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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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НАУЧНО-ТЕХНИЧЕСКАЯ КОНФЕРЕНЦИЯ

на тему

ПРОБЛЕМЫ ГИДРАВЛИЧЕСКИХ ТУРБОМАШИН

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Effects of Cavitation in Hydraulic Machines

The paper has the character of a review. It is based on the results of own and foreign research. Information is presented on energy effects of cavitation, which manifest themselves by a collapse of the machine performance characteristics. Information concerning dynamic influences which destabilize the flow, generate vibrations and noise and cause damaging of the machines (erosion, cracks), is also given.

1. Introduction

The development of hydraulic turbomachines is characterized by a constant increase of their specific speed and unit power. Cavitation is one of the barriers to this development. It occurs in places at which pressure in the liquid decreases to a value near the saturated vapour pressure p_v at a given temperature. This occurs, first of all, in suction areas and flow channels of runners/impellers and guide rings. Favourable conditions for creating cavitation are: high suction heads, high liquid velocities, sudden changes of flow direction, incorrect conditions of runner/impeller supply and separation of streamlines from the walls forming the flow boundaries. In order to evaluate the danger of occurrence of cavitation and the degree of cavitation development inside machines the Thoma number is commonly used

$$\sigma_{Th} = \frac{\mathrm{NPSH}}{H} \propto n_{SQ}^{4/3}$$

where NPSH is the net positive suction head, H — total head, n_{SQ} — specific speed of machine ($n_{SQ} = nQ^{1/2}/H^{3/4}$), n — runner/impeller speed, Q — flow intensity. The relationship between the number σ_{Th} and specific speed n_{SQ} for pumps and turbines is shown in Figs 1 and 2 [6]. It should be mentioned here that as a rule pumps are more sensitive to cavitation than water turbines. This is proved by higher σ values for machines of similar specific speed, and higher cavitation intensity in pump operation of reversible machines than in their turbine operation ($\sigma_{turbine} \approx 0.7\sigma_{pump}$). In order to prevent cavitation in a machine, the following condition must be fulfilled

$$\sigma_{permis.} < \sigma_{inst}$$

where $\sigma_{inst.}$ is the cavitation number of installation (power plant). The number σ_{inst} can

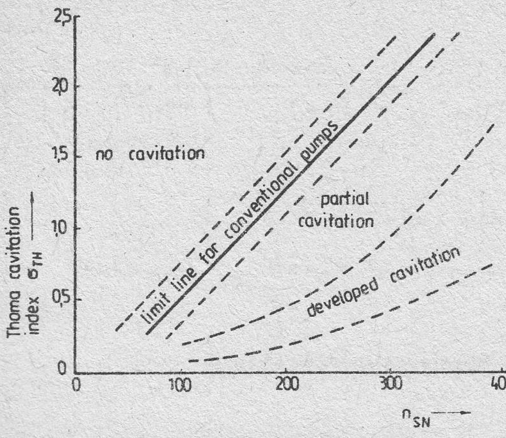

Fig. 1. Specific speed influence on cavitation properties of impeller pumps

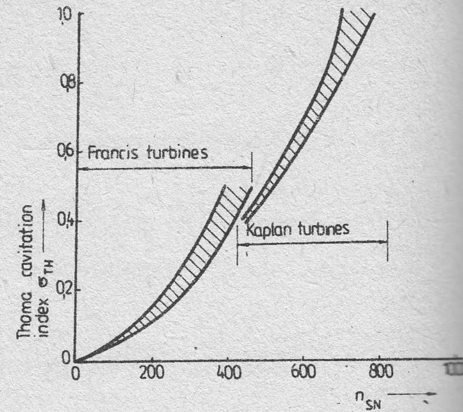

Fig. 2. Specific speed influence on cavitation properties of water turbines (Francis and Kaplan)

be calculated from the formula:

$$\sigma_{inst} = \frac{H_b - H_v - H_s}{H}$$

in which H_b is the atmospheric pressure head measured at the tail water free surface, H_s — suction head (distance between the element exposed to cavitation and the tail water free surface), H_v — liquid evaporation pressure head.

To prevent cavitation, first of all limitations are put on the suction head, and the following condition should be fulfilled:

$$H_s < H_b - H_v - \sigma_{permis.} H.$$

In practice this condition is not always met. Generally, in presently designed and built high power hydro plants, operation of hydraulic machines in the so called controlled cavitation range is accepted. This is done for reasons of economy, i.e. in order to lower the cost of building the plant by situating the machine foundation higher. In most cases, operation in the controlled cavitation range has no negative influence on energy exchange in the flow and does not cause significant erosion damage.

However, cavitation often influences the machine performance properties, generates vibrations of the walls forming flow boundaries and is the reason of noise and cavitation erosion. The magnitude of these symptoms depends on the degree of cavitation development and on structural features and machine operation parameters. At high intensity of the phenomenon and low resistance of structural materials, damages leading even to the damage of the machine itself should be expected. In Table 1 quantitative information concerning damages of water turbines and reversible machines in 28 U.S. hydro plants are presented [5]. It may be concluded that the main reason of the damages were cavitation and vibrations. It also may be supposed that some part of the cracks of important machine elements occurred due to cavitation.

Nearly all turbines and reversible machines in Polish high power hydro plants are exposed to cavitation. As an example may serve reversible machines in the hydro

Table 1

Damages in 28 U.S. hydro plants (generating capacity 27400 MVA, data from the years 1928-1982)

Type of turbine	Total		P	F	F	PT	PT	K
Range of head in meters; from			300	128	25	150	·	
to				210	100		150	30
Number of turbines	195	100%	6	25	49	22	16	77
Material								
Welded runner	24	12%	—	3	18	3	—	—
Cast steel runner	147	75%	—	22	31	9	8	77
Cast stainless steel runner	24	12%	6	—	—	10	8	—
Padded runner with stainless padding weld	35	18%	—	21	—	6	8	—
Guide ring vanes — steel	185	95%	—	25	49	18	16	77
Guide ring vanes — stainless steel	4	2%	—	—	—	—	—	—
Damages								
Vibrations in general	62	32%	—	—	4	8	8	42
Vibrations at optimum opening	28	14%	—	5	8	11	—	4
Intense cavitation	9	5%	—	2	—	7	—	—
Moderate cavitation	24	12%	—	1	3	4	8	8
Slightly developed cavitation	65	33%	—	3	21	3	—	38
Impermissible deformations	3	1.5%	—	—	—	3	—	—
Surface cracking in more important parts	30	15%	—	—	11	3	16	—
Cracks or breaking of more important parts	17	8%	—	2	—	15	—	—
Replacement of more important parts	9	5%	—	6	—	3	—	—
Repairs by welding								
— not required	13	7%	2	—	1	2	8	—
— no recognition	30	15%	4	—	13	13	—	—
— every 1 year	18	9%	—	5	6	7	—	—
— every 2 years	15	8%	—	3	—	—	8	4
— every 3—5 years	98	50%	—	—	29	—	—	69
— every 5—10 years	21	11%	—	17	—	—	—	4

Explanations: P — Pelton turbine
F — Francis turbine
PT — reversible machine (pump/turbine)
K — Kaplan turbine

plants at Solina, Żydowo, Porąbka-Żar and Żarnowiec and Kaplan turbines in the hydro plants at Żur and Koronowo. In thermal power plants, steam boiler supply pumps are most exposed to cavitation. Cavitation damages occur mainly within the first stage.

In general, it should be stated that development of hydraulic machines and also their durability and performance efficiency, are closely connected with cavitation. Therefore increasing attention is given to this phenomenon, especially to the methods of preventing the negative effects of cavitation. For this aim, it is proposed [5] to use well tested design and materials, to carry out periodical inspections and repairs and to operate the machines basing on the knowledge of the cavitation process.

This paper presents a review of the negative effects of cavitation occurring in hydraulic machines. The basis of the review have been the results of research carried out by the Department of Fluid Dynamics of the Institute of Fluid-Flow Machinery in Gdańsk and foreign research.

2. Negative Influence of Cavitation

2.1. Performance effects

The performance effects manifest themselves by a break-down in the characteristic curves. This concerns mainly the decrease in the discharge, head and efficiency of pumps, and decrease in power and efficiency of water turbines. As an example may serve break-downs in pump characteristics $H(Q)$ and $\eta(Q)$ shown in Fig. 3 [6]. They are closely connected with the pump suction head (represented in the figure by the dynamic head NPSH).

The influence of cavitation on energy exchange in the machine is visible at deve-

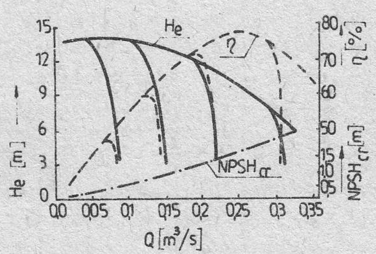

Fig. 3. Deformations of impeller pump characteristics caused by cavitation

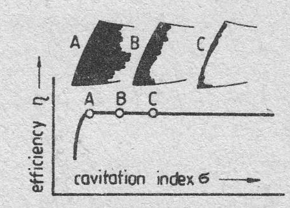

Fig. 4. Relationship between the area of cavitation and machine efficiency

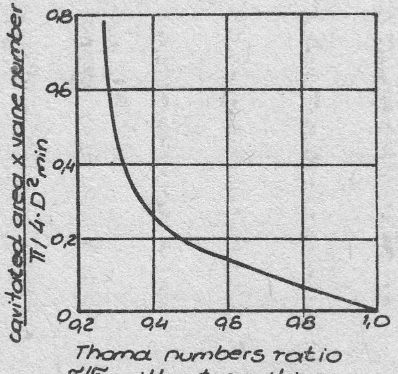

Fig. 5. Propagation of a cavitation cloud on a reversible machine blade (suction side)

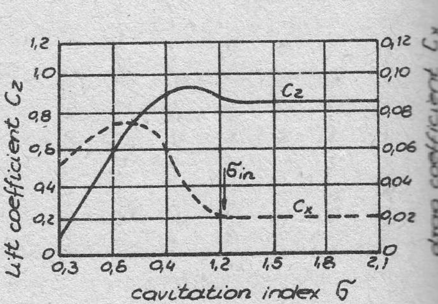

Fig. 6. Influence of the degree of cavitation development on the change of the lift c_z and drag c_x coefficient for a Clark Y 11.7 profile [4]

oped cavitation. The relationship between the cavitation pattern and the efficiency of energy conversion is shown in Fig. 4. The figure shows also that the area in which cavitation occurs increases with the decrease of pressure in the flow. In consequence of these changes the interblade channels may become blocked by the cavitation cloud.

Therefore, as the pressure becomes lower the area covered by cavitation grows larger [2], flow resistance increases and the aerodynamic lift decreases [4]. This is illustrated in Figs 5 and 6.

It should be mentioned here that the values of σ_{crit}, corresponding to the beginning of the changes in performance parameters, are as a rule smaller than the values of σ_i corresponding to the initiation of the phenomenon and of $\sigma_{erosion\,init.}$ corresponding to the occurrence of erosion, i.e.

$$\sigma_{crit} < \sigma_{erosion\,init} < \sigma_i.$$

Strict relations between these indices depend not only on machine structure and conditions of machine operation, but also on the kind and state of liquid and on the physical, chemical and structural properties of the material.

2.2. Acoustic symptoms

Operation of hydraulic machines under developed cavitation conditions is undesirable because of the performance and dynamic effects. Some of them, e.g. noise, appear at various stages of cavitation, i.e. at different σ values. However, the highest noise level occurs in the range of performance effects. For example, in Fig. 7 there

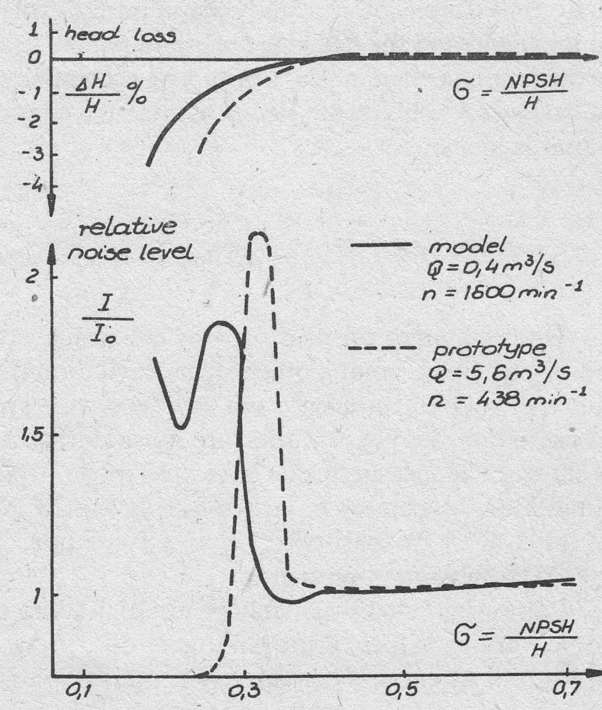

Fig. 7. Model test results for the prototype of the Superphenix pump [1]

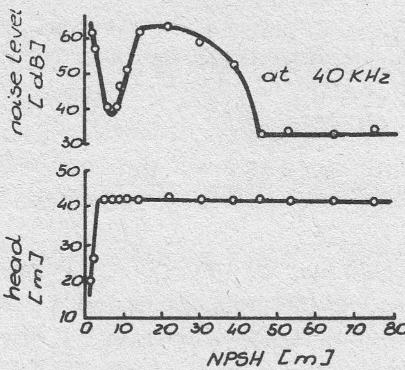

Fig. 8. Influence of cavitation in a pump on its efficiency and noise [6]

are presented results of model and prototype test of a Superphenix pump designed for pumping sodium in fast breeder reactors [1]. Other authors (e.g. G. Sebestyen et al [8]) present a somewhat different picture of noise level variation versus NPSH. To the last group belong also W. M. Deeprose et al [6], who point to the fact that acoustic signals appear in the earlier stages of cavitation development, attaining peak value before the collapse of characteristic curves (Fig. 8). Own investigations [11, 12], confirm that cavitation noise appears at weakly developed cavitation, and that its level increases while approaching the collapse point of the characteristic curves. It is supposed that disagreements presented here are caused by differing conditions in which the tests were performed, especially by different conditions of acoustic radiaton measurement. Certainly, an important role is also played by the gas content in the liquid and the machine operation parameters. It is known that dynamic phenomena (impingement, noise, vibrations), accompanying the growth and disappearance of cavitation bubbles, are stronger when the gas content is lower and pressure in the liquid is higher.

2.3. Impingement and vibrations

Water hammer effects caused by collapsing cavitation bubbles and pressure pulsations resulting, among others, from cavitation cloud movement, collision and restitution of bubbles, turbulence and flow separation are the reason for dynamic symptoms of cavitation. In Fig. 9 a pressure pulse during a single cavitation bubble collapse is shown. The measurements have been made [3] in the laboratory of the Institute of Fluid-Flow Machinery in Gdańsk, using a PCB Piezotronics piezoelectric transducer of 0.145 mV/kPa sensitivity, 1.4 kPa resolution, 500 kHz resonance frequency and 100 MPa maximum pressure.

Pulses generated by cavitation are of random character. Histograms of such pulses at various values of the parameter describing the state of the system are shown in Fig. 10. Attention is drawn to the marked variability of the number and value of

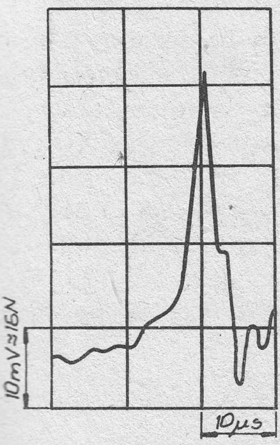

Fig. 9. Single cavitation pulse (IF-FM Lab.)

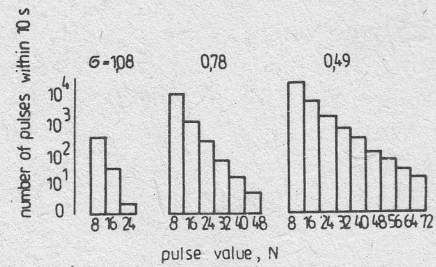

Fig. 10. Cavitation pulse histograms (IF-FM Lab.)

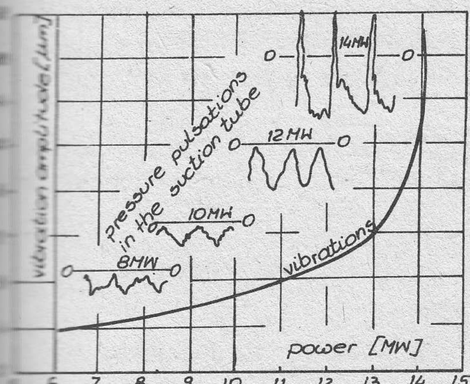

Fig. 11. Vibrations vs power for a Kaplan turbine casing; Koronowo Water Power Plant

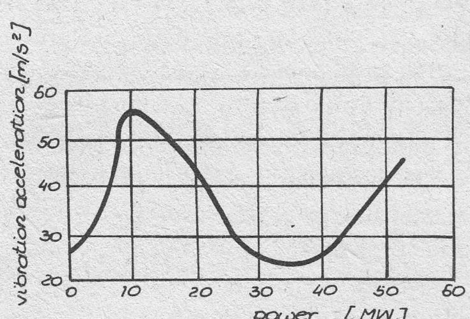

Fig. 12. Vibration acceleration of reversible machine suction pipe at turbine operation; pumped-storage hydro plant at Żydowo

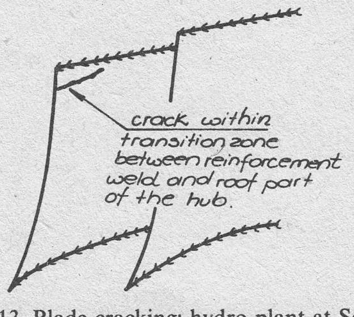

Fig. 13. Blade cracking; hydro plant at Solina

pulses depending on the cavitation index σ*. They may be taken as a measure of cavitation intensity, and the direct reason of the vibrations and erosion of walls forming fluid flow boundaries. As an example one may use vibrations observed in the Kaplan turbine of the hydro electric power plant at Koronowo (Fig. 11) and in the reversible machine of the pumped-storage power plant at Żydowo (Fig. 12). The quickly growing level of vibrations in the Kaplan turbine at $P > 13$ MW is worth noting. This phenomenon correlates well with the pressure pulses downstream of the turbine runner (curves shown in Fig. 11) and audiovisual observations [11].

Vibrations may result in fractures of the guide vanes and runner/impeller blades (Fig. 13).

2.4. Cavitation erosion

According to the data given in Table 1 and Hydro-Quebec information published by R. Simoneau [9], cavitation erosion is the most often observed symptom of cavitation. The data published by Simoneau give the following picture for Canada:
— 68 cast iron and cast carbon steel Francis turbines of 1 to 10 MW unit power show small cavitation damage,
— 55 Francis turbines and 6 propeller turbines made from cast iron and cast carbon steel, of 10 to 30 MW unit power, show moderate cavitation damage (repairs consist in padding with stainless steel),
— 10 propeller turbines, 14 Kaplan turbines and 146 Francis turbines from cast martensitic or carbon steel covered with stainless steel, of 30 to 333 MW unit power and total power of 20000 MW show severe cavitation damages.

Medium erosion of carbon steel, specially in the carbon steel/stainless steel transition areas is between 0.2 and 2 mm/year and occurs on surface areas up to 4 m². Intensive erosion, at heads $H > 30$ m, occurs on small areas (from 0.1 to 0.7 m²) ranging between 0.5 and 3 mm/year. Erosion intensity of 10 mm/year is also sometimes observed. Specially disadvantageous erosion occurs in machines which are repaired too late (e.g. after 10 years). In such cases erosion losses attain 3 to 8 mm^3/MWh.

In Figs 14, 15 and 16 are presented photographs showing cavitation damages in a Francis turbine (hydro plant at Gródek), Kaplan turbine (hydro plant at Koronowo) and reversible hydraulic machine (hydro plant at Żydowo). These examples and data given in Table 2 give evidence of the magnitude of damages occurring in the Polish hydro electric power plants.

The course of cavitation erosion is determined by the cavitation load level, the ability of material to resist this load (cavitation resistance of material) and by the duration of material exposure to the phenomenon. Cavitation destruction is strongly influenced by corrosion which significantly hastens decohesive processes.

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* $\sigma = 2(p_\infty - p_v)/\varrho v_\infty^2$, where p_∞ and v_∞ are the pressure and velocity at undisturbed flow, p_v is the evaporation pressure of liquid of density ρ.

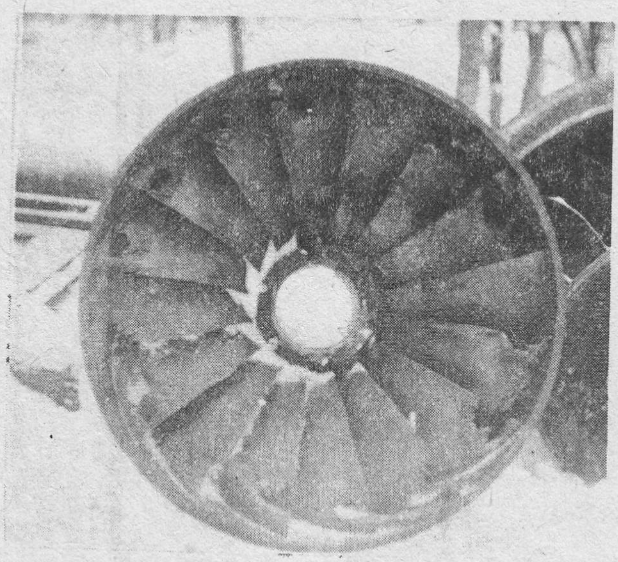


Fig. 14. Francis runner at Gródek Water Power Plant after seven years of operation; blades made of carbon steel

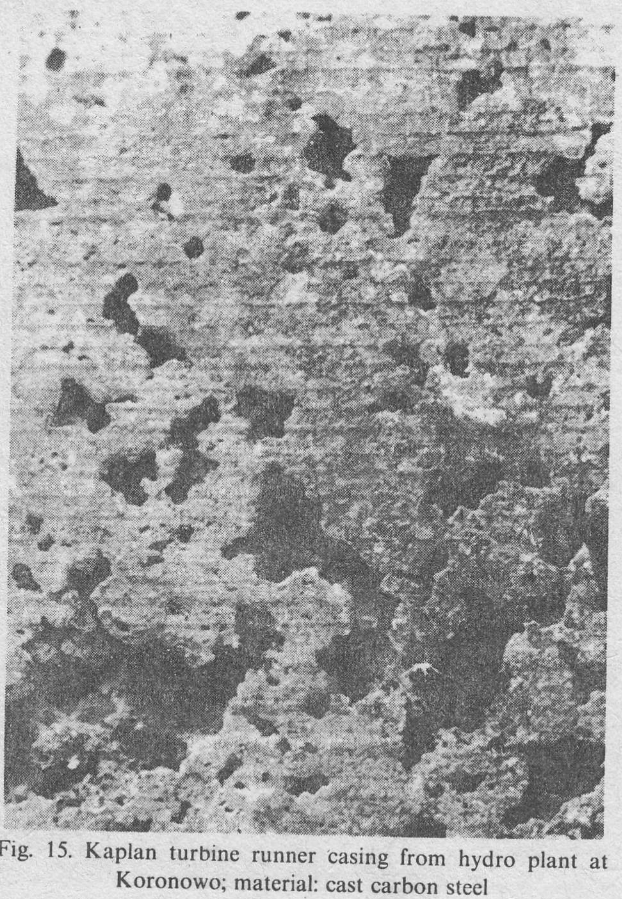
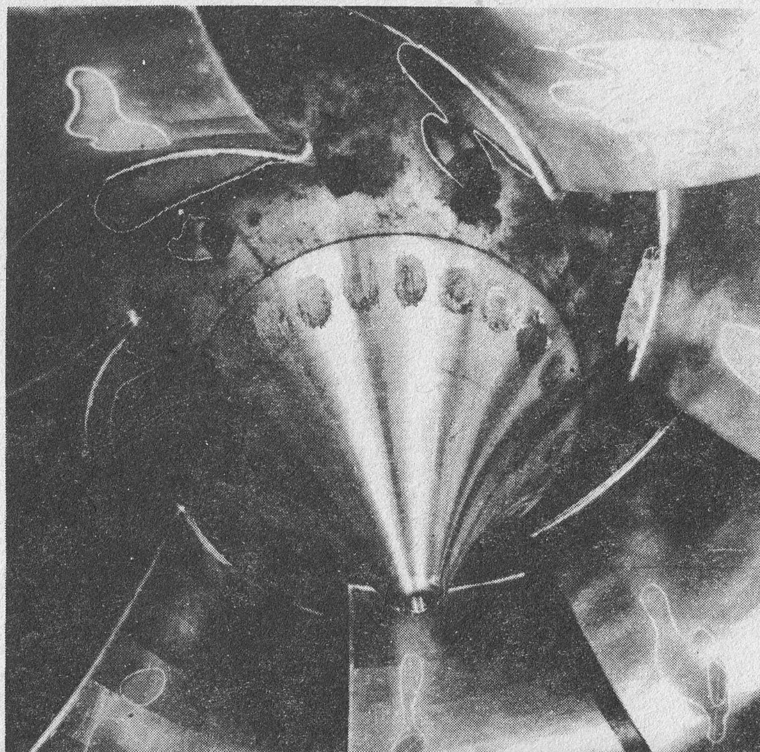


Fig. 15. Kaplan turbine runner casing from hydro plant at Koronowo; material: cast carbon steel

a)



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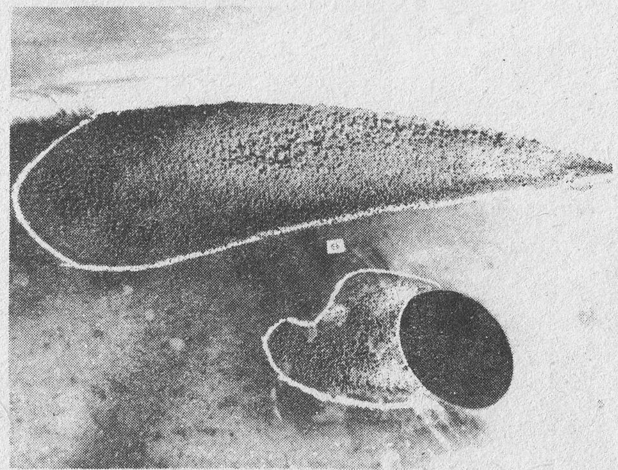

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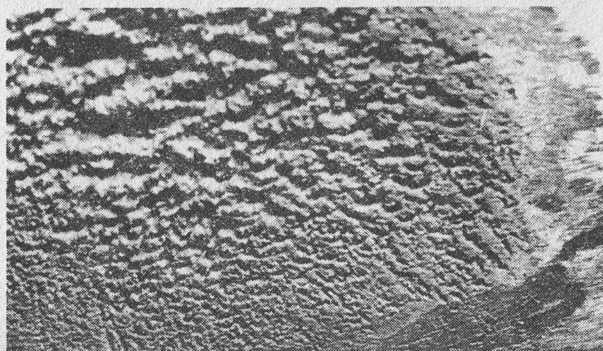

Fig. 16. Reversible machine runner from hydro plant at Żydowo; a) general view, b) part of damaged hub (cast manganese steel), c) part of damaged blade (cast chromium-nickel steel)

Table 2

Cavitation Damages in Reversible Machines at Żydowo

Location of damage	Time of operation of generating set in hours	Cavitation pitting depth in mm	
		local maximum	local average
runner blades	8624	1.0 ... 3.2	0.2 ... 2.5
guide vanes	9935	1.0 ... 6.0	0.6 ... 4.0
runner hub	8624	4.0 ... 11.5	3.0 ... 5.0
runner hub	11467	4.0 ... 22.5	3.5 ... 12.0

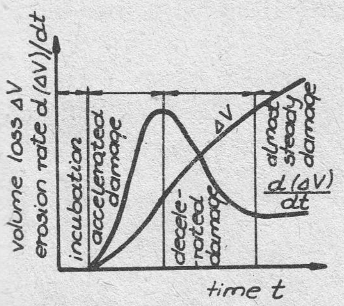

Fig. 17. Typical course of cavitation damage

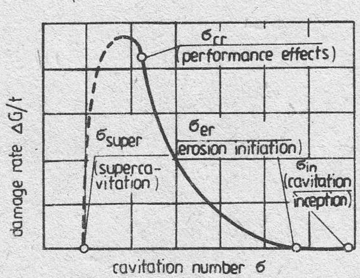

Fig. 18. Cavitation erosion in a model pump in dependence on the σ number

A typical erosion course versus time is shown in Fig. 17. Possible modifications of this course result from varying properties of material and from differences in the type and degree of development of cavitation. The influence of the degree of cavitation development in a centrifugal pump on the damage rate of pump elements is shown in Fig. 18 [2]. It may be concluded that the largest load exerted on the material appears during developed cavitation, and that the beginning of erosion is connected with weakly developed or moderate cavitation.

At present, correct forecasting of structural material behaviour in a machine exposed to cavitation is impossible. At the most, basing on model tests, we can indicate places endangered by cavitation erosion. Therefore, it is attempted to evaluate cavitation damages using various simplifying assumptions and comparative studies. A method of forecasting damage in a machine was developed at the Institute of Fluid-Flow Machinery in Gdańsk. The method is based on results of material sample tests performed under known cavitation conditions and on the knowledge of cavitation loads [13]. Using this method and the additional assumptions that the resistance and the energy absorption efficiency of the material are similar under natural (P) and laboratory (L) conditions, the average durability of material may be evaluated from the formula:

$$\delta_P = \delta_M \left(\frac{H_M}{H_P}\right)^{\alpha} \left(\frac{D_M}{D_P}\right)^{\beta}$$

where H is the head and D is the runner/impeller diameter. Preliminary investigations indicate that exponents α and β attain values between 2 and 3.

3. Counteracting the Negative Effects of Cavitation

In order to prevent cavitation or decrease its negative effects, design, process engineering, installation and operational methods may be used.

The design methods consist mainly in forming such flow channels that kinematically optimum streamline pattern is obtained and in using profiles of low susceptibility to cavitation. Special devices used for changing the flow field in the area exposed to cavitation also belong to this type of methods. An example are the "anticavitation strips" (Fig. 19) used in the Kaplan turbines and ejectors or inducers used in centrifugal pumps.

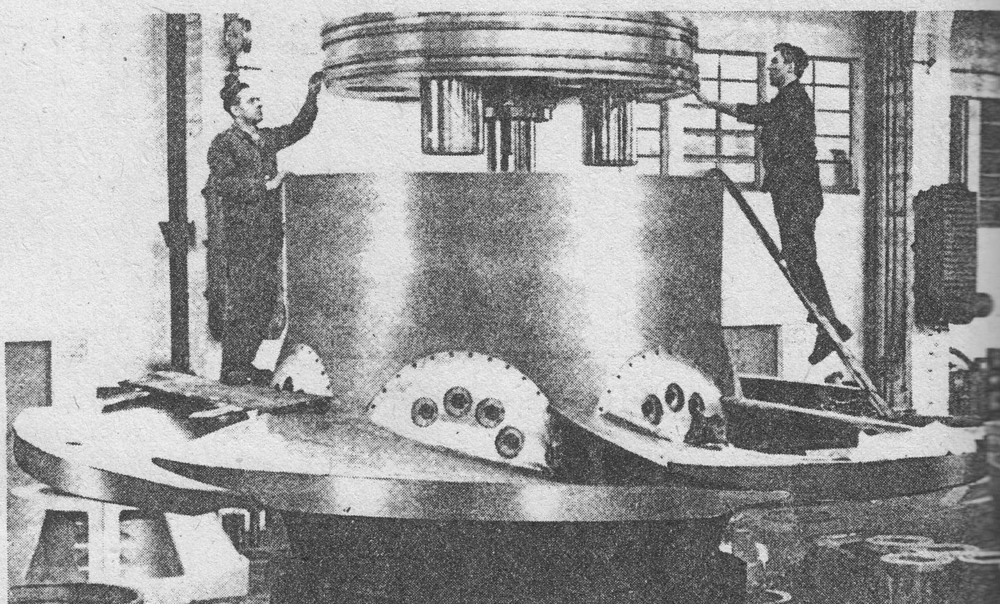

Fig. 19. Kaplan runner blade with an anticavitation strip

Process engineering methods concern the material and the working medium. The objective is to ensure high cavitation resistance of the structural elements and to weaken erosive effects of cavitation by aerating the flow, blowing through (ventilating) the cavitation zones, using cathodic protection and processing the liquid contained in the closed circuit.

The installation methods aim at ensuring that the machines have a sufficiently large excess of pressure head at the suction side. This is connected with appropriate situating of the machine, which requires taking into account two contradictory tendencies. Because of cavitation, the machine should be located in a low position, and because of the cost a higher position is required. As it was already mentioned, in practice a compromise is reached, allowing weakly or partially developed cavitation in the machine.

Operational methods consist in limiting the dynamic depression and in eliminating

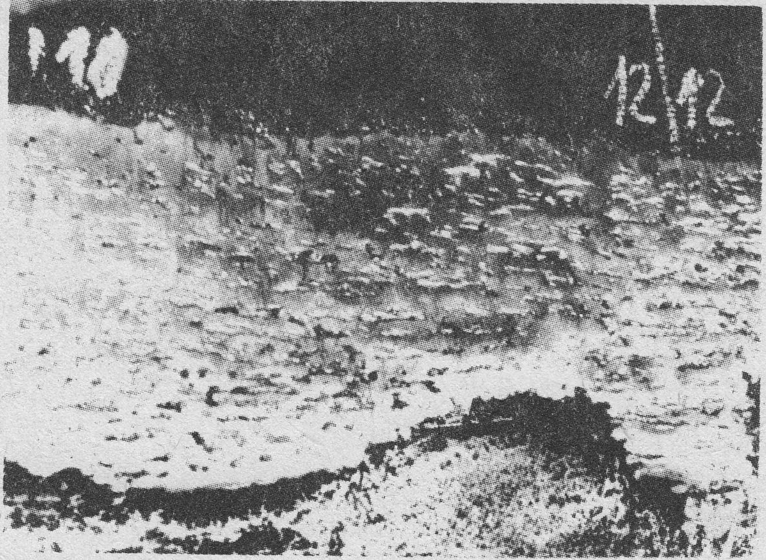

Fig. 20. An example of careless repair of a turbine chamber damaged by slot cavitation

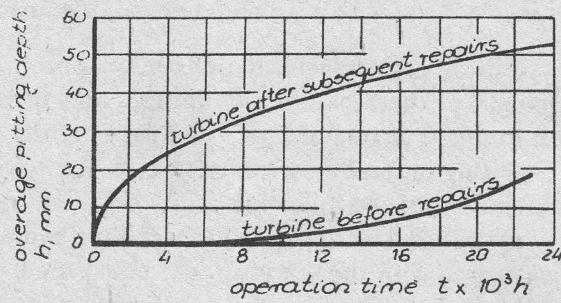

Fig. 21. Comparison of cavitation erosion before and after repairs of the turbine at the Bratsk Water Power Plant (acc. to [1])

impact, flow separations and swirls both at the inlet and outlet of flow channels. The problem consists in rational machine operation control with regard to cavitation. Therefore the machines should be equipped with appropriate diagnostic apparatuses — cavitation detectors.

It appears that machines exposed to cavitation require special treating. This observation concerns not only control of operation but also checking the technical conditions of the machines (inspections, tests), removal of defects (finding and removing troubles), maintenance (everyday inspection and running repairs) and periodical regeneration.

The periodical inspections and repairs are very important for durability and availability of machines. Repairs which cause stresses and deformations and increase roughness of surfaces coming into contact with the liquid are the reason of additional cavitation damages. In this respect, special attention is drawn to the effects of padding (Fig. 20). As a result of repairs the course of damaging may be changed as shown in Fig. 21 [10]. This means that special attention should be given to the problem of cavitation damage repair.

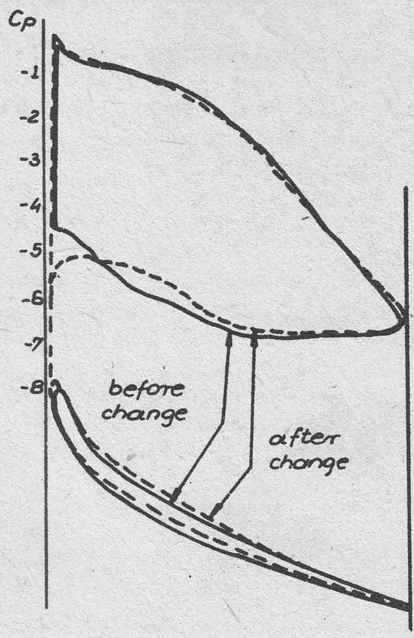

Fig. 22. Influence of blade profile deformation on the pressure distribution (acc. to [14])

During repairs deformations may appear, e.g. deformation of blades lea... changes in the pressure distribution, and therefore changing cavitation cond... An example of such changes and their results is shown in Fig. 22 [14].

Basing on multiyear experience, E. Randegger of Escher Wyss [7] recomm... observance of the following principles:

a) In order to avoid or at least limit hydraulic losses, smoothness of all s... contacting with the liquid should be ensured.

b) Periodical inspecting of all parts under hydraulic and mechanical loa... necessary. Special attention should be paid to cracks and scratches. If repa... necessary they should be agreed upon with the manufacturer of the machine.

c) The machine should be operated in an economically justified way, bas... running inspection of its technical condition.

d) The knowledge of the behaviour of hydraulic machines under cavitation con-tions is mainly based on experience. Therefore it is necessary to collect and ana... systematically various information coming from machine users and measuring te... Conclusions drawn from such research should be used in design and operation pra...

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Skutki działania kawitacji w maszynach hydraulicznych

Streszczenie

Praca ma charakter przeglądowy; jest oparta na wynikach badań własnych i obcych.

Na wstępie zamieszczono informacje ogólne na temat warunków pracy maszyn hydraulicznych, wskazując na kawitację i wibracje jako na główne przyczyny powodujące uszkodzenia pomp i turbin wodnych (tabela 1). Szczególną uwagę poświęcono skutkom energetycznym, objawom akustycznym, mikrouderzeniom oraz drganiom i erozji kawitacyjnej.

Wpływ kawitacji na wymianę energii w maszynie jest na ogół dobrze znany. Niektóre osobliwości z tym związane przedstawiono na rysunkach 3÷6.

Związek między skutkami energetycznymi i objawami akustycznymi w pompach ilustrują krzywe zamieszczone na rysunkach 7÷8. Rysunek 7 ukazuje ponadto przebieg sygnałów akustycznych zarejestrowanych w podobnych warunkach w pompie modelowej i w prototypie.

Zwracając uwagę na fakt, iż główną przyczyną dynamicznych oznak kawitacji są implozje pęcherzyków kawitacyjnych, przedstawiono typowy przebieg pojedynczego impulsu ciśnienia (rys. 9) oraz rozkład takich impulsów w zależności od stopnia rozwoju kawitacji (rys. 10).

Więcej uwagi poświęcono drganiom i erozji kawitacyjnej. Na rysunkach 11 i 12 przedstawiono krzywe obrazujące drgania elementów maszyn w elektrowniach wodnych Koronowo i Żydowo, a na rysunku 13 zniszczenie łopatki w EW Solina. Inne uszkodzenia spowodowane kawitacją ukazują fotografie zamieszczone na rysunkach 14, 15 i 16.

Związek między czasem działania oraz stopniem rozwoju i erozją materiału przedstawiają rysunki 17 i 18.

Na zakończenie wskazano na sposoby postępowania, które służą przeciwdziałaniu szkodliwym skutkom kawitacji. Zwrócono uwagę na sposoby konstrukcyjne (rys. 19), technologiczne i instalacyjno-ruchowe. Podkreślono znaczenie bieżącej diagnostyki maszyn oraz okresowych przeglądów i napraw pokawitacyjnych (rys. 10, 21 i 22).

Следствия действия кавитации в гидравлических машинах

Резюме

Работа имеет обзорный характер. Она основана на результатах собственных и чужих исследований.

В начале даны общие информации на тему условий работы гидравлических машин, с указанием на кавитацию и вибрации как на основные причины вызывающие повреждения насосов и гидротурбин (таблица 1). Особое внимание уделяется энергетическим следствиям, акустическим симптомам, микроударам, а также колебаниям и кавитационной эрозии.

Влияние кавитации на обмен энергией в машине в общем хорошо изучено. Некоторые особенности с этим связанные представлены на рисунках 3÷6.

Связь между энергетическими следствиями и акустическими симптомами в насосах иллюстрируют графики представленные на рисунках 7÷8. Рисунок 7 указывает кроме того ход акустических сигналов зарегистрированных в похожих условиях в модельном насосе и в прототипе.

Обращая внимание на факт, что основной причиной динамических признаков кавитации являются имплозии кавитационных пузырьков, представлены типичный ход одиночного импульса давления (рис. 9), а также распределение таких импульсов в зависимости от степени развития кавитации (рис. 10).

Больше внимания уделяется колебаниям и кавитационной эрозии. На рисунках 11 и 12 представлены кривые изображающие колебания элементов машин в гидроэлектростанциях Короново и Жыдово, а на рисунке 13 трещина лопатки в Гидроэлектростанции Солина. Другие повреждения вызванные кавитацией показывают фотоснимки представленные на рисунках 14, 15 и 16.

Связь между временем действия, а также степенью развития и эрозией материала указывают рисунки 17 и 18.

В заключении указываются способы поведения, служащие противодействию вредным следствиям кавитации. Обращается внимание на конструкционные (рис. 19), технологические и монтажно-эксплуатационные способы. Подчёркивается значение постоянной диагностики машин, а также периодических просмотров и послекавитационных ремонтов (рис. 10, 21 и 22).