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Vpliv količine plinov v vodi in hitrosti toka na agresivnost kavitacijske erozije

The Influence of the Gas Content of Water and the Flow Velocity on Cavitation Erosion Aggressiveness

Matevž Dular - Brane Širok - Bernd Stoffel

V prispevku je predstavljena študija vpliva količine plinov v vodi in hitrosti toka na agresivnost kavitacjske erozije. Preizkusi so bili opravljeni na osamljenem profilu v kavitacijskem kanalu. Medtem ko sta bila kavitacijsko število in hitrost toka nespremenljiva, smo v korakih spreminjali količino plinov v vodi od majhne (približno 1%) do velike vsebnosti (4%). Količino plinov v vodi smo nadzorovali z generatorjem mehurčkov. Pri tem so bili narejeni preizkusi ob konstantnem kavitacijskem številu in količini raztopljenih plinov, vendar različnih hitrostih toka (10, 13 in 16 m/s). Za zaznavalo kavitacijske erozije je rabila tanka bakrena folija, nanesena na profil. Pod določeno povečavo smo posneli slike poškodovane površine bakrene folije. Za neposredno meritev kavitacijske erozije smo uporabili metodo štetja luknjic, ki temelji na računalniško podprti vizualizaciji. Preizkusi so pokazali očiten vpliv količine plinov in hitrosti toka na intenzivnost erozije. Agresivnost kavitacijske erozije se eksponentno zmanjšuje, ko večamo količino raztopljenih plinov. Potrjena je bila hipoteza o potenčnem zakonu za vpliv hitrosti toka na agresivnost kavitacijske erozije. Predstavljeni rezultati obetajo dobre možnosti za razvoj modela kavitacijske erozije ter možnost napovedi kavitacijske erozije z izključno numeričnimi metodami.

(Ključne besede: kavitacija, erozija, plini v vodi, količine plinov, hitrosti tokov)

A study of the influence of the gas content of water and the flow velocity on cavitation erosion aggressiveness was performed. A cavitation tunnel with a single hydrofoil was used for the experiments. While the cavitation number and the mean flow velocity remained constant throughout the tests, the gas content of the water was changed in steps from low (approximately 1%) to high (4 %). The gas content of the water was adjusted with a bubble generator. In addition tests at a constant cavitation number and water gas content but different mean flow velocities (10, 13 and 16 m/s) were made. A thin copper foil, applied to the surface of the hydrofoil, was used as an erosion sensor. Images of the damaged, copper-coated hydrofoil surface were taken at an appropriate magnification. A pit-count method, based on computer-aided image processing, was used for direct measurements of the cavitation erosion by evaluating the damage on the surface of the hydrofoil. Clear evidence for the influence of the gas content and the velocity on the erosion intensity was found. The cavitation erosive aggressiveness exponentially drops when the content of the water is increased. A power law was confirmed for the velocity's influence on the cavitation erosive aggressiveness. The presented results promise the possibility of deriving a cavitation erosion model and the possibility of cavitation erosion prediction using only numerical tools in the future.

(Keywords: cavitation, erosion, water with gas content, flow velocity)

0 UVOD

Pojav kavitacije, ki je karakteriziran z nastajanjem in kondenzacijo pare, je pogosto opazen v hidravličnih strojih. Povzroča vibracije, povečanje hidrodinamičnega upora, spremembe v

0 INTRODUCTION

The cavitation phenomenon, characterised by vapour generation and condensation, occurs frequently in hydraulic machines. It causes vibration, an increase of hydrodynamic drag, changes in the hidrodinamiki toka, hrup, toplotne in svetlobne učinke ter najpomembnejše kavitacijsko erozijo.

Kavitacijsko stanje običajno opišemo z brezrazsežnim številom (kavitacijskim številom), ki je definirano kot razlika med tlakom sistema in tlakom uparjanja (pri temperaturi sistema), deljena z dinamičnim tlakom:

flow hydrodynamics, noise, thermal and light effects and, most important of all, cavitation erosion.

We usually describe the cavitation condition by using a non-dimensional number (the cavitation number), which is defined as the difference between the system and vapour pressure (at the system temperature) divided by the dynamic pressure:

$$\sigma = \frac{p_\infty - p_v(T_\infty)}{\rho \cdot v^2 / 2} \quad (1).$$

Zmanjšanje kavitacijskega števila pomeni večjo verjetnost pojava kavitacije, oziroma povečanje že opazne kavitacije.

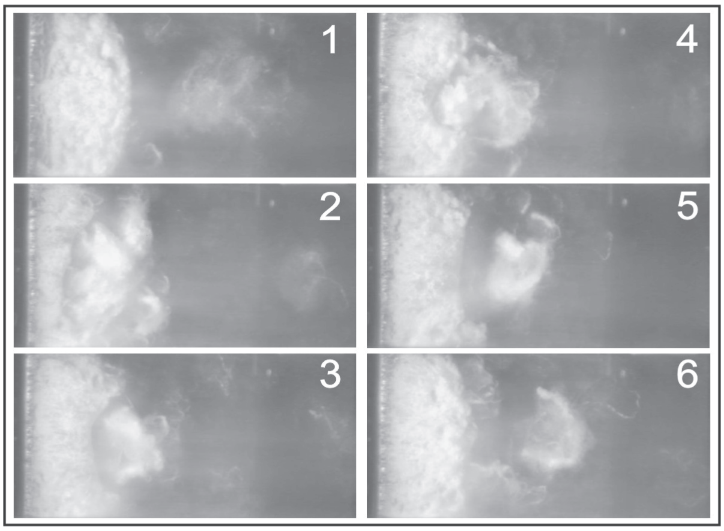
Najpomembnejši mehanizem nastanka kavitacijske erozije je tako imenovani mikrocurek ([1] do [3]). Postopek kolapsa kavitacijskega oblaka se prične z njegovo ločitvijo od pritrjenega dela kavitacije. Oblak nato potuje s tokom in implodira v območju z višjim tlakom. Kolaps oblaka zbuja povratni tok, ki povzroči novo trganje oblaka. Sliki 1 in 2 prikazujeta trganje kavitacijskega oblaka na osamljenem profilu, ki je bil uporabljen pri preizkusih. Tok teče z leve proti desni. Slike so posnete pri hitrosti toka 13 m/s, majhni količini plinov (1,15 %) in kavitacijskem številu 2,3.

Ob kolapsu kavitacijskega oblaka se sprosti tlačni val velikostnega reda nekaj 100 kPa (preizkusi [1] kažejo na vrhove velikosti 2,5 MPa). Tlačni val, dovoljšne velikosti, vpliva na krogelno simetrijo mehurčkov, ki se nahajajo tik ob steni

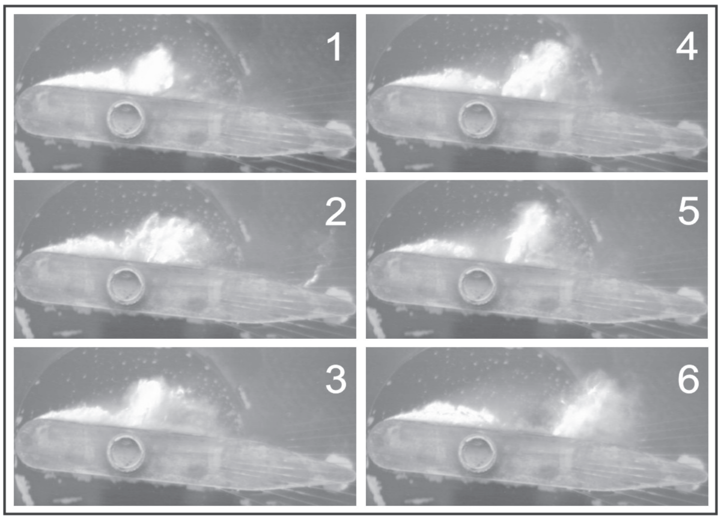
Decreasing the cavitation number results in a higher probability of cavitation occurring or in an increase in the magnitude of the already present cavitation.

The most common mechanism of cavitation erosion is the so called micro-jet phenomenon ([1] to [3]). The process of cavitation-cloud implosion begins with its separation from the attached part of the cavitation. It then travels with the flow and collapses in the higher pressure region. Its collapse causes the formation of the backflow (re-entrant jet), which causes a new separation of the cavitation cloud. Figures 1 and 2 show the process of cavitation-cloud separation and cloud collapse on a single hydrofoil geometry that was used for the experiments. The images were taken at a flow velocity of 13 m/s, a low water-gas content (1.15 %) and cavitation number 2.3.

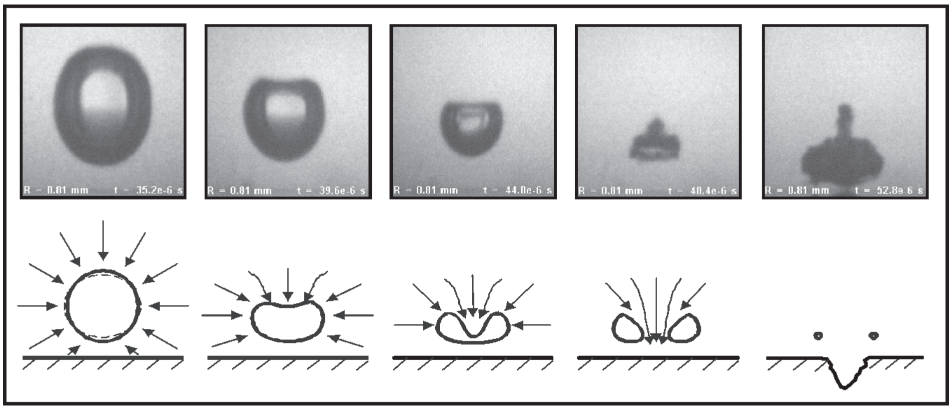
Because of the cavitation-cloud collapse a pressure wave with a magnitude of several 100 kPa is emitted (experiments [1] show pressure peaks with a magnitude up to 2.5 MPa). The pressure wave with sufficient magnitude acts on the bubbles with a spherical shape that are positioned close to the surface



Sl. 1. *Trganje in kolaps združene skupine mehurčkov (kavitacijskega oblaka) – pogled od zgoraj*
Fig. 1. *Separation and collapse of the united group of bubbles (cavitation cloud) – top view*



Sl. 2. *Trganje in kolaps združene skupine mehurčkov (kavitacijskega oblaka) – pogled od strani*
Fig. 2. *Separation and collapse of the united group of bubbles (cavitation cloud) – side view*



Sl. 3. *Mehanizem mikrocurka (slike so vzete s filma, ki ga je posnel prof. Lauterborn)*
Fig. 3. *Micro-jet mechanism (pictures taken from the movie by Prof. Lauterborn)*

potopljenega telesa. Oblika mehurčka postane nestabilna – začne nihati. Ob dovolj veliki amplitudi nihanja lahko pride do nastanka mikrocurka. Okoliška tekočina zavzame obliko curka skozi mehurček v smeri trdne površine (sl. 3).

Mikrocurek lahko doseže velike hitrosti, ki povzročijo udar (velikostni red je lahko večji od 1 GPa, čas trajanja je približno 1 ns, prizadeta površina pa ima red velikosti nekaj μm^2) z veliko lokalno napetostjo materiala [4]. Poškodba površine zavzame obliko mikroskopske plastične deformacije – luknjice [5] (sl. 6).

Zaradi težav merjenja tlačnih udarov, ki nastanejo ob imploziji mehurčkov, velikosti

of the submerged body. The shape of the bubble becomes unstable; it begins to oscillate. If the amplitude of the oscillations is big enough, a micro-jet phenomenon can occur. The fluid that surrounds the bubble takes shape of the jet through the bubble in the direction towards the solid surface (Fig. 3).

This micro-jet can reach high local velocities that cause a shock (the order of magnitude can be bigger than 1 GPa, the duration is approximately 1 ns and the affected area is of the order of a few μm^2) with high local tension of the material [4]. The damage of the surface appears in the form of microscopic plastic deformations called pits [5] (Fig. 6).

Due to difficulties with measuring the pressure peaks caused by the bubble implosions it kavitacijske erozije ni mogoče definirati le na hidrodinamični podlagi. Metode merjenja so na primer vibracijske [6] ali pa za zaznavalo uporabimo mehke kovinske (aluminij ali baker) ali barvne prevleke potopljenega telesa ([7] do [13]). Metoda vrednotenja kavitacijske erozije, ki temelji na številu, porazdelitvi in obliki luknjic na mehki prevleki potopljenega telesa, ki so nastale zaradi implozije mehurčkov, podaja natančno poznavanje mehanizma kavitacijske erozije.

Obstaja več razlag, kako in zakaj vsebnost plinov v vodi vpliva na agresivnost kavitacijske erozije, vendar doslej še ni bilo sistematične raziskave. Obstajajo nekatere specifične raziskave vpliva lastnosti tekočin na agresivnost kavitacije. Na primer raziskave vpliva površinske napetosti vode [14]. Ugotovljeno je bilo, da zmanjšana površinska napetost vode, zmanjša agresivnost kavitacijske erozije. Razprave o vbrizgu zraka z namenom zmanjšanja in nadzora kavitacijske erozije najdemo v [1] in [2]. Nekatere razlage vpliva plinov v vodi je moč najti tudi v [15]. Glavna zamisel, ki jo podajajo omenjene študije, je, da se s povečanjem deleža plinov v vodi tej poveča stisljivost, kar posledično zmanjša agresivnost kavitacije.

Predstavljena raziskava podaja in kakovostno razlaga rezultate meritev kavitacijske erozije v štirih različnih razmerah (ob nespremenljivi hitrosti toka in kavitacijskem številu ter spreminjajoči se količini plinov v vodi).

Drugi parameter, ki vpliva na agresivnost kavitacijske erozije in je bil predmet raziskave, je hitrost toka (ob nespremenljivi količini plinov in kavitacijskem številu). Vpliv hitrosti toka je poznan. Prejšnje raziskave [16] in [17] kažejo, da se velikost poškodbe (A) veča s potenčnim zakonom (n = 5 do 8), ko večamo hitrost toka:

is not possible to define the magnitude of the cavitation erosion on a purely hydrodynamic basis. The measuring methods are, for example, vibratory determination [6] or the use of soft metal (aluminium or copper) or paint coating of the submerged body as a sensor ([7] to [13]). The erosion evaluation method using the number, distribution and shape of the pits caused by bubble implosions on the soft surface coating gives us a detailed knowledge of the cavitation erosion mechanism.

There are more theories about how and why the presence of gas influences the cavitation erosion aggressiveness, but until now there has been no systematic study of the influence of the gas content of water on the aggressiveness of the cavitation. There are, however, some specific studies of the influence of liquid properties on the aggressiveness of cavitation erosion. For example, [14] deals with the influence of the water's surface tension. It was found that decreased surface tension decreases the aggressiveness of the cavitation. Discussions of air injection for the control and prevention of cavitation erosion can be found in [1] and [2]. Some brief explanations of the aeration of water are also given in [15]. The basic idea of the mentioned studies is that the water-gas content increases the compressibility of the fluid and that this consequently decreases the aggressiveness of the cavitation.

The present study shows and qualitatively explains the results of erosion measurements under four different conditions (during constant flow velocity and cavitation number and changing water-gas content).

The other studied parameter that influences the aggressiveness of the cavitation erosion was the mean flow velocity (during constant water-gas content and cavitation number). The influence of the flow velocity is well known. Past experiments [16] and [17] show that the magnitude of damage (A) increases with the power law (n = 5 to 8) when the velocity is increased:

$$\frac{A_1}{A_2} = \left(\frac{v_1}{v_2}\right)^n \text{; n = 5 do/to 8} \qquad (2).$$

Preizkusi so potrdili teorijo o potenčnem zakonu (ugotovljen je bil količnik $n = 6{,}1$). Podane so tudi nekatere teoretične razlage rezultatov.

The experiments confirmed the theory ($n = 6.1$ was found). Some theoretical explanation of the results is also given.

1 PREIZKUS

1 EXPERIMENT

Kavitacijski preizkusi so bili narejeni v kavitacijskem kanalu v Laboratoriju za turbinske stroje in tekočinsko energetiko – Tehnične univerze v Darmstadtu.

Cavitation tests were performed in a cavitation tunnel at the Laboratory for Turbomachinery and Fluid Power – Darmstadt University of Technology.

1.1 Priprava preizkusa

Osnovna geometrijska oblika (sl. 4), ki smo jo uporabili pri preizkusih, je bil 50 mm širok, 107,9 mm dolg in 16 mm debel simetrični profil s polkrožnim vpadnim robom ter vzporednima stenama.

Profil je bil nameščen v pravokotni testni odsek kavitacijskega kanala (sl. 5) z zaprtim obtokom. Testni odsek kanala je 500 mm dolg, 100 mm visok in 50 mm širok. Nameščeni ima dve okenci za opazovanje od zgoraj in od strani.

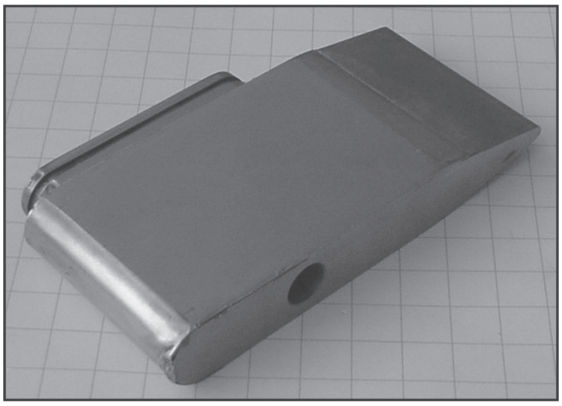
Upoštevajoč kombinacijo negotovosti meritev tlaka (+/- 0,2 %), hitrosti (+/- 0,25 %) in temperature (+/- 0,06 %), je bilo moč kavitacijsko število določiti z +/- 0,02 celotne negotovosti.

1.1 Experimental set up

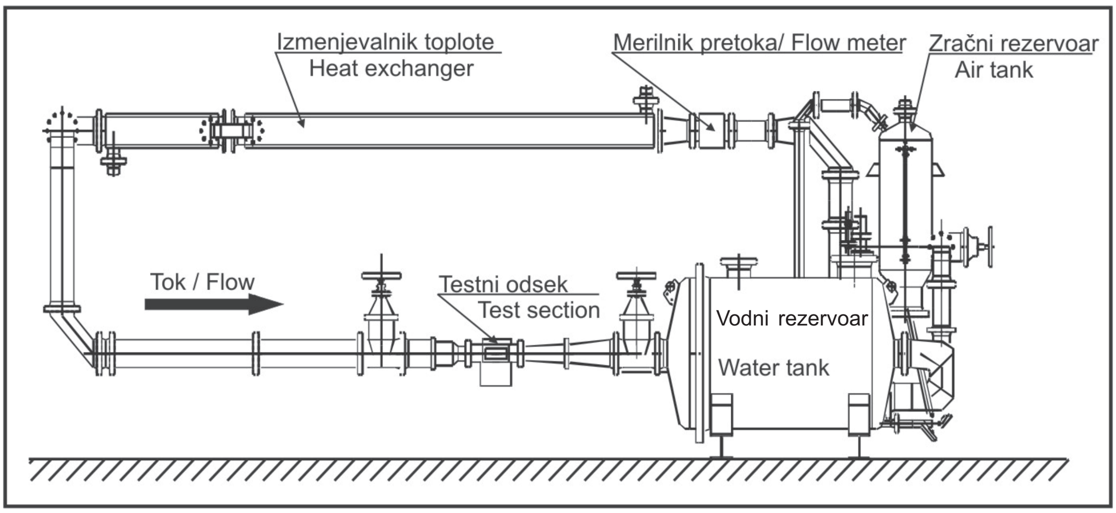
The basic geometry (Fig. 4) was a 50-mm-wide, 107.9-mm-long and 16-mm-thick symmetric hydrofoil with a circular leading edge and parallel walls.

The hydrofoil was put into a rectangular test section of the cavitation tunnel (Fig. 5) with a closed circuit. The test section of the cavitation tunnel is 500 mm long, 100 mm high and 50 mm wide. Two observation windows are mounted for top- and side-view observation.

Considering the combination of the inaccuracies of pressure (+/- 0.2 %), velocity (+/- 0.25 %) and temperature (+/- 0.06 %) measurements, the cavitation number could be determined to within +/- 0.02 of global uncertainty.



Sl. 4. *Z bakreno folijo prevlečen profil, ki smo ga uporabili pri preizkusih*
Fig. 4. *Copper-coated hydrofoil that was used for the experiments*



Sl. 5. *Kavitacijski kanal*
Fig. 5. *Cavitation tunnel*

Preglednica 1. *Parametri preizkušanih kavitacijskih stanj*
Table 1. *Parameters of tested cavitation conditions*

Test	σ	v	α
1.	2,3	13 m/s	1,15 %
2.	2,3	13 m/s	2,15 %
3.	2,3	13 m/s	3,05 %
4.	2,3	13 m/s	4,07 %
5.	2,3	10 m/s	1,15 %
6.	2,3	16 m/s	1,16 %

Parametre preizkusov podaja preglednica 1.

Vpadni kot profila je bil za vse preizkuse enak in je znašal 5°.

Kavitacijski kanal ponuja možnost nastavljanja količine plinov v vodi. Merimo lahko le skupno količino plinov v vodi, se pravi količino raztopljenih in neraztopljenih plinov v vodi. Ocenjeno je, da je pri tlaku sistema, količina raztopljenih plinov v vodi za nekaj velikostnih redov večja od količine prostih plinov. Če želimo doseči majhno stopnjo plinov v vodi, pustimo tok nekaj časa teči pri nizkem tlaku (20 kPa). Ker je stanje nasičenosti vode s plini pri nizkem tlaku nižje, se plini sprostijo in izločijo. Na ta način je mogoče doseči približno 1 % (prostorninski delež) plinov vodi.

Za zagotovitev velikega deleža plinov uporabimo generator mehurčkov. Z uporabo generatorja mehurčkov v ločenem rezervoarju dobimo s plini nasičeno vodo pod visokim tlakom (2 MPa). Nasičeno vodo nato skozi več šob premera 0,1 mm vbrizgamo v sistem kavitacijskega kanala. Tako je mogoče doseči skoraj nasičeno stanje vode pri tlaku sistema. Največji prostorninski delež plinov, ki ga je mogoče zagotoviti, je približno 4,2 %.

Negotovost merjenja količine raztopljenih plinov v vodi je +/- 1 % merjene vrednosti.

1.2 Metoda štetja luknjic

Zaradi problemov s ponovljivostjo mehanskih lastnosti galvanskega nanosa bakra so bile meritve prejšnjih raziskav omejene le na majhno površino. Erozija je bila vrednotena na vzorcih iz čistega bakra, ki so bili vstavljeni v profil ([2], [12] in [13]). Študija erozije je bila omejena na čas inkubacije, se pravi na čas, ko že zaznamo poškodbo površine (plastične deformacije - luknjice), ne pa tudi odnašanja materiala. Da bi dobili informacije o eroziji na celotni površini profila, smo na njegovo površino z lepilnim filmom namestili 0,2 mm debelo polirano

The parameters of the experiments can be found in Table 1.

The incidence angle was held constant at 5° for all the tests.

The cavitation tunnel system gives the possibility to adjust the content of the gases in the water. If a low gas content is desired we let the flow run at low pressure (approximately 20 kPa) for some time. Since the saturation level of the gases at low pressure in water is smaller than at high pressure, the gases are freed and a low gas content is reached. In this way we can achieve approximately 1% volume fraction of gas in the water.

To reach a high level of gas content a bubble generator system is used. With a bubble generator, water that is practically saturated with gas at high pressure (2 MPa) is achieved in a separate tank. The saturated water is then injected into the cavitation tunnel system through multiple nozzles with a diameter of 0.1 mm. It is possible to reach the almost saturated condition of water-gas content at system pressure in this way. The maximum volume fraction of gas content that can be reached is approximately 4.2 %.

The uncertainty of the measurements of water-gas content was +/- 1 % of the measured value.

2.2 Pit-count method

Due to problems with the reproducibility of the galvanic copper-coating method, only a small part of the surface was investigated for the cavitation erosion in previous investigations. This was done using pure copper specimens inserted into the hydrofoil ([2], [12] and [13]). To get information about the erosion on the whole surface of the hydrofoil, a polished copper foil, 0.2 mm thick, was fixed to its surface using adhesive film. The hardness of the copper coating was approximately 40 HV. A sufficient number of pits was obtained after 1 hour of exposure bakreno folijo. Površinska trdota bakrene folije je bila približno 40 HV. Zadostna količina luknjic je bila dosežena po tem, ko je bil profil za eno uro izpostavljen kavitirajočemu toku (čas preizkusov je bil nespremenljiv).

Luknjice imajo premer velikostnega reda 10^{-5} m in so vidne šele pod določeno povečavo. Slike poškodovane površine so bile narejene z mikroskopom Olympus BX-40 in CCD kamero.

Povečava je bila 50:1, kar je dalo ločljivost 1,95 μm na točko. Za vsako merjeno kavitacijsko stanje je bilo narejenih 925 slik površine (vsaka slika je merila 1,09x1,46 mm). Ovrednotena površina je predstavljala približno 48 % z bakreno folijo prekrite površine profila.

Slika 6 prikazuje sliko površine pred preizkusom (levo) (0 % poškodovane površine) in po preizkusu (desno) (4,98% poškodovane površine).

Intenzivnost kavitacijske erozije je bila določena z metodo štetja luknjic. Temelj metode je predpostavka, da površina poškodovane površine v določenem času podaja kolikostno merilo intenzivnosti kavitacijske erozije.

Metoda štetja luknjic, ki je bila razvita v Laboratoriju za turbinske stroje in tekočinsko energetiko, kot luknjice prepozna temnejša območja na sliki, medtem ko svetlo območje obravnava kot nepoškodovano površino (natančen opis dvorazsežne optične analize luknjičaste površine najdemo v [5]).

Sliko površine rekonstruiramo s krožnim strukturnim elementom. Ugotovljeno je bilo, da da krožni element s premerom 8 točk (približno 16 μm) najugodnejše rezultate.

Problem, ki ga je treba upoštevati je tudi možno prekrivanje luknjic. Gruče luknjic nastanejo po naključju pri daljših preizkusih, ob kolapsu skupine mehurčkov ali ob večkratnem kolapsu enega mehurčka.

to the cavitating flow (the exposure time was constant for all tests).

Pits have a diameter of magnitude order 10^{-5} m, and can be distinguished only with sufficient magnification. Images of the pitted surface were acquired using an Olympus BX-40 microscope and a CCD camera.

The enlargement scale was 50:1, leading to a resolution of 1.95 μm per pixel. A total of 925 images (one image embraces an area of 1.09x1.46 mm) of the pitted surface were taken for each operating point (the part of the surface evaluated by the images represents approximately 48 % of the copper-coated hydrofoil surface).

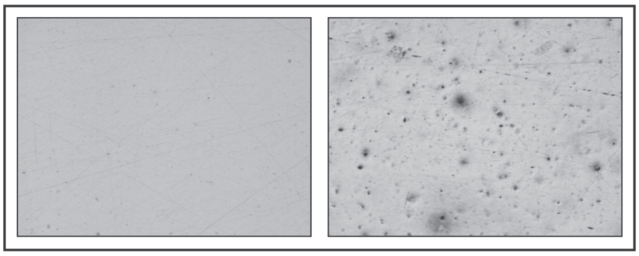
Fig. 6 shows an image of the surface before the exposure to cavitating flow (left) (0 % eroded surface) and after 1 hour of exposure (right) (4.98 % eroded surface).

The intensity of cavitation erosion was determined by the pit-count method. The method is based on the assumption that the area of the surface that is covered by pits after a certain time of exposure to cavitating flow gives a quantitative measure of the intensity of the cavitation erosion.

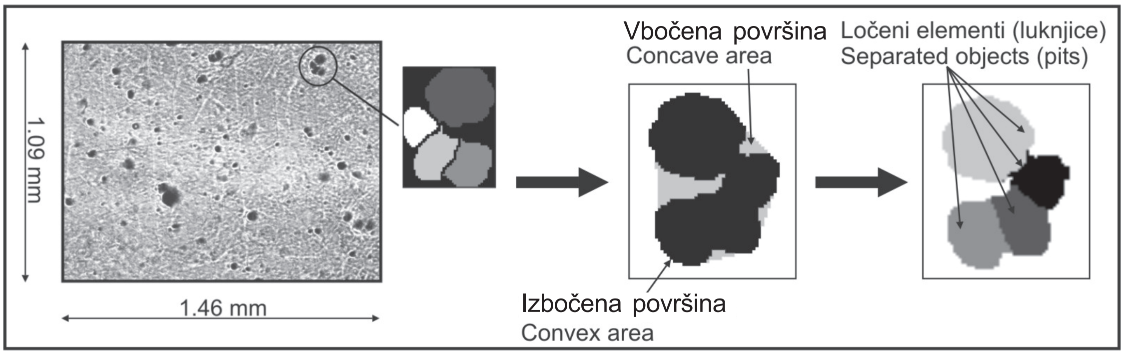
The pit-count software developed at the Laboratory for Turbomachinery and Fluid Power determines the pits from the darker regions in an image, while the brighter area is assumed to be undamaged surface (a detailed description of optical 2D analyses of a pitted surface can be found in [5]).

The surface image is reconstructed by using a circular structuring element. It has been determined that a circularly shaped structural element that is 8 pixels (about 16 μm) in diameter gives the most reliable results.

A problem that has to be considered is the possibility of the overlapping of the pits. Pit clusters are created by chance during longer tests, by the collapse of a group of bubbles or by rebounds of a single bubble.



Sl. 6. *Slika površine pred preizkusom (levo) in po preizkusu (desno)*
Fig. 6. *Image of surface prior (left) and after (right) the exposure to the cavitating flow*



Sl. 7. *Prepoznavanje luknjic na površini z metodo štetja luknjic*
Fig. 7. *Detection of pits on the surface using the pit–count method*

Načelo, po katerem ločimo skupino luknjic, temelji na predpostavki, da osamljena luknjica ne more zavzeti vbočene oblike. Tako vbočene elemente na sliki razdelimo na več elementov izbočene oblike. Osamljeni elementi so nato povečani, da zapolnijo izvirno obliko luknjice. Če je slikovni element sestavljen iz prekrivajočih se luknjic, je mogoče, da je posamezna slikovna točka skupna dvema ali več luknjicam (Sl. 7).

Metoda štetja luknjic podaja porazdelitev števila in površine luknjic, posledično pa porazdelitev intenzivnosti kavitacijske erozije po površini.

The principle that is used for pit separation is that a single pit cannot form a concave shape. Hence, a concavely shaped dark region is divided into a number of individual objects, each having a convex shape. The separated objects are then enlarged to fill out the original object size. If an image object is caused by overleaping pits it is possible that one pixel is shared by two or more pits (Fig. 7).

The pit-count method gives a distribution of the number and the area of the pits and consequently the distribution of the magnitude of cavitation erosion on the surface.

2 REZULTATI

2 RESULTS

Prikazane so porazdelitve intenzivnosti kavitacijske erozije po površini profilov za parametre, podane v preglednici 1. Vrednosti med posameznimi merilnimi točkami (slikami površine) so dopolnjene z interpolacijsko metodo Kriging. Vrednost spremenljivke erodirana površina (*EP*) podaja delež celotne poškodovane površine (delež površine, ki je prekrita z luknjicami):

The distributions of the magnitude of cavitation erosion on the surfaces of the hydrofoils for parameters given in Tab. 1 are presented. The values between the evaluation points (surface images) are determined using the Kriging interpolation scheme. The value of the eroded surface (*EP*) represents the part of the whole surface that is damaged (covered by pits):

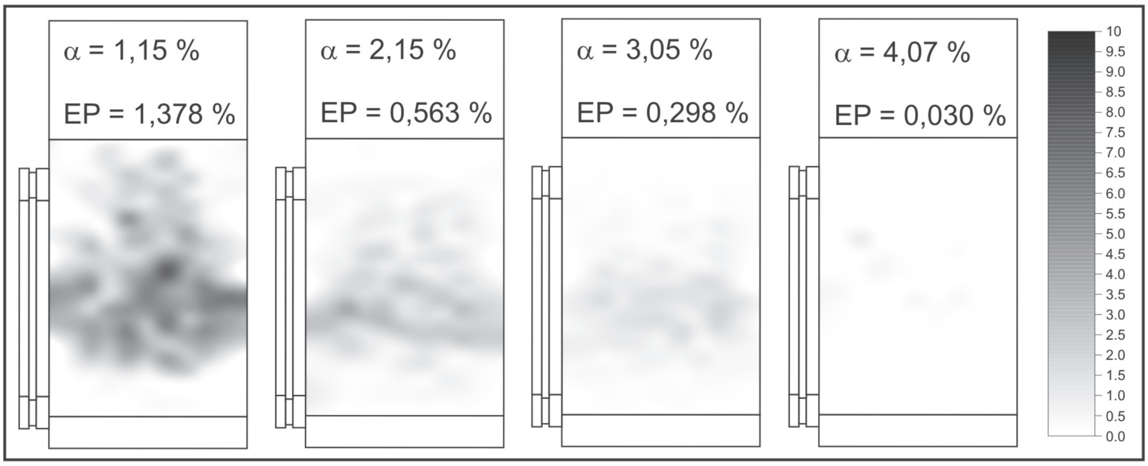
$$EP = \frac{\sum_{i=1}^{925} A_{pi}}{\sum_{i=1}^{925} A_i} \cdot 100\ \% \qquad (3).$$

Rezultati poškodb površine ob spremenljivi količini plinov v vodi so predstavljeni na sliki 8. Tok teče od spodaj navzgor. Merilo pomeni lokalno vrednost erodirane površine (belo 0 %, črno 10 %).

Vidimo, da se ob povečanju količine plinov v vodi agresivnost erozije očitno zmanjša. Pri velikem deležu vsebnosti plinov (4,07 %) utrpi površina

The results of the surface damage for the variations of water-gas content are shown in Figure 8. The flow is from the bottom to the top. The scale represents the local percentage of eroded surface (white 0 %, black 10 %).

One can see that the erosive aggressiveness decreases significantly when the gas content rises. The surface sustains almost 50 times less damage in the case



Sl. 8. *Porazdelitev velikosti poškodbe za različne deleže plinov v vodi*
Fig. 8. *Erosion magnitude distribution for different water-gas contents*

skoraj 50-krat manjšo količino poškodb, kakor pri majhnem deležu plinov (1,15 %). Ker je bilo kavitacijsko število skozi preizkuse nespremenljivo, ostajata mesto največje erozije ter porazdelitev luknjic po površini profila za vse primere enaka (topologija kavitaciskih struktur se ob spremembi deleža plinov vodi praktično ne spremeni). Če primerjamo porazdelitev luknjic s slikami kavitacijskih struktur (sl. 1, 2), vidimo, da se mesto največje erozije ujema z mestom, kjer pride do trganja kavitacijskega oblaka.

Slika 9 prikazuje diagram spremenljivke *EP* kot funkcije količine plinov v vodi.

Vidimo, da agresivnost kavitacijske erozije (karakterizirana s parametrom *EP*) eksponentno pada, ko večamo količino plinov v vodi.

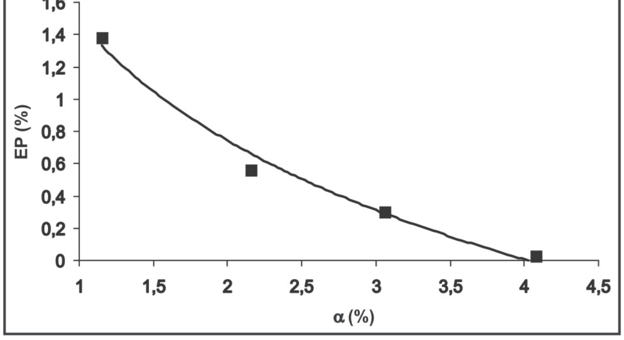
Razlogi za manj agresivno kavitacijsko erozijo zaradi večjega deleža plinov v vodi so:

of a high gas content (4.07 %) than in cases with a low gas content (1.15 %). The position of maximum erosion magnitude and the distribution of the pits on the hydrofoil remain constant for all the cases, since the cavitation number was constant (the topology of the cavitation structures does, in practical terms, not change when the gas content is altered). Comparing the distribution of the pits with the images of cavitation (Fig. 1 and 2) one can see that the maximum magnitude of the cavitation damage corresponds to the point where the cavitation cloud separates from the attached part of the cavitation.

Figure 9 shows a diagram of *EP* as a function of water-gas content.

It can be seen that the aggressiveness of the cavitation erosion (characterised by *EP* parameter) decreases exponentially when the gas content is increased.

The reasons for the less aggressive cavitation erosion due to the increase of the water-gas content are:



Sl. 9. *Erodirana površina (EP) kot funkcija količine plinov v vodi*
Fig. 9. *Eroded surface (EP) as a function of gas content*

- Voda z več raztopljenimi plini ima večjo stisljivost. Dušenje tlačnega vala, ki nastane ob kolapsu kavitacijskega oblaka je tako večje – amplituda vala je manjša, ko ta doseže površino profila. Hitrost mikrocurka v_{jet}, ki je sorazmerna s tlakom, ki obdaja mehurček blizu površine, je tako manjša.
- Pri večjem deležu plinov je gostota tekočine manjša.
- V območju kavitacije, kjer je tlak precej nižji od sistemskega tlaka (približno 2 kPa), se raztopljeni plini sprostijo v obliki mehurčkov. Večja začetna količina plinov v vodi vpliva na večjo količino sproščenih mehurčkov. Zaradi tega je hitrost zvoka v mešanici mehurčkov in vode odvisna od začetnega deleža plinov v vodi.

Napetost v materialu, ki jo povzroči udarec mikrocurka, je primerljiva z napetostjo ob vodnem udaru ($p = v_{jet} \cdot c \cdot \rho$) [18]. Verjetno je, da kombinacija prej omenjenih razlogov (zmanjšanje hitrosti mikrocurka v_{jet}, zmanjšanje gostote tekočine r in zmanjšanje zvočne hitrosti c) vpliva na drastično zmanjšanje agresivnosti kavitacijske erozije pri povečanju deleža plinov v vodi.

Slika 10 prikazuje rezultate preizkusov s spremenljivo hitrostjo toka. Količina plinov v vodi je bila pri preizkusih skoraj nespremenljiva (pregl. 1), tako da je na agresivnost kavitacijske erozije vplivala le hitrost toka.

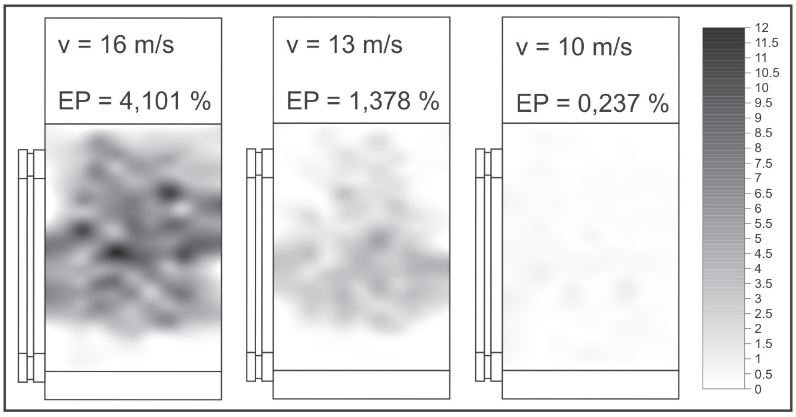
Tok teče od spodaj navzgor. Merilo predstavlja lokalno vrednost erodirane površine (belo 0 %, črno 12 %).

- The water with higher gas content is more compressible, hence the attenuation of the shock wave that is emitted during the bubble-cloud collapse is higher – the magnitude of the shock wave as it reaches the surface of the hydrofoil is smaller. The micro-jet velocity v_{jet} that is proportional to the pressure surrounding the bubble near the surface is therefore smaller.
- The density of the fluid is smaller at a high gas content.
- In the region where cavitation occurs is the pressure much smaller than the system pressure (approximately 2 kPa). The gases that are dissolved in the water are released in the form of bubbles. The bigger the initial gas content the more bubbles are released. The sonic velocity c is therefore a function of the initial gas content of the water.

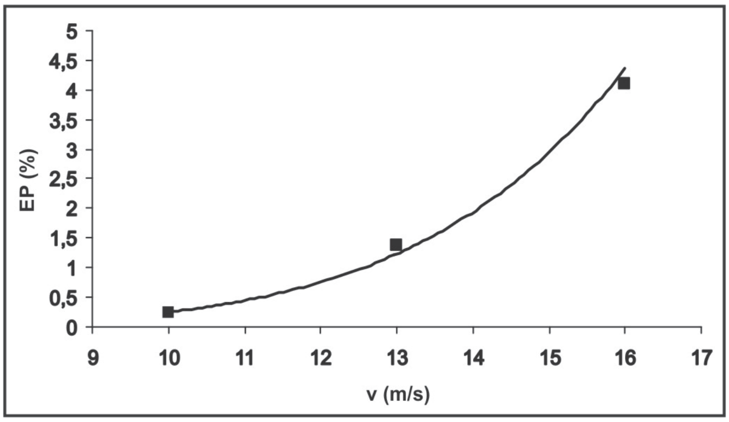
The stress applied to the material during a micro-jet impact can be considered to be of the same magnitude as the water hammer stress ($p = v_{jet} \cdot c \cdot \rho$) [18]. Combining the before-stated reasons (decrease of the micro-jet velocity v_{jet}, decrease of the fluid density ρ and decrease of the sonic velocity c) could explain the drastic decrease of the aggressiveness of cavitation erosion when the gas content is increased.

Figure 10 represents the results of tests with a mean flow-velocity variation. The gas content of water remained almost the same for the experiments (Tab. 1), so only the flow velocity influenced the aggressiveness of the cavitation erosion.

The flow is from the bottom to the top. The scale represents the local percentage of eroded surface (white 0 %, black 12 %).



Sl. 10. *Porazdelitev velikosti poškodbe za različne hitrosti toka*
Fig. 10. *Erosion magnitude distribution for different mean-flow velocities*



Sl. 11. *Erodirana površina (EP) kot funkcija hitrosti toka*
Fig. 11. *Eroded surface (EP) as a function of mean flow velocity*

Povezava med hitrostjo toka in erozijo je očitna. Kavitacija je precej agresivnejša pri večjih hitrostih toka. Ker je bilo kavitacijsko število za vse preizkuse enako, lahko, kakor pri preizkusih s spreminjajočim se deležem plinov v vodi, opazimo, da je porazdelitev luknjic in mesto največje erozije podobno za različne hitrosti toka.

Diagram na sliki 11 prikazuje spremenljivko *EP* kot funkcijo hitrosti toka.

Zopet je vidno očitno povečanje agresivnosti kavitacijske erozije z večanjem hitrosti toka. Vzpostavljen je bil potenčni zakon (en. 2) z $n = 6{,}1$.

Ker je nastanek luknjice zelo zapleten pojav, vrednosti količnika n v potenčnem zakonu ni preprosto razložiti. Nekateri razlogi za povečanje agresivnosti kavitacije, ko se poveča hitrost toka, so:

- Če je kavitacijsko število (en. 1) nespremenljivo, se mora pri spremembi hitrosti razlika tlakov spremeniti kvadratično. To pomeni, da se bo amplituda tlačnega vala, ki se sprosti ob kolapsu kavitacijskega oblaka, prav tako povečala z eksponentom 2.
- Znano je, da je Strouhalovo število (en. 4) za enako kavitacijsko število razmeroma nespremenljivo. Torej se povečanje hitrosti toka kaže v linearnem povečanju frekvence trganja kavitacijskih oblakov; sledi povečanje kolapsov kavitacijskih oblakov, tlačnih valov, udarcev mikrocurkov ob površino in nazadnje luknjic. Strouhalovo število je definirano z:

An obvious relation between the flow velocity and the erosion rate can be seen: the cavitation is much more aggressive at higher flow velocities. As in the case with varying gas content the distribution of the pits and the position of the maximum magnitude of damage is similar for all the tests, since the cavitation number was held constant.

The diagram in Figure 11 shows the variation of *EP* with flow velocity.

Once again an obvious increase of cavitation erosion aggressiveness with velocity can be seen. A power law relation (Eq. 2) with $n = 6.1$ was determined.

Since the pit-formation process is a very complicated phenomenon, the value of the coefficient n of the power law cannot be easily explained. Some reasons for the increase of the cavitation aggressiveness when the flow velocity increases are:

- When the cavitation number (Eq. 1) is constant the pressure difference has to increase with a power of 2 when the velocity is increased. This means that the pressure emitted during bubble-cloud collapse will also rise with the power of 2.
- It is known that the Strouhal number (Eq. 4) remains relatively constant for the same cavitation number [1], hence the increase of the flow velocity leads to a linear increase of the shedding frequency – there are more cavitation-cloud collapses and consequently more shock waves, micro-jet impacts and finally pits. The Strouhal number is defined as:

$$St = \frac{f \cdot d}{v} \qquad (4),$$

kjer so: f značilna frekvenca trganja kavitacijskega oblaka, d značilna (srednja) dolžina kavitacije

where f is the significant shedding frequency, d is the characteristic cavitation-cloud length (remains

(ostaja nespremenjena za nespremenljivo kavitacijsko število [1]) in v hitrost toka.
- V toku obstaja končno število mehurčkov, ki imajo možnost za nastanek mikrocurka. Ker je čas implozije mehurčka (približno 1 ns) precej manjši od časa, ki ga mehurček potrebuje od vstopa do izstopa iz nadzorne prostornine (približno 1 ms), je verjetnost implozije mehurčka v obliki mikrocurka neodvisna od hitrosti toka (hipotezo so potrdili tudi prejšnji preizkusi, npr. [16] govori o verjetnosti 1/30000). Ob povečanju hitrosti se glede na časovni korak število mehurčkov, ki implodirajo v obliki mikrocurka, poveča.

Opisani razlogi bi zadostili povečanju agresivnosti kavitacije za količnik 4. Vendar pa je, kakor smo že omenili, celoten postopek nastanka luknjice (kolaps kavitacijskega oblaka, dušenje amplitude tlačnega vala, nastanek mikrocurka ter vpliv parametrov materiala, ki ga uporabljamo za zaznavalo kavitacijske erozije) prezapleten, da bi lahko vrednost količnika n = 5 do 8 razložili na ta način. Podamo lahko le razloge, ki vodijo do povečanja agresivnosti.

4 SKLEPI

Opisana je bila raziskava vpliva količine plinov v vodi in vpliva hitrosti toka na agresivnost kavitacijske erozije. Metoda štetja luknjic in metoda nanosa tanke bakrene folije na površino profila sta se pokazali kot primerni za meritve kavitacijske erozije.

Preizkusi so pokazali očiten vpliv količine plinov v vodi na agresivnost kavitacijske erozije. Pokazala se je eksponentna zveza, ki je bila tudi kakovostno utemeljena.

S preizkusi smo preverjali in uspešno potrdili hipotezo o potenčni zvezi med hitrostjo toka in agresivnostjo kavitacijske erozije. Prejšnje raziskave so pokazale, da količnik n leži med 5 in 8. Pri prikazani raziskavi je bila določena vrednost količnika 6,1. Podane so tudi nekatere razlage velikega vpliva hitrosti toka na agresivnost kavitacije.

Naslednji korak je povezava rezultatov, ki smo jih dobili z metodo štetja luknjic, z dejansko količino odnesenega materiala. Vzpostavljena povezava bi lahko vodila do precej krajših preizkusov odpornosti materiala na kavitacijsko erozijo.

Končni cilj raziskave je vzpostavitev splošnih povezav in zakonov, ki določajo porazdelitev in velikost poškodb kavitacije, ter razvoj ekspertnega sistema za nadzor kavitacije v hidravličnih strojih.

constant with a constant cavitation number [1]) and v is the flow velocity.
- There is a finite number of bubbles that have the potential to form a micro-jet in the flow. Since the time of bubble implosion (approximately 1 ns) is much smaller than the time needed for the transition of the bubble through the control volume (approximately 1 ms) the probability that a bubble will implode in micro-jet form does not alter with velocity (this hypothesis was also confirmed by past experiments, for example [16] speaks of a probability of 1/30000). Hence, when the velocity is increased, more bubbles implode in the form of a micro-jet in a certain time period.

The stated reasons sum up to the power of 4. But as was stated before, the processes included in pit formation (bubble-cloud collapse, the attenuation of the pressure wave, the micro-jet formation and the parameters of the material used as erosion sensor) are too complicated for the factor n = 5 to 8 to be explained in this manner. We can only suggest where the reasons might lie.

4 CONCLUSIONS

A study of the water-gas content and the flow velocity influence on the aggressiveness of cavitation erosion was presented. A pit-count technique combined with copper coating proved to be a well suited method for measurements of the cavitation erosion.

A clear influence of the water-gas content on the cavitation erosion aggressiveness was found. An exponential relation was established and qualitatively explained.

The well-known power-law for the velocity influence on the cavitation erosion was also tested and successfully confirmed. Previous experimental studies found the factor n to lie between 5 and 8; for these experiments the factor was determined to be 6.1. Also, some explanations for the strong influence are given.

The next step is to link the pit-count results with the actual material mass loss. A possible correlation could lead to a much shorter duration of the tests concerning the material's resistance to cavitation erosion.

The final goal of the research is to find general correlations and rules that determine the distribution and magnitude of damage caused by the cavitation erosion and the development of an expert system for monitoring and controlling the cavitation in hydraulic machines.

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