Evaluation and Analysis of Cavitation Phenomenon in Rosieres Power Plant, Sudan, 2011-2012

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ABSTRACT – Cavitation is one of the serious problems in hydraulic turbines negatively affects their efficiency and may cause damages. Cavitation is a phenomenon which occurs as a pitting of metallic surfaces of turbine parts because of the formation of cavities. In this paper, cavitation in Kaplan turbine unit 2 in Rosieres power plant was studied and analyzed during flood, water restriction and blackout periods. The general features of cavitation were described and cavitation variables were determined in the plant. Cavitation indexes and critical cavitation factors were calculated and compared during these three periods. The results showed that: the turbines were operated within cavitation limit during these periods. Cavitation index was found to be higher in water restriction, while minimum power and drop of pressure, which also increase the possibility of cavities were found in flood and blackout.

Keywords: *Cavitation, Cavitation periods, Cavitation factors, Rosieres dam.*

المستخلص – التكهف أحد العيوب الخطيرة في التوربينات الهيدروليكية التي تؤثر سلبا على كفاءتها وقد يسبب أضرارا فيها. وهو يظهر في شكل تنقر على سطح أجزاء التوربينات مسببا أشكالا مجوفة. في هذه الورقة تمت دراسة وتحليل التكهف في توربين كابلان وحده 2 في محطة كهرباء الرصيرص، أثناء فترات الفيضان وانحسار الماء والإظلام التام . إن السمات العامة لهذه الظاهرة تم توصيفها وتحديد عواملها. كما تم حساب ومقارنة مؤشرات التكهف وعوامله الحرجة في الفترات الثلاثة. أظهرت النتائج إن التوربين يعمل في مدى حد التكهف ، أثناء هذه الفترات. وأن أعلى مؤشر للتكهف وجد في فترة الانحسار بينما وجد اقل قدرة وهبوط في الضغط في فترة الفيضان والإظلام التام وهذا أيضا يزيد من احتمال حدوث التكهف.

Nomenclature:

A	[m^2]	Area of the flow cross-section.	U/S	[m]	Upstream water level
			D/S	[m]	Downstream water level
Q	[m^3s^{-1}]	Discharge	h_{net}	[m]	Net head
V	[ms^{-1}]	Velocity of the flow	h_{gross}	[m]	Gross head
D_2	[m]	Runner diameter.	g	[ms^{-2}]	Acceleration due to gravity
N	[r.p.m]	Rotating machine speed	h_f	[m]	Head losses
N_s	[KWRev s^{-1}]	Specific speed.	σ	[-]	Cavitation index
P_{atm}	[bar]	Atmosphere pressure	σ_c	[-]	Critical cavitation factor
P_{min}	[bar]	Minimum pressure			
P	[kgm^{-3}]	Density of water			
P_w	[MW]	Power			

INTRODUCTION

Cavitation was used to describe the phenomenon of liquid-to- gas and gas-to-liquid phase changes that occur when the local fluid dynamic pressures in the areas of accelerated flow drop below the vapor pressure of the local fluid. The liquid boils and large number of small bubbles mainly formed on account of low pressure are carried by the steam to higher pressure zones. Then the vapor condenses and the bubbles suddenly collapse, as the vapor is condensing to liquid again. These results in formation of cavity and high pressure are repeated many thousand times a second [1-4]. This causes a pitting on the metallic surface of the runner blades, the materials fail by fatigue added by corrosion [5, 6]. There are many efforts regarding the evaluation and the analysis of cavitation in hydropower machines as reported in [1,7]. In this work, cavitation in Kaplan turbines unit 2 in Rosieres power plant was studied. The aim is to determine, evaluate and analyze the factors that cause the pitting cavitation during flood, water restriction and blackout periods.

Literature review

Cavitation commonly occurs in hydraulic turbines, around runner exit and in the draft tube. In general there are two ways to reduce the cavitation damage. One involves optimizing the hydraulic design of equipment; the other involves developing thermally sprayed coating [8,9,10]. Cavitation in general is a slow process but the effect of cavitation is severe. Damages caused by cavitation, if summarized are: erosion of material from turbine parts, distortion of blade angle, loss of efficiency due to erosion/distortion [11]. Thoma suggested a dimensionless number called as Thoma's cavitation factor σ (sigma) or cavitation index, which can be used for determining the region where cavitation takes place in reaction turbines [1]. Cavitation index can be determined by using the following equations:

Bernoulli equation:

$$\frac{V_1^2}{2g} + \frac{P_1}{\rho g} + Z_1 = \frac{V_2^2}{2g} + \frac{P_{\min}}{2g} + Z_2 + h_f \qquad (1)$$

$$h_f = h_{gross} - h_{net} \qquad (2)$$

$$h_{gross} = U/S - D/S \qquad (3)$$

$$\frac{P_{\min}}{\rho g} = \frac{P_2}{\rho g} - \frac{V_2}{2g} - Z \qquad (4)$$

Volume flow rate:

$$Q = A \times V \qquad (5)$$

Cavitation index:

$$\sigma = \left(\frac{P_{atm}}{\rho g} - \frac{P_{\min}}{\rho g} - Z \right) \div h_{net} \qquad (6)$$

Critical cavitation factor for Francis turbine:

$$\sigma_C = 0.625 (N_S / 380.78)^2 \qquad (7)$$

Critical cavitation factor for Propeller turbine:

$$\sigma_C = 0.28 + \left[\frac{1}{7.5} \left(\frac{N_S}{380.78} \right)^2 \right] \qquad (8)$$

Specific speed [12]:

$$N_S = \frac{N \times (0.76 \times P_W)^{0.5}}{h_{net}} \qquad (9)$$

If the value of $\sigma > \sigma_c$ cavitation will not occur in that turbine and cavitation ranges are [13]: The cavitation sound level peak 1, if σ range is 0.12-0.2 b. The cavitation sound level peak 2 if σ range is 0.05-0.3

Cavitation features description

The main cavitation features of the Rosieres power plant are described as follows:

Areas subjected to cavitation

Areas subjected to cavitation in machine runner chamber are: Runner hub**,** blade roots and blade tip as shown in Figure 1.

Cavitation problem

Rosieres power plant suffers from cavitation, abrasion and erosion phenomenon exactly during flood season. The rate of erosion, abrasion by solid particles (debris and sand) and pitting by cavitation is very high. The problem was detected during annual maintenance and this led to low reliability and other problems

Study of cavitation during cavitation periods

This study is carried out during three periods for unit 2 and the plant has seven units. The details of each period are as shown in the next section.

The flood period

This period take a time of 3 months (first of July – end of Sep.) and the units become under the following conditions: average net head 20m , minimum output limit 8 MW and safe out put power 10 MW. The operation of the plant and the output were affected by: grid situation, cleaning by trash rake machine and the blockage of the intake screen. Cavitation index is the major factor to evaluate cavitation phenomenon during this period. Parameters that affect the determination of cavitation index were taken from monitor screen unit 2 and manuals cavitation as in Figure 2 and Figure 3.

Figure 1: Cavitation areas in machine runner chamber

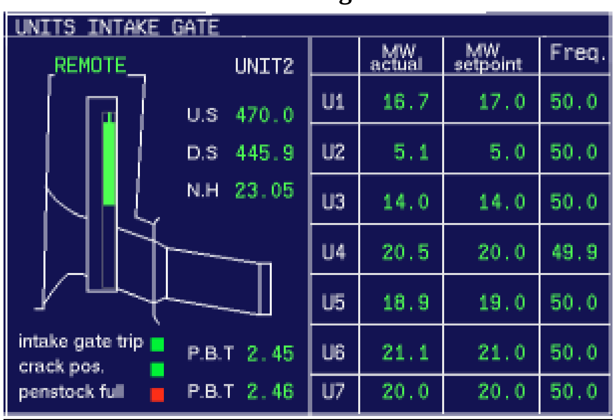

Figure 2: Turbine monitor screen of unit 2 intake gate

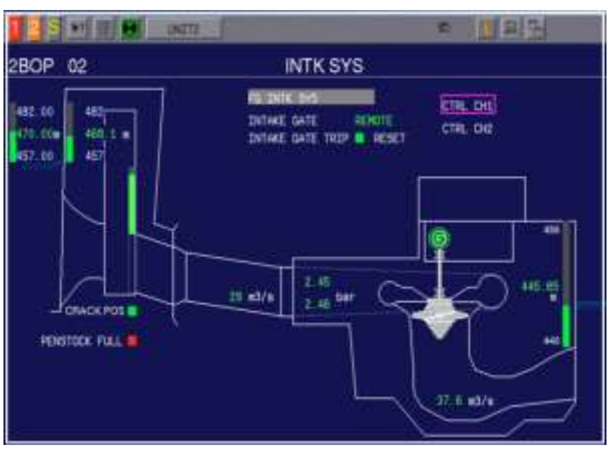

Fig 3: Turbine monitor screen of unit 2 intake system

From Equ (3) and from turbine monitor screen in Figure 2:

$$470.00 - 445.85 = 24.15m$$

$$h_{net} = 23.05m$$

$$h_f = h_{gross} - h_{net}\ 24.15 - 23.05 = 1.1m$$

$$Q = A \times V$$

$$Q_2 = 37.6 m^3/s$$

where D_2 = runner diameter and

$$A_2 \frac{\pi}{4} D_2^{\,2} = \frac{\pi}{4} \times 4.42^2 .$$

From Equ (4) and turbine monitor screen in Figure 3:

$$V_2 = \left(37.6 \Big/ \frac{\pi}{4} \times 4.42^2\right)^{1/2} = 2.45 m/s$$

$$Z = Z_1 - Z_2$$

$$= 444.80 - 438.165 = 6.635m$$

$$P_{\min} = \left(\frac{1.013 \times 10^5}{1020 \times 9.81} - \frac{2.45^2}{2 \times 9.81} - 1.1 - 6.635\right)$$

$$\times 1020 \times 9.81 = 0.208\ bar$$

$$\sigma = \left(\frac{P_{atm}}{\rho g} - \frac{P_{\min}}{\rho g} - Z\right) \div h_{net}$$

$$= (10.1123 - 2.079 - 6.635) \div 23.05 = 0.06099$$

The rotating speed of the turbine is 137.4 r.p.m then NS and σc are [12]:

$$N_S = \frac{N \times (0.76 \times P_W)^{0.5}}{h_{net}}$$

$$= \frac{137.4\left(0.76 \times 10^3 \times 5\right)^{0.5}}{23.05} = 367.46$$

$$\sigma_C = 0.28 + \left[\frac{1}{7.5}\left(\frac{367.46}{380.78}\right)^2\right] = 0.411$$

The water restriction period

This period begins from February up to end of May. The net head during this period is between 25 to 33 m. According to the mentioned head the minimum cavitation limit varies between a load 11 MW and 13 MW respectively. During this period the plant operates daily from early morning hours until the peak hours in minimum load, so these units were operated within cavitation zone or close to cavitation limit. The cavitation index, specific speed and critical cavitation factor can be found as follows (the data was taken from screen monitor and log sheets similar to Figure 2 and Figure 3):

$$h_{gross} = U/S - D/S$$

$$= 468.95 - 443.75 = 25.2\,m$$

$$h_{net} = 24.2\,m$$

$$h_f = h_{gross} - h_{net} = 25.2 - 24.2 = 1m$$

$$Q = A \times V, Q_2 = 50 m^3/s$$

$$A_2 = \frac{\pi}{4} D_2^{\,2} = \frac{\pi}{4} \times 4.42^2$$

$$V_2 = \left(50 \Big/ \frac{\pi}{4} \times 4.42^2\right)^{\frac{1}{2}} = 3.26\,m/s$$

$$Z = Z_1 - Z_2 = 443.75 - 438.165 = 5.59\,m$$

$$P_{\min} = \left(\frac{1.013 \times 10^5}{1020 \times 9.81} - \frac{3.26^2}{2 \times 9.81} - 1 - 5.59\right)$$

$$\times 1020 \times 9.81 = 0.21 bar$$

$$\sigma = \left(\frac{P_{atm}}{\rho g} - \frac{P_{\min}}{\rho g} - Z\right) \div h_{net}$$

$$= (10.33 - 2.14 - 5.59) \div 24.2 = 0.107$$

The blackout period

Beside the above mentioned periods, also the blackout increase the possibility of operation within cavitation because the line was energized with two units on loads less than cavitation limit (at least 15min/blackout). The cavitation index and critical cavitation factor can be calculated as follows (the data was taken from screen monitor and log sheets):

$$h_{gross} = U/S - D/S$$

$$= 469.00 - 448.00 = 21m$$

$$h_{net} = 20\,m$$

$$h_f = h_{gross} - h_{net} = 21 - 20 = 1m$$

$$Q = A \times V,\ Q_2 = 45 m^3/s$$

$$A_2 = \frac{\pi}{4} D_2^{\,2} = \frac{\pi}{4} \times 4.42^2$$

$$V_2 = \left(45 \Big/ \frac{\pi}{4} \times 4.42^2\right)^{1/2} = 2.93 m/s$$

$$Z = Z_1 - Z_2 = 444.80 - 438.165 = 6.635m$$

$$P_{\min} = \left(\frac{1.013 \times 10^5}{1020 \times 9.81} - \frac{2.93^2}{2 \times 9.81} - 6.635 - 1\right)$$

$$\times 1020 \times 9.81 = 0.22\ bar$$

$$\sigma = \left(\frac{P_{atm}}{\rho g} - \frac{P_{\min}}{\rho g} - Z\right) \div h_{net}$$

$$= (10.33 - 2.243 - 6.635) \div 20 = 0.0726$$

$$N_S = \frac{137.4\left(0.76 \times 10^3 \times 4\right)^{0.5}}{20} = 328.66$$

$$\sigma_C = 0.28 + \left[\frac{1}{7.5}\left(\frac{328.66}{380.78}\right)^2\right] = 0.379$$

RESULTS AND DISCUSSION

The variables that affect the cavitation index and critical cavitation factors are tabulated in Table 1. The results of the study are summarized in Table 2. Discussion and analysis of the cavitation attributes and features are as follows:

- Cavitation occurred during the three periods because cavitation indexes are less than critical cavitation factors: 0.06099 <.0.411, 0.107< 0.528 and

- 0.0726 < 0.379 for flood, restriction and blackout periods.
- The cavitation indexes at power 4, 5 and 11 MW are: 0.0726, 0.06099, and 0.107 for blackout, flood, and restriction periods respectively. These values range between 0.05 and 0.3; these limits of cavitation sound level peak 2. So severe damage may occur during this period.
- During water restriction period the machines operate with minimum load, so this units was operated within cavitation zone.
- The maximum critical cavitation factor (0.528) was found to be in the water restriction period, this gives high probability of cavitation failure which may occur during this period. Water restriction has high velocity (3.26 m/s) and high cavitation index (0.107); hence the cavitation failure may occur during this period.
- To minimize pitting cavitation in turbines, cavitation variables such as velocity (3.26 m/s), pressure (22 bar) must be optimized.

Table 2: Cavitation variables

Periods	$\mathbf{P_w}$ (MW)	**Q** (m^3s^{-1})	***P*** (kgm^3)	$\mathbf{P_{atm}}$ (bar)	$\mathbf{H_{gross}}$ (m)	$\mathbf{H_f}$ (m)
Flood season	5	37.6	1020	1.013	24.15	1.1
Water restriction	11	50	1000	1.013	25.2	1
Blackout	4	45	1000	1.013	21	1

Table 3: Results of the study

Period	**A** (m^2)	**V** (ms^{-1})	$\mathbf{P_{min}}$ (bar)	$\mathbf{H_{net}}$ (m)	$\mathbf{N_S}$ (kWRev s^{-1})	σ_c	σ
Flood season	15.35	2.45	0.208	23.05	367.46	0.411	0.06099
Water restriction	15.35	3.26	0.21	24.2	519.13	0.528	0.107
Blackout	15.35	2.93	0.22	20	328.66	0.379	0.0726

CONCLUSION

In this paper, cavitation phenomenon in Rosierres power plant has been studied and analyzed. The areas in turbines subjected to cavitation were described and sever pitting in this areas was found. This study includes three predefined periods: flood, water restriction, and blackout periods. The required data for this study was obtained from turbine screen monitor, log sheets and manuals. Specific speed, cavitation indexes and critical cavitation factors during the three periods were calculated. The results showed that: all machine subjected to cavitation during the three periods with sound level peak 2. The study also, revealed that the values σ_c and σ during water restriction and blackout periods are high, these cause high pitting cavities.

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