VIBRATION REDUCTION IN HADITHA HYDROPOWER PLANT KAPLAN TURBINE WITH AIR INJECTION- REVIEW AND PROPOSED STUDY

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Abstract. Kaplan turbine tip vortex cavitation is a well-known phenomenon that im-pacts the performance of large-diameter turbines. This phenomenon is associated with high levels of structural vibration that can severely affected the structural integrity of such turbines. Severe metal erosion and high levels of sound and structural fatigue are among the major adverse manifestation of flow induced vibration. Mechanical erosion due to cavitation occurs at the tip end of the runner blades on the suction side and the discharge seal. In this work a review of the current mitigation techniques is explored and discussed. Air injection is one of the well-known approaches in this area and this study explore the benefit of using such techniques in Haditha hydropower plant in Iraq. Haditha plant is the second largest hydropower plant in Iraq which suffer from severe mechanical erosion and component degradation due to cavitation related issues. It had been reported that air injection has the potential to mitigates the adverse effect caused by cavitation.

Keywords: cavitation, Kaplan turbine, vibration, hydro-turbines, runner blades

Introduction:

Conventional hydroelectric power plants (HPP) are likely to suffer from many problems related to cavitation. This is because in many flow situations, inside the hydro unit, the pressure will drop far enough to reach the vapor pressure of water. Vapor or gas-filled cavities, bubbles might be generated in those regions, and it will have a strong influence on the flow stability and the hydro unit vibration behavior. When these cavities collapse, the released energy will produce shock waves, micro jets, and noise emission. Also, because of the different bubble sizes their collapse and oscillation inside the flow will create a wide range of intense noise and vibration [1]. The potential of erosion is then proportional to the amount of energy available for the collapse.

Axial turbines require a clearance, or a small gap, between the tip of the turbine blade and the discharge ring, as illustrated in Figure 1. The design limitation of such clearance requires that it has kept as small as possible to minimize the energy losses. This design feature combined with the high-pressure difference between the pressure (top) and suction (bottom) side of the blade will trigger a leakage flow, a secondary flow, through the clearance region [2]. This flow can be a source of cavitation, which in some cases leads to the most aggressive type of erosion. The turbine tip clearance, mentioned early, will initiate two types of cavitation, as shown in Figure 2. The first is known as tip clearance cavitation, which situated on the tip of the runner blade. The second type, which emerges from the turbine tip clearance, is called a tip vortex cavitation. It happens when the leakage flow leaves the clearance a jet is generated. The jet then departs the suction side of the blade and initiate the tip vortex [4].

Cavitation developed in the core of such a vortex can also lead to many adverse effects. It reduces the unit efficiency because the water that flows through the gap will not generate any torque on the runner blades. Also, it produces a severe mechanical erosion of the discharge ring, turbine blades, and draft tube inlet surface. Finally, it causes an increase in the structural vibrations of the generating unit [2, 3, and 4]. All of that can reduce the potential lifetime of the turbine or cause expensive emergency maintenance stops.

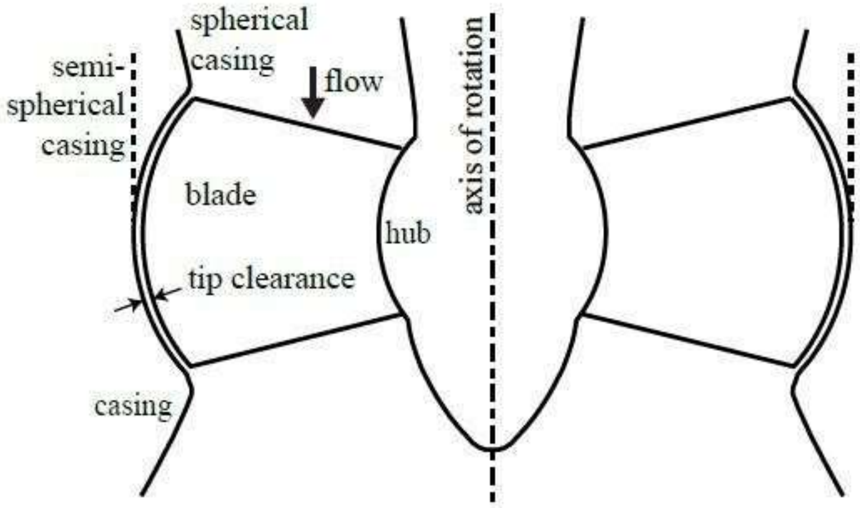

Figure 1: Runner blade and casing in a Kaplan turbine [3].

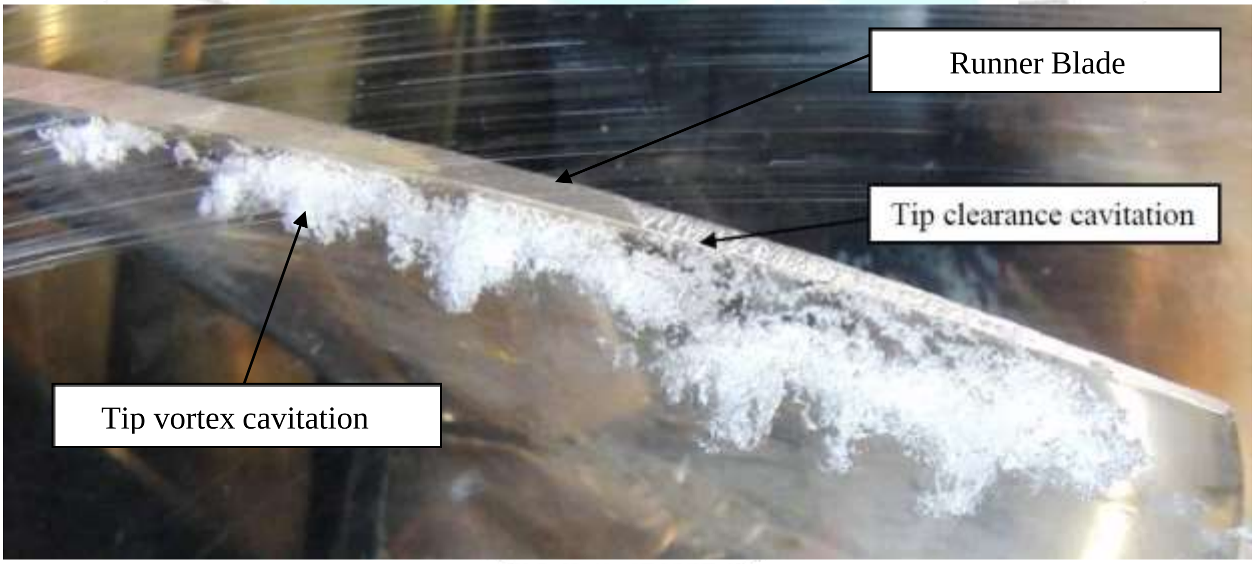

Figure 2: Tip clearance and vortex cavitation in Axial Kaplan Turbine [4].

In many cases, HPP has to operate out of the optimal design point to match the high demand on power or due to the lack of required amounts of water flow in rivers. Operation at off- design will cause the water to exit the runner with a strong vortical (swirling) flow. The existence of swirl gives rise to a strong unsteady draft tube vortex core; this will often cause separations and pressure fluctuations in the draft tube of the unit [1]. Fluid will transport in the outer region while the inner region may contain a stagnation zone or dead water core, as illustrated in Figure 3. The oscillations of the vortex can increase the pressure fluctuations and structural vibrations up to a level that not only will decrease the efficiency but may also cause structural damage to the turbine.

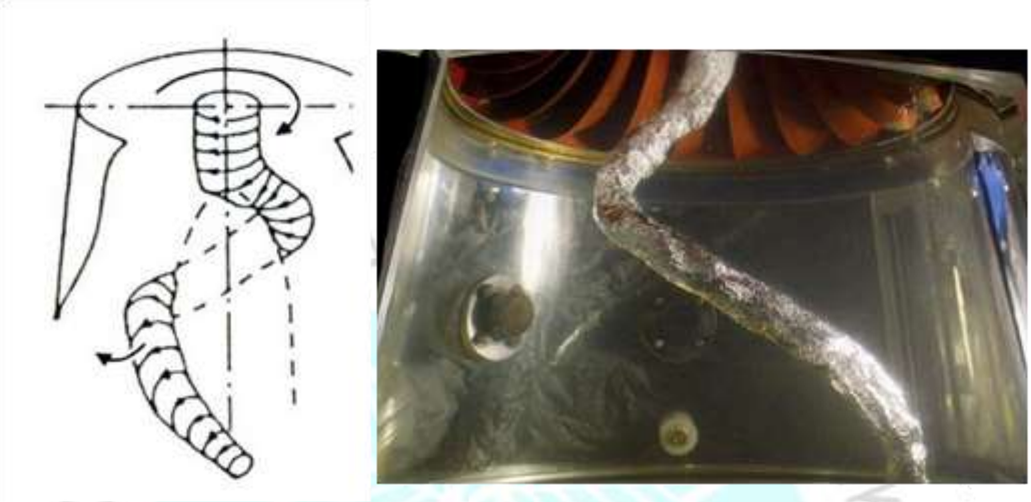

Figure 3: Dead water core (left), and draft tube vortex with a vapor core [1].

Haditha HPP represents a very precise example of the severe adverse effect of cavitation in the hydro plant. This plant is situated on the Euphrates River in Iraq, it contains six vertical type Kaplan turbine, with a unit capacity of 110MW, and currently, it is the largest fully operated hydropower plant in Iraq. Due to the high demand on energy, with the low flow rates in the river, the plant operation regime is mainly out of the optimal design point, and most of the time below the minimum required water head. These operational conditions resulted in very severe damage due to cavitation. This was manifested by the high structural vibration, due mainly to draft tube vortex, which caused numerous fatigue type failure in several mechanical parts, as illustrated in Figure 4. Adding to that the discharge ring and turbine blades severe erosion, due to tip clearance and vortex cavitation, as illustrated in Figure 5.

Figure 4: Runner blade damage (top), and structural cracks in Haditha HPP (bottom) [13].

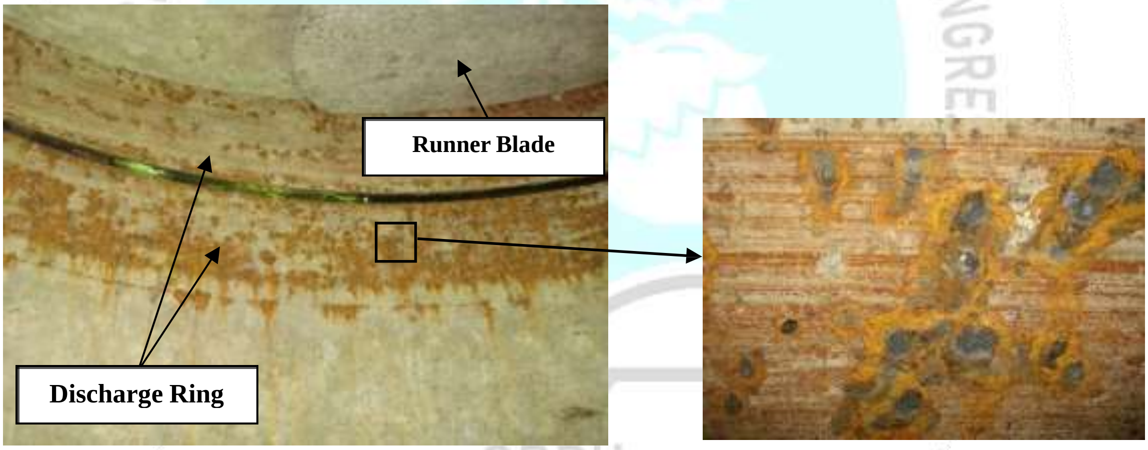

Figure 5: Discharge ring severe erosion in Haditha HPP [14].

Air injection considered to be, in most cases, an effective technique in decreasing the adverse effect of cavitation. The injected air will have a cushioning effect on the higher components of both noise and vibration. Adding to that the possibilities of mitigating the flow instabilities patterns inside the draft tube of the hydro unit [1]. Introducing air into the cavitation zone will decrease the severity of bubble collapse when the bubble reached a high-pressure zone inside the flow. This will reduce the amount of energy released into the surrounding, which causes the erosion in the near metal boundaries, and reduces the shock waves intensity. This work will present the experimental and numerical techniques used in mitigating the effect of cavitation by aeration. The literature review will be presented focusing on the available experimental work conducted on a Kaplan turbine. The reasons for that will be to use this information as a base for the proposed work that will be presented at the end of this work. The proposed work is aimed to be used in Haditha HPP, to reduce the high levels of structural vibration in the generating units. The proposed work will include both experimental and numerical approach to investigate the effectiveness of air injection in the reduction of cavitation adverse effect in general and specifically its effect on the vibration severity.

Air admission systems in conventional hydro turbine (Background):

Air introduced into hydro turbine flow for many reasons. Examples of some intended application include the following [5]:

- Reducing the flow noise, which is the result of continues collapsing of cavities

- Reducing the erosion on the runner blade by reducing the cavitation

- Eliminating the helical (unsteady) flow pattern inside the draft tube

- Increasing the dissolved oxygen (DO) content in water

Choosing the right method for introducing the air into turbine flow is essential for the effectiveness and cost of the aeration system, and for the integrity of the hydro unit in general. Doerfler [5] presented several experimental results, for some studies, related to this subject. His work aimed to provide a data for the optimal layout of Francis turbine aeration systems, from technical and economic aspects. In this work, it was clear that changing the location of the injected air, along with the draft tube, can provide different results about the mitigation of noise, unsteady flow patterns, and cavitation impact on runner blades. The results of these experiments show high effectiveness for the air when it been injected from the draft tube.

Doerfler explained some of the physical aspects behind the air injection techniques and why it’s effective in mitigating cavitation adverse effects. Introducing air inside the flow will create or enlarge cavities. The air injection will have two main effects: The flow will be more compressible, and air will replace low-pressure areas inside the fluid flow. The effect of the additional compressibility is to reduce the flow noise and the erosion effect on the runner blade. The redution will happen by filling the cavities inside the flow with air instead of water vapour. Air will prevent the instantaneous collapse of the cavities inside the flow. This will also be beneficial in cushioning pressure shocks that happens during the transition between different flows patterns inside the draft tube [5].

Reducing cavitation erosion in turbine components can contribute to the improvement of hydropower generation. That’s why it was essential to investigate the effectiveness of air injection on minimizing the metal erosion of the turbine parts, thus minimizing the high cost of emergency and preventive maintenance conducted on turbine parts. Arndt et al. [6] presented experimental work that was conducted on a hydrofoil, NACA 0015, which was intended to measure the pit size on the ductile metal probe attached to the surface, and the rate of this pitting at different cavitation index with flow velocity up to 20 m s-1. To measure the erosion severity, the authors used two techniques; the first was to measure the pit size caused by erosion on the surface of the foil. The second technique was intended to measure the rate of pitting indirectly by measuring the impulsive pressure on the foil surface. The collected results showed that air injection was very effective in reducing the erosion.

The full understanding of the exact mechanism of attenuation for noise, vibration, and erosion due to air injection is important for the development of the aeration system. The main reason for this attenuation comes from the fact that the existence of non-condensable gas, air, inside the cavitation bubble reduces the rate at which the bubble will collapse [7]. A build-up of the non- condensable gas at the interface will create a barrier that the water vapour must diffuse through it to condense on the interface. This will cause additional cushioning of the bubble collapse.

Recently, Simo et al. [8] investigated the influence of non-condensable gas injection on cavitation dynamics. The authors conducted experimental work using a wedge to investigate this type of application, as illustrated in Figure 6. Gas was introduced from the wedge apex and also injected into the mid of the cavity. The results showed that even a small amount of non-condensable gas, injected into the shear layer of a partial cavity, will weaken the periodic nature of the shedding cycle by reducing the vaporization rate of the fluid. This will reduce the void fraction, thus reducing noise and pressure pulsations. This was not the case when the gas was introduced into the mid of the cavity, as illustrated in Figure 7.

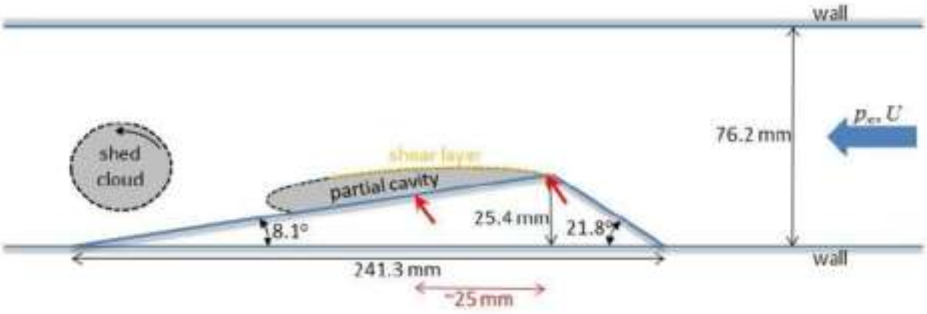

Figure 6: Schematic of the experimental setup Simo et al. [8]. The red arrows indicate the apex and gas injection locations.

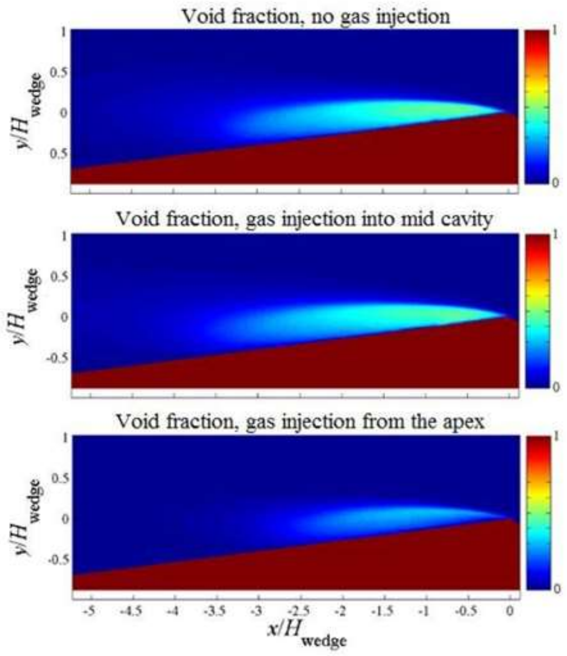

Figure 7: Void fraction with and without gas injection [8].

Air injection has proven to have a potential in mitigating the effects of cavitation, as shown in the above literature. However, its application in conventional hydro turbines is still uncommon, and it has been mainly limited to Francis turbines. Recently, Rivetti et al. [9] conducted an experimental work using air injection aiming to reduce tip cavitation adverse effects in a Kaplan turbine model. The air was injected above the runner centre line using twenty evenly spaced holes that provided with air from a manifold, as shown in Figure 3. The cavitation was induced by manipulating the absolute pressure in the downstream tank, which give a range of cavitation number from σ = 2.26 to σ = 0.66.

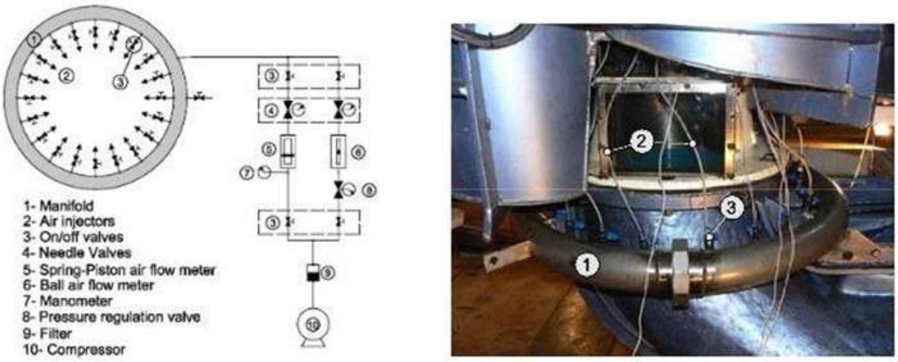

Figure 8: Air injection system on Kaplan model [9].

The result shows a very effective attenuation for the vibration level associated with tip vortex cavitation. The reduction in vibration signals, collected locally by accelerometers, reached up to 57% at some position on the model, Figure 9. The main parameter that should be kept under control is the amount of the air injected into the flow. This can severely impact the efficiency of the generating unit if it reached a high level. The authors kept this amount below 2% of the generating unit flow rate, which gave them a reduction in efficiency up to 0.7%. The authors suggested that an increase of the injected will cause a dramatic decrease in the efficiency, which is in agreement with Doerfler [5] recommendations.

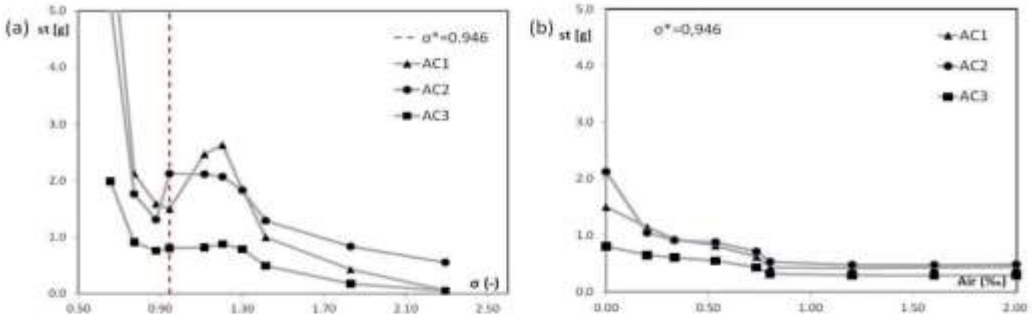

Figure 9: (a) Vibration (standard deviation *st*) vs cavitation number (σ) without air; (b) Vibration with air injection at constant σ. AC1 (accelerometer) location is below the injection plane; AC2 on the blade passage plane; and AC3 at the draft tube inlet [9].

Most of the work conducted to investigate the effect of aeration on the vibration severity, and another adverse effect of cavitation in the conventional hydro turbine was experimental rather than computational. This might be due to the complex nature of flow inside the hydro turbine at off-design operation regimes and the unsteady turbulent flow nature that comes with this kind of operation. Adding to that the process of injecting air inside the unit will make the problem even more complex since it will make the flow a two-phase turbulent flow. However, experimental studies can sometimes be very expensive, especially if it to be implemented on a model, and in some cases, the result from the model will not be completely valid for prototype [10]. That's why accurate numerical simulations, using Computational Fluid Dynamics (CFD) tools, are very useful for the understanding of flow characteristic inside the hydro unit.

Cavitation and turbulent model is essential parts in getting accurate simulation results. Cavitating flow inside the hydro turbine consists of two phases, the water, and the vapour phase. For any CFD simulation to be realistic it should implement a cavitation model, or to be a two-phase simulation [1], however a one phase model without cavitation can give a good insight about the pressure fluctuations inside the unit [4]. When implementing cavitation model, the transition from the fluid phase to vapour phase can be modelled, for a spherical bubble of radius R(t), by using Rayleigh–Plesset equation (1), with the following procedure [1,7]:

$$\frac{p_B(t)-p_\infty(t)}{\rho_L}=R\frac{d^2R}{dt^2}+\frac{3}{2}\left(\frac{dR}{dt}\right)^2+\frac{4\nu_L}{R}\frac{dR}{dt}+\frac{2S}{\rho_L R}\quad ;\; p_B=p_V(t)+p_{GE}(t)\qquad 1$$

Where:

$p_B(t)$ is the internal bubble pressure
$p_V(t)$ the vapor pressure
$p_{GE}(t)$ the partial pressure of the non-condensable gas content
$p_\infty(t)$ the ambient pressure
ρ_L the density of the surrounding liquid
R is the radius of the bubble
ν_L the kinematic viscosity of the surrounding liquid
S is the surface tension of the bubble

The above equation defines the dynamic of growth and decay of the bubbles in the fluid, and its considered to be one of the most used equation for the modeling of complex real cavitating flows, and its implemented under the two-phase framework as an interface mass transfer model [10,11]. Simplification to the version of equation 1 is usually suggested and used by many literature [1,7,10,11], which is:

$$\frac{dR}{dt} = \sqrt{\frac{2}{3}\frac{p_v - p}{\rho}} \quad (2)$$

Equation 2 was a result of the assumptions: $p_B = p_v$; bubbles are filled with saturated vapor continuously, and the second order derivative term, surface tension , viscous term are abbreviated [1,7]. The void fraction can be expressed using the bubble radius R, and assuming a uniform population of n_0 bubbles , as :

$$\alpha = \left(n_0 \frac{4}{3}\pi R^3\right) / \left(1 + n_0 \frac{4}{3}\pi R^3\right) \quad (3)$$

Then the above equations are solved together with the Navier-Stokes equations.

Turbulent model is essential when it comes to the simulation of the complex in hydro unit [12]. The behaviour of the flow at the exit side of the runner and in the draft tube is complex, and its need to be simulated with an accurate model to capture the pressure fluctuations at these areas. The turbulent model will help in identifying the locations of sudden pressure drop, possible cavitation locations, and the sudden pressure rise, bubble collapse. Many turbulent models are available, and the choice should be based on the amount of accuracy vs. the computational cost. A comparison of three turbulent models has been presented by Jošt et al. [10]. This work aimed to predict pressure fluctuations in the Francis turbine draft tube only. This was done with cavitating and non-cavitating models and compared against experimental work. Scale- Adaptive Simulation with Shear Stress Model (SAS-SST), Reynolds Stress Model (RSM), and Large Eddy Simulation (LES) have been used in the numerical simulation. In this work, the authors used the Rayleigh–Plesset model with the homogenous two-phase model, which assumes that transported quantities are the same for the two phases. The result shows that without cavitation model, the result of the three models showed no significant differences in the accuracy. However, when the cavitation model was applied, LES showed higher accuracy than the SAS-SST and RSM models, as shown in Table 1.

Table 1: Numerical and experimental results of pressure pulsation frequency and amplitudes [10].

	Frequency [Hz]	Position 1 *App* [%]	Position 2 *App* [%]
Experiment	3.50	2.77	4.67
SAS-SST, cavitation not modeled	3.26	2.25	3.21
ω-RSM, cavitation not modeled	3.21	2.57	3.23
LES Smagorinsky not modeled	3.12	2.32	2.96
SAS-SST, cavitation modeled	3.32	2.67	2.00
BSL-RSM, cavitation modeled	Results too irregular	Results too irregular	Results too irregular
LES WALE, cavitation modeled	3.55	2.43	3.20

Simulation of cavitating flow, for the entire Francis turbine components, was conducted by Gohil et al. [11]. The main aim was to investigate the effect of cavitation on the performance of the Francis turbine. The authors used the homogenous multiphase model in the CFX commercial code, with the Rayleigh-Plesset model. SST turbulence model has been implemented for the turbulence analysis. The authors mentioned that they used the SST model due to the combined advantageous features of k-ε and k-ω models. However, the result for the hydraulic efficiency shows an error, which they indicate to be the result of the chosen model shown in Figure 10.

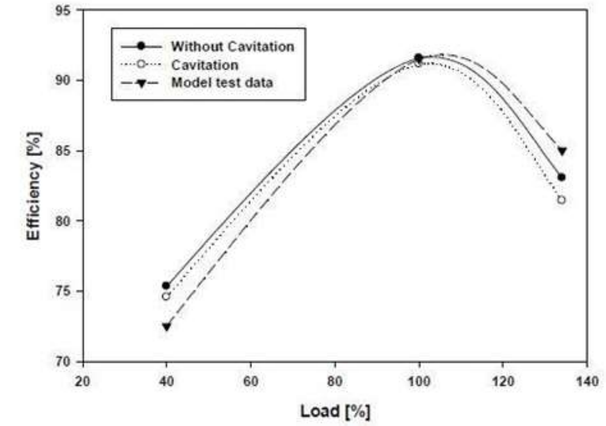

Figure 10: Comparison of performance predicted with CFD against experimental data [11].

When it comes to CFD analysis for turbines with an aeration system; very little work has been conducted [1]. Most of the literature was focusing on understanding the flow pattern inside the turbine passage with and without cavitation models. Yu et al. presented a numerical simulation for a Francis turbine with an aeration system [12]. In this work, the authors conducted a three-dimensional unsteady turbulent flow simulation for the entire passage of a Francis model. The simulation based on homogenous flow assumptions. The aim was to investigate the pressure fluctuation caused by vortex rope, and also the effect of air admission on pressure fluctuations in the draft tube. In the simulation, the author implemented the turbulent model by using both Reynolds-averaged Navier– Stokes (RANS) equations as well as the SST turbulence model. The results show that air injection with a suitable amount of air can dampen the vortical flow and alleviate the pressure fluctuation in the turbine draft tube, as shown in Figure 11.

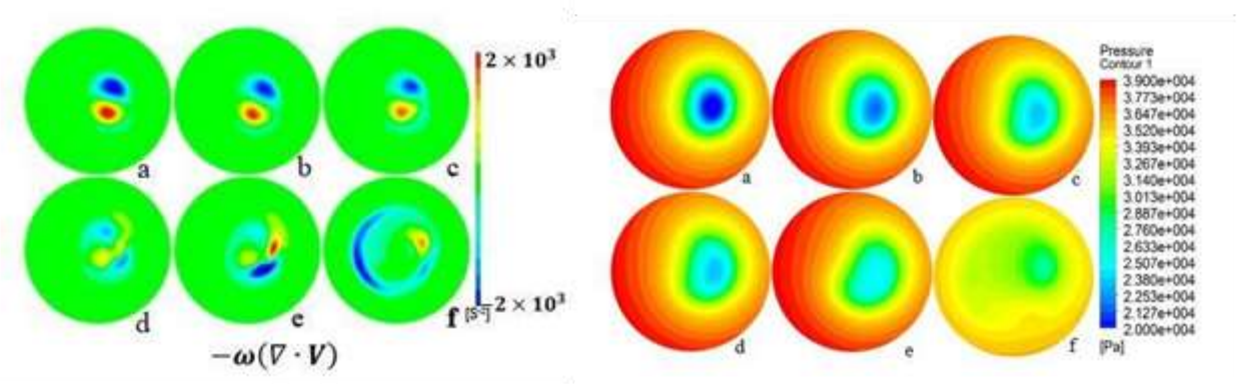

Figure 11: Contours of vortex dilation (left), and Pressure distributions with different air admission[12]:(a) Qair=0,(b)Qair=0.5%, (c) Qair =1%,(d)Qair =2%, (e)Qair =3%, (f)Qair =4% .

Proposed Work:

It has been shown in the air admission system background, that this area is still not fully investigated. Even the few research that was conducted in this area was done on Francis turbines. However Kaplan turbine is still not getting enough work [1, 11]. Therefore, more investigation is needed to understand the effect of an aeration system in the reduction of vibration and another adverse effect of cavitation in Kaplan turbines. This work propose to investigate the effectiveness of pressurized air injection technique, in alleviating the high levels of both vibration and noise in Haditha HPP Kaplan turbine. The technical specifications are shown in Table 2, and Figure 12. The proposed work will be consisting of two parts: an experimental and numerical investigation.

Table 2: Haditha HPP Technical Specifications.

Haditha HPP Technical Specifications	
Operating Head: H_{max}=46.6m……………………………………H_{min}=18m	
Unit Flow Rate: Q @ H_{max}=259 m^3/sec…………………………………. Q @ H_{min}=223 m^3/sec	
Power: P_{max}=110 MW…………………………………P_{min}=33.5 MW	
Runner Diameter=6600mm	Type of Turbine:6-K-50

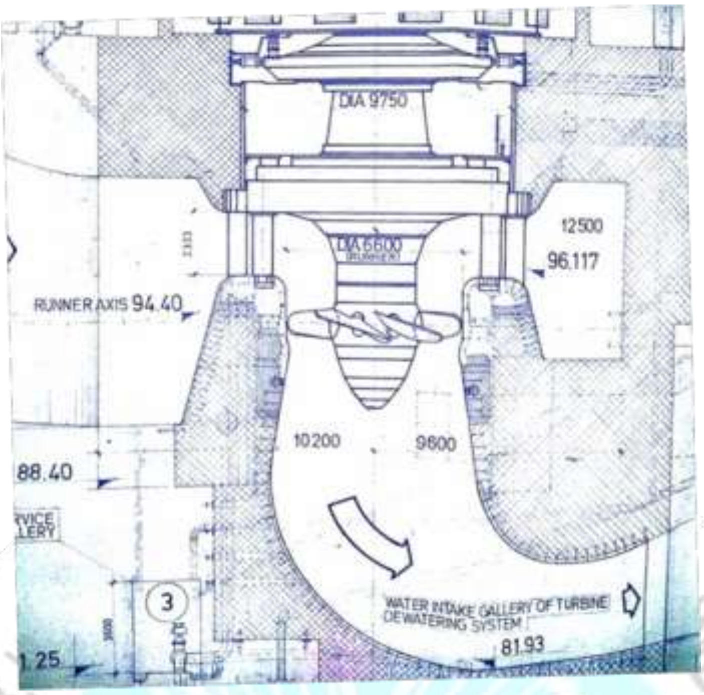

Figure 12: As-Built drawing of Haditha HPP. Image courtesy of Ministry of Electricity\Iraq.

Proposed Experimental Work:

The general components of the proposed experimental work are shown in Figure 13. Unlike previous experimental works, shown in the background part, the air will be injected from two locations: a synchronous condenser existing aeration system, and turbine discharge ring custom made holes. A second air injection location will allow the experiment to be conducted with the flexible setting, with more control over the amount and location of the injected air. This addition will not increase the cost of the experiment because Haditha HPP has an existing air injection system; that was originally intended to be used when operating the unit as a synchronous condenser. The number of the custom-made holes should be increased as much as possible to have a better airflow distribution, which would lessen the amount of air required.

Condition monitoring system will be used to monitor the necessary operational parameters like pressure, vibration levels, and noise. Two sets of data will be collected, one without any air admission, the other with air admission. These two sets will then compare against each other to see the effect of the different air quantity and location combinations on the above measured operational parameters. As mentioned before the amount of air will hurt the efficiency of the unit. Thus, to be able to monitor this factor; all the experimental work will be conducted while the turbine in off- cam operation mode, which is eliminating the governor system from manipulating the runner and wicket gate opening. This will allow the collected data to reflect the effect of the air amount on the generating output of the unit.

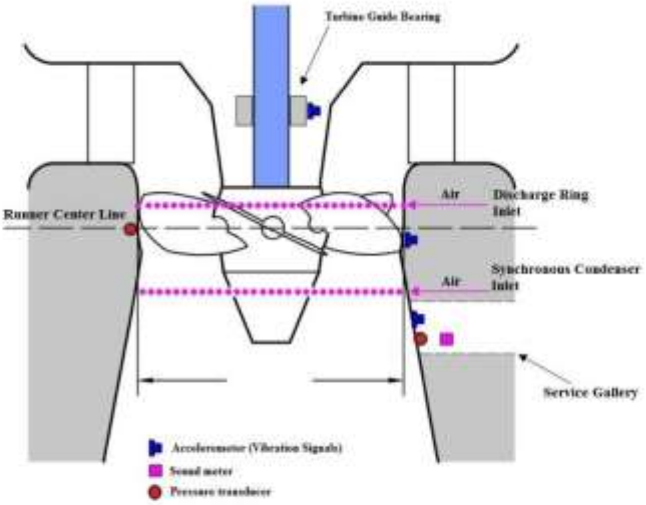

Figure 13: Schematic diagram of the proposed experimental work, showing the condition monitoring system components and air admission locations.

Proposed Numerical Work:

In the numerical work, a CFD simulation will be conducted. Due to the complex nature of the flow inside the hydro unit, adding to that the admission of air inside the flow domain; a three-dimensional two-phase flow model is proposed to be used in the simulation of flow inside the hydro. The CFD model that will be used in this study will be using the Rayleigh-Plesset equation for cavitation modeling. LES turbulent model will be implemented as a turbulent model since it shows much better results in capturing the 3D flow structures. The wall-adapted local eddy- viscosity model (WALE) will be applied as the subgrid-scale (SGS) model in the LES, this will be used to model scales that is less than the grid size. This choice is because this model does not need any wall damping, and because it will not implement any wall functions that will affect the accuracy of the model near the boundaries i.e. the runner and draft tube walls. This fact will be very important to the accuracy of the simulation, since we are very interested in the flow patterns near the wall of turbine different components, especially the draft tube wall. The main aim of the CFD simulations will be to compare the computed pressure fluctuation (low and high regions) inside the flow domain with the ones obtained from the experimental work.

Conclusions

The blade tip vortex cavitation that builds up at Kaplan turbine is one of the major factors behind the increased levels of structural vibration and hence degradation if the mechanical parts of the hydro unit. Different techniques have been used and proposed over the years to mitigate the adverse effect of unit cavitation. In this work the air and water injection techniques have been reviewed and discussed aiming to present a solution for the ongoing mechanical equipment failure in Haditha hydropower plant. The reviewed studies indicated clearly that air admission system implementation in Kaplan turbine is very promising in alleviating the pressure fluctuations inside the unit and the draft tube. This result is reduction in the adverse effects associated with the cavitation without sacrificing the generating capacity of the unit. In this work experimental and numerical approaches were proposed to use air injection in Haditha plant Kaplan turbine to make use of this techniques to give an option for eliminating the ongoing issues in the plant turbines. Condition monitoring system must be used to monitor the required functional parameters like pressure, vibration noise and levels. This approach can help in saving millions of dollars in emergency maintenance and unit outage that is currently lost in the plant to deal with this issue.

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