficiency was found to be negligible. The attenuation observed is seen to be proportional to the air flow rate, in a range that goes from 0.06 up to 0.8‰, expressed as a proportion of the discharge at the best efficiency point. Noise emission had a similar behavior to that of vibration. However, pressure pulsation has showed some discrepancies at higher loads.
An expression for injection pressure P_i was given as a function of the operating point of the unit (H_n, P_e) and the air flow rate Q_a^*. According to it, the greater the load, the smaller the injection pressure, whereas the pressure P_i varies over a range from 0.85 up to 1.4 times the net head H_n.
A conceptual model of the mitigation mechanism produced by the air injection was developed, according to which the potential energy of tip cavitation is reduced by the mixture with air. Further research is needed on this topic.

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