S. MARKOVIC

RESEARCH

Cavitational Wear of the Blades of Francis Turbine

The breakdown of the blades inevitably brings about the hydro turbine or the whole power plant outage. The removal of the damage causes long stoppages in work and, accordingly, the coefficient of availability of the system is reduced. Blade breakages are the cause of serious damage in turbines which demand long overhaul processes with high expenditure. All this increases the importance of establishing the causes which bring about the damage of the blades circuit as well of elaborating precautions against their occuurence. The damage implies not only the breakages but also the occurence of the damage (erosion, corrosion, cracks) which demand their repacement or overhaul.

This work describes the harmful effects of cavitational wear upon the lifespan of Francis turbines. Furthermore, there is a concrete example of regeneration of the blades damaged by cavitational erosion.

Keywords: cavitational wear, Francis turbines

1. INTRODUCTION

Cavitation can be the cause of wear of many machinery elements. Above all, this refers to friction bearings, hydraulic systems, pumps, turbines and servo devices but, also, to common machinery elements such as gears. The term cavitational wear refers to the loss of material from surfaces of the elements in relative motion with liquid in the area of implosion (disappearance) of steam bubbles contained in the fluid.

High local pressures and temperatures are created in the area of implosion.

In practise, there are numerous two-phase situations when gas or steam bubbles are surrounded by liquid. Their occurence is related to increase in temperature of motionless liquid or to decrease in ambient pressure in stationary liquid (boiling). But when free gas or steam bubbles appear as a result of relative motion of bodies and liquids, this process is called cavitation. It can be either gas or steam cavitation depending on whether the bubbles are those of gas or steam. From the aspect of tribology, the steam cavitation is more interesting because it causes damage of contact layers of machinery parts [6].

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Cavitational steam bubbles (of the size of a tenth of a millimetre) occur when the pressure in a following liquid drops below the steam pressure. However there are other conditions under which the cores of steam bubbles can occur above this pressure,during liquid flow, naturaly.

The mechanism of cavitational wear itself is of mechanical nature because the products of wear appear as a consequence of fatigue in materials at the places of implosion of steam bubbles. The examination of damaged surfaces of machinery elements points to local hardening of the materials in surface layers and the presence ofcracks characteristic for fatigue in materials. Beside mechanical impact, the presence of corrosion is often evident on surfaces damaged by cavitation. Corrosion plays a very important role in the process cavitational wear [5]. Corrosive effect is far more significant when water is the medium, while in oil systems tais occurence is of much less extent [4].

Beside this, the local increase in temperature in cavitational zone is a factor which has an influence upon destruction of materials. But is, also, a witness to the coplexity of cavitational wear. The speed of cavitational wear can be a hundred time the speed of corrosive destruction of surface layers.

The dissapearence of the formed bubbles commences when pressure in the liquid increases or the bubbles are transferred by folowing to the area where the pressure is higher from the pressure of evaporation. According to this, process of cavitation represents a set of complex occurencies such as creation of empty spaces (bubbles, cavities) their growth, merging, division, pulsations, transferring and implosion (disappearance).

During the creation of the bubbles,a considerable amount of energy is consumed and released instantaneously at their implosion, which is, most probably, the main cause of the damage on the surfaces of the parts. Sound waves particulary ultrasound waves, can cause the so-called vibrational cavitation. The intensity of cavitational wear depends on temperature, the properties of the liquid and material of a machinery part, while the impact of viscosity is negligible [4].

The influence of cavitation can be reduced by increasing the pressure of the liquid in the system, by choice of the construction solutions with reduced gaps which provide less frequent cavitations, by application of materials more resistant to cavitational wear and by selection of lubricants with more convenient characteristics.

2. THE OCCURENCE OF CAVITATION IN HYDRAULIC MACHINERY

In particular places in the working circuit of the hydro turbine there is decrease in pressure during passing of water through the flow-through line can lead to occurence of cavitation. The word “cavitation” is originates from the latin word “cavus” which means “empty, void”. The original meaning of the word describes the essence of process: during liquid flowing there is creation of zones (pockets) with very low pressure which can drop below the critical pressure level, at which steam bubbles are followed, whose implosions bring about gradual damaging of materials and enlarging of cracks in the frame. The physical process of cavitation aroused great interest of the researchers at the beginning of the twentieth century by development of hydraulic turbines. The main reason that the interest in this occurrence has been raised is the fact that cavitation causes undesirable consequences and great damage in hydraulic devices.

Cavitation can be simply explained in the following manner: if in a continuous flow of liquid, the speed is raised from v_1 to v_2 kinetic energy rises and pressure drops from p_1 to p_2. If the pressure drops below the critical level, liquid is transformed into steam which leads to local breaking of continuity of liquid and formation of cavities filled mostly with steam. The surrounding particles of liquid gain great acceleration, bumping against each other and producing a strong blow against the frame [1].

In physical sense, this blow is manifested through abrupt increase in pressure. Since the blows occur very frequently, cavitational fatigue in materials in the impact zone and gradual damaging appear. Once damaged material is suitable for creation of even more unconvenient cavities so that the process of cavitational damage is progressively accelerated.

Cavitation in hydro machinery can be avoided on condition that absolute pressure at each point in the flow-through (p_a) line is higher than the pressure of the saturated steam (p_{vp}), i.e. [1]:

$$p_a > p_{vp}$$

The formed bubbles (phase 1) flows downstream and during its movement it is distorted into a flat form due to resistance (phase 2). Further, the bubble takes the position which allows its shape to move with the least resistance (phase 3). Entering the zone of increased pressure, the bubble (cavity) collapses as a VORTEX TORUS creating high pressures (up to 10^9 Pa). The bubbles in the liquid form pressure pulsations of high frequency. The material surface layers are subjected to fatigue and disintegration as a result of the multiple effects of the spout blow during collapsing of the bubbles and then of an abrupt pressure drop. Cavitational erosion begins by formation of microcracks. Constant blows loosen the grains of the metal structure which are broken down and carried away by the flow of the liquid. Intensive cavitational acting can destroy the surface of the material rapidly.

This condition has a significant role in the choice of equipment. There is an inclination towards finding projection solutions which prevent the occurrence of cavitation because:

- Cavitation can cause serious damage of turbines,
- The efficiency of turbines and their power output are reduced,
- Formation of bubbles and their sudden implosion create characteristic cavitational noise,
- Cavitation makes turbines vibrate which can considerably damage a machine.

3. CAVITATIONAL WEAR OF THE BLADES CIRCUIT OF FRANCIS TURBINE

During exploitation of power plants there may be failures which demand additional checking on condition of the blades circuit of the turbine, which may be exposed to excessive load in particular situations. Besides the examination by non-destructive methods, the stress conditions which occur at failures can be checked by calculation, because establishing of the condition of excessive local tension or even discovering of cracks in proper time can prevent heavy breakdowns.

Cavitational erosion is the most significant consequence of cavitation in hydro turbines. The blades are particularly exposed to destruction. It is almost impossible to avoid destructive impact of liquid. According to the results of examination, it has been established that the greatest destruction of materials occurs because the high-speed microcurrent hits the hard surface at the right angle when the bubble adheres to that surface. The influence of the speed of the current is crucial for the extent of destruction. The presence of abrasive particles in the current intensifies erosive effect (it helps cavitation to occur).

The depth of destruction determines the characteristics of endurance of turbine elements. That is the reason why the depth of destruction for a corresponding period of exploitation has been chosen as a basic criterion in marking the intensity of cavitational erosion under the conditions existing in power plants during exploitation. Considering the deepest cracks, in each blade, the average value of the depth of destruction is calculated according to the formula [3]:

$$h = \frac{h_{\max 1} + h_{\max 2} + ... + h_{\max m}}{m}$$

where indices 1, 2, ..., m - signify the number of blades in the working circuit.

Basically, the intensity of erosion is raised by the increase in turbine power, but the position of erosive zones is essentially changed by the change in power.

Turbine circuits are exposed to hard working conditions and their maintenance should be paid special attention. Maintenance implies not only the repairing of damage, but also the close supervision of the state of circuit and conditions of exploitation, which can be successfully performed only by trained personnel. All damage must be discovered in proper time, supervised systematically and repaired by checked technology either within the planned overhaul of at periodical interventions.

The failures which occur on the wheels during operation comprise: cavitational and erosive damage, as well as fatigue cracks which appear in so-called critical zones.

Certain metals are resistant to cavitation, but none can endure its long-term impact. The basic precaution against cavitation implies prevention of its creation. Unless cavitation can be avoided, metal constructions of hydraulic machinery are made of stainless steel containing 11-18% of chrome and 1-4% of nickel which is more resistant to cavitation [1].

The steel containing 13% of chrome and 4% of nickel has many advantages concerning strength and cavitation resistance, toughness and fatigue strength [2].

The moment when cavitation occurs depends on the quantity of air and solid particles present in the water, so that cavitation can occur even at pressures slightly higher than the pressure of saturated steam.

4. DIAGNOSTICS OF THE BLADES OF FRANCIS TURBINE

In order to discover defects in certain parts of the turbine during exploitation, the following non-destructive methods are used: visual, penetrant (the application of capillary active liquids-penetrants), magnetic, ultrasound, and, in special occasions, the radiographic method and three-dimensional scanning.

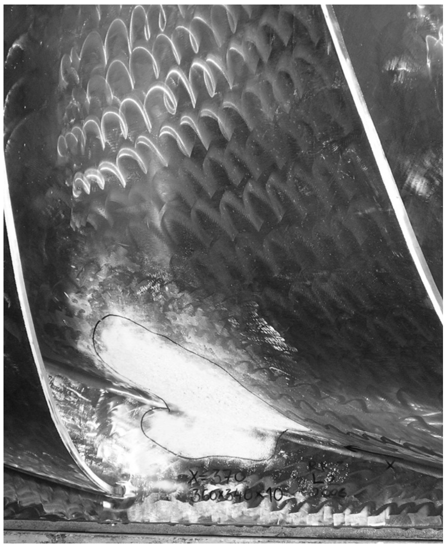
The following damage was noticed by visual examination of accessible surface of the working wheel [3]:

- Cavitational damage of 0.5 mm in depth at the entrance of the working wheel, on the left side of all blades and in the inter-blade spaces on the lower wreath.
- Initial cavitation of 0.5 mm in depth and cavities of 1-2 mm in perimeter and more than 0.5 mm in depth on the left side of the blades No. 4, 5, 6, 7, 8, 9, 11 an13.
- The zones with cavitational damage of considerable depth (up to 10 mm) and extent were seen on the back of the blades. This refers to the blade No. 2 (the depth of cavitational damage up to 10 mm), No. 3 (the depth of cavitational damage up to 8 mm), No. 10 (the depth of cavitational damage up 7 mm), and No. 12 (the depth of cavitational damage up to 4 mm).

Picture 1. The turbine rotor on the shaft

Picture 2. Cavitational damage on the back of the blade No. 7

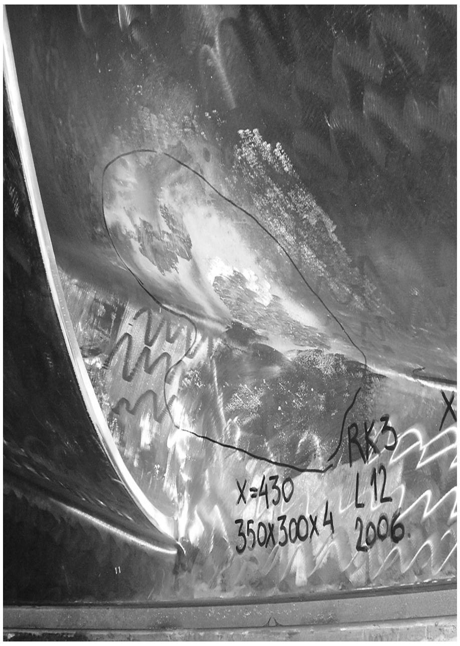
Picture 3. Cavitational damage on the back of the blade No. 13



Picture 4. Cavitational damage on the back of the blade No. 2

Picture 5. Cavitational damage on the back of the blade No. 3

Picture 6. Cavitational damage on the back of the blade No. 10



Picture 7. Cavitational damage on the back of the blade No. 12

5. REGENERATION OF WORN OUT BLADES

The places with cavitational damage of the perimeter 1-2 mm and deeper than 0.5 mm were first "opened" by grinding down to healthy material and in such a way prepared for built-up welding. This was done with the blades No. 4, 5, 6, 7, 8, 9, 11 and 13.

All the places with cavitational damage of greater depths (up to 12 mm) and extents, noticed on the blades No. 2, 3, 10 and 12, were ground down to healthy material and prepared for built-up welding.

Cavitational damage at the entrance of the working wheel was first ground by grinding wheel and then polished by sandpaper (grain size 60-120 μm), until gained metallic shine [3].

After the shaping, the ground parts were welded. They were subjected to built-up welding by the electrode Piva 29/9 R (29% Cr and 9% Ni), perimeter ϕ2.5 mm and ϕ3.25 mm, by ARC procedure without preheating.

Built-up welding was done at 1-2 mm above the surface of the blades. This layer was ground and polished down to the specified geometry and surface quality ($R_a \leq 16$ μm).

The electrode used has the following chemical and mechanical characteristics:

Chemical composition of the pure built-up welding seam

Manufacturer	Electrode sign	C (%)	Mn (%)	Cr (%)	Ni (%)	Si (%)	Mo (%)
The factory of electrodes Pluzine	PIVA 29/9 R	0,15	1,2	29	9	-	-

Mechanical characteristics of the pure built-up welding seam

Manufacturer	Electrode sign	$R_{p0.2}$ (MPa)	R_m (MPa)	A_5 (%)
The factory of electrodes Pluzine	PIVA 29/9 R	500	740-840	20

6. CONCLUSION

Cavitation can provoke the following undesirable effects:

- It changes the structure of currents in the rotating circuit, since the cavitational bubble closes the flow- through space between the blades partly or completely.
- The energetic characteristics of the turbine are worsened. The turbine power is decreased due to lowering of efficiency and flowing-through and ancreased losses in the circuit.
- The creation of cavitation makes characteristic cavitational noise.
- Cavitational implosions damage the walls of the flow-through line and destroy their metal structure – cavitational erosion.
- Cavitational blows cause vibrations of hydro aggregates and of the power plant itself. During this process, the elements of the turbine develop the cracks which can bring about considerable damage to the machine.

All above mentioned consequences of cavitation point to the necessity of avoiding it. This is why it is necessary to know what brings about the creation of steam bubbles in the liquid flow of hydraulic turbines and the ways to avoid harmful cavitational conditions.

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