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Razsipanje moči curka vode v umirjevalni posodi z iglastim zasunom

Dissipation in a Vertical Needle Valve Induced Jet in a Pressure Chamber

Nikola Jelić - Tomaž Kolšek - Anton Bergant - Jože Duhovnik

V tem prispevku prikazujemo rezultate raziskave disipacije moči in vzbujenih nihanj vodnega curka v umirjevalni posodi valjaste oblike. Namen raziskave je bil ugotoviti nestacinarno tokovno polje, ki povzroča močne vibracije okrova posode ter telesa iglastega zasuna. Raziskava je temeljila na uporabi RST metode (računalniška simulacija toka fluida), ki je bila uporabljena na pomanjšanem modelu in skaliranem prototipu konstrukcije. Izkazalo se je, da je mogoče rezultate z modela uporabiti tudi na prototipu z uporabo preprostih skalirnih faktorjev. Pokazali smo, da je mogoče rezultate numerične metode primerjati z eksperimentalnimi rezultati z natančnostjo, ki je uporabna tako za inženirske kakor za znanstvene namene.

(Ključne besede: simuliranje toka, simuliranje računalniško, modeliranje numerično, curek vodni)

In this paper we present the results of a study of power dissipation and induced oscillations in a water jet in a pressure chamber. The purpose of the study was to detect transient flow causing extensive structure oscillations on the chamber and valve body. The study was performed by applying the CFD code to the model and prototype scales and comparing the results. It turned out that the results obtained at the model scale could be applied to the prototype by applying simple scaling rules. It has been shown that the numerical method yielded results that fit reasonably with experiments and might be applied with confidence for both engineering and scientific purposes.

(Keywords: flow simulations, computer simulations, numerical modelling, water jets)

0 UVOD

Raziskava tokovnega polja za izbrano geometrijsko obliko in robne pogoje je pomembna inženirska in raziskovalna naloga, navadno jo je treba rešiti za različne pogoje toka, ki nas zanimajo. Meritve so v splošnem drage in se po navadi izvajajo le na pomanjšanih modelih. Vrednosti na prototipu konstrukcije so navadno predpostavljene z uporabo ustreznih podobnostnih kriterijev, ki pa žal pogosto ne morejo biti izpolnjeni vsi hkrati. To velja še posebno za zapletene geometrijske oblike, pri katerih se pojavlja večje število lokalnih karakterističnih velikosti in s tem povezanih časovnih skal. V takih primerih se zdi najbolj obetajoča metoda računalniško simuliranje toka (RST - CFD), povezana z računalniškim simuliranjem mehanike konstrukcij (RSK - CSM), ki lahko identificirata inženirske in znanstvene probleme. Žal pa so rezultati (podobno kakor pri

0 INTRODUCTION

Investigating fluid flow field distribution for a particular geometry under particular boundary conditions is an important engineering and scientific task that has to be solved for a large number of various complex fluid flow conditions that might be of interest. The experimental method is in general an expensive one and is frequently applied only at laboratory model scale. Results at the prototype scale are usually predicted by using appropriate similarity criteria which, unfortunately, might not all be satisfied simultaneously. This is especially true for complex geometries in which a large number of local characteristic lengths and related time scales play a role. In this situation Computational Fluid Dynamics (CFD) coupled with Computational Structural Mechanics (CSM) appears to be most promising method for finding appropriate engineering solutions and identifying engineering and scientific problems. However, as in experiments, the underlying physics in CFD and meritvah), dobljeni na temelju metod CFD in CSM, pogosto napačno interpretirani. Mnogokrat je to posledica uporabe neprimernih matematičnih modelov ali uporabljenih predpostavk in aproksimacij pri numeričnem modelu kakor tudi morebitnih numeričnih nestabilnosti. Zato mora biti postopek računanja ne samo pazljivo načrtovan in izveden, temveč morata biti primernost in natančnost rezultatov preverjena za vsako novo geometrijsko obliko. Primer geometrijske oblike, ki ga opisuje prispevek, je sestavljen iz navpičnega regulacijskega iglastega zasuna, ki je povezan z valjasto umirjevalno posodo z dodano izhodno cevjo. Tak sistem določa več različnih parametrov, ki jih je treba določiti preden se izvede ekonomsko upravičena, varna in zanesljiva konstrukcija. Med temi parametri so višina posode glede na moč disipacije, kavitacijske karakteristike, pretočni koeficient in spekter ter amplituda nihanja tlaka na stenah. V tem prispevku predstavljamo rezultate, ki utegnejo biti pomembni za bodoča računalniška simuliranja toka v zapletenih sistemih podobnega tipa. Raziskava je bila osredotočena na:

a) raziskavo višine umirjevalne posode glede na optimalno disipacijo moči ter nihanja tlaka,
b) določanje nihanj na pomanjšanem modelu kakor tudi na prototipu (podobnostni zakoni),
c) ugotavljanje pretočnega koeficienta za različna odprtja zasuna,
d) primerjavo z orientacijskimi meritvami na pomanjšanem modelu.

1 OPIS SISTEMA

Slika 1 prikazuje obravnavani sistem. Taka postavitev je značilna in se pogosto uporablja za disipacijo moči ([1] do [4]). Eden od možnih postopkov v numerični analizi je modeliranje le polovice simetričnega sistema, toda tokovno polje bi utegnilo biti asimetrično iz več razlogov, npr. kot posledica "izmenične nestabilnosti" [5]. Namen iglastega zasuna je sprememba potencialne energije vode v kinetično, ki se v obliki vodnega curka s hitrostjo več deset metrov na sekundo vbrizga v umirjevalno posodo. Ta energija se nato disipira v turbulenci, ki jo popisuje v splošnem neznani spekter k-ω, ki končno pojenja na mikroskopskem nivoju v toploto zaradi nelinearnih pojavov.

Območje projektne višine ΔH prototipa je bilo med 100 in 200 metri. Projektna moč, ki jo je bilo treba sipati, je bila 60 MW. Premer umirjevalne posode je bil $d_{ch} = 7$ m in projektna višina umirjevalne posode $h = 17$ m (20 m od dna umirjevalne pososde do zgornjega roba zasuna). Navpični iglasti zasun (sl. 2) je bil postavljen na vrhu v osi posode. Dovod vode v zasun je bil speljan skozi cevno koleno. Notranji premer zasuna na spoju zasun - posoda je znašal 0,7 m (nominalni premer zasuna $d_v = 1{,}4$m). Raziskan je bil primer s t.i. "nenadno razširitvijo"

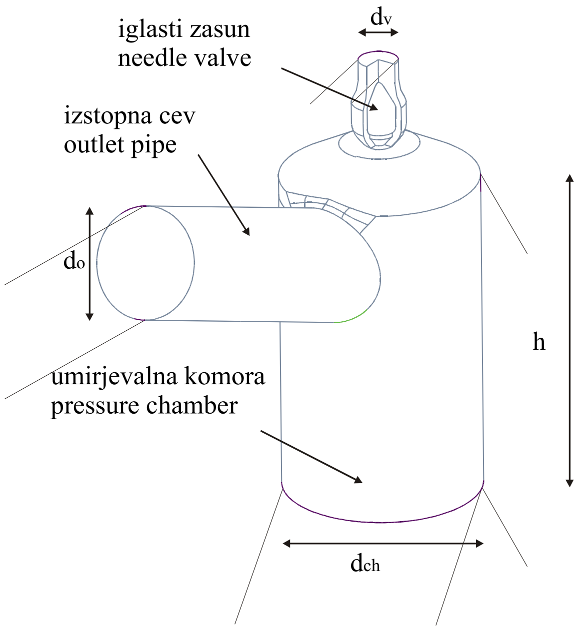
CSM might still remain unclear and largely misinterpreted. This is usually due to effects that arise from improper use of mathematical models or particularly adopted solver assumptions and implemented approximations, as well as due to possible numerical instabilities. Therefore the computational procedure should not only be carefully planned and prepared but the relevancy of the results should be investigated for every new particular geometry. Such a geometry is presented in this paper by a vertical regulating needle valve connected to a dissipation pressure chamber with an outflow pipe. This system is characterized by a variety of fixed and variable parameters that have to be determined before cost-effective design and proper safe and reliable operation can be implemented. Such parameters are chamber height for the predicted water power to be dissipated, cavitation characteristics, discharge coefficient and flow-induced wall pressure oscillations. In this paper we present some of the results that might be relevant for future CFD investigations of complex systems of similar type. These results include:

a) study of chamber height in order to determine the most favorable conditions regarding both power dissipation and pressure oscillations
b) assessing oscillations at both model and prototype scales (similarity rules)
c) determining the discharge coefficient for various valve openings
d) comparison with preliminary measurements at the model scale

1 DESCRIPTION OF THE SYSTEM

The system in question is shown in Fig 1. It represents one of common arrangements used for water power dissipation ([1] to [4]). One approach in numerical analysis could be to model only half of the symmetric system, but we supposed that the flow might not be symmetric for many reasons, e.g., due to a so-called "exchange of instabilities" [5]. The role of the needle valve (Fig. 2) is to transform the potential energy of the water column into kinetic energy in order to be further injected by a high speed of several tens of meters per second into the chamber. This energy is then dissipated into a generally unknown three-dimensional k-ω spectrum that finally decays due to nonlinear phenomena at microscopic level into thermal energy.

The interval of the design head ΔH of the selected prototype valve was between 100 and 200 m. The nominal power which was dissipated was 60 MW. The diameter of the pressure chamber was $d_{ch} = 7$ m and the nominal height was $h = 17$ m (20 m from the chamber bottom up to the valve top). The vertical needle valve (Fig. 2) was positioned at the top of the chamber. The water was supplied to the needle valve through a pipe elbow. The inner diameter of the needle valve at the valve-chamber interface was 0.7 m (nominal valve diameter $d_v = 1.4$ m). The study was performed for a



Sl. 1. *Umirjevalna posoda z iglastim zasunom*
Fig. 1. *Dissipation chamber with needle valve*

izhoda ([6] in [7]), ki ga ponazarja slika 2. Odprtje zasuna smo spreminjali med 10% in 100% pri različnih vhodnih tlakih.

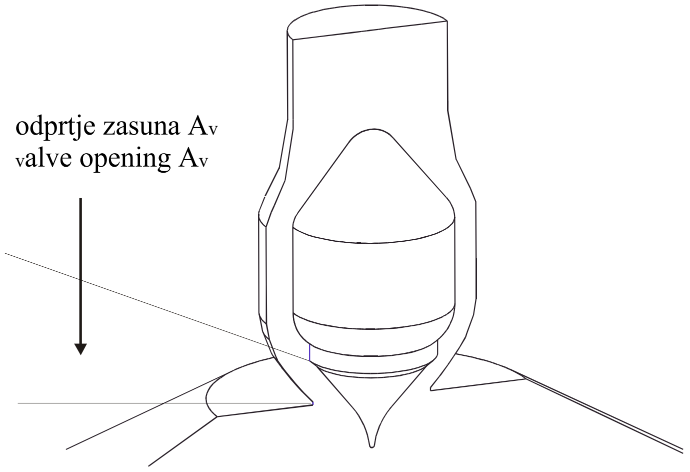
Na voljo smo imeli meritve na modelu, pomanjšanem za faktor $\lambda = 14$ glede na prototip. Glede na Froudov podobnostni zakon morajo veljati naslednji skalirni faktorji:

- dolžina, tlak	λ
- prerez, površina	λ^2
- prostornina, masa, sila	λ^3
- hrapavost sten v ceveh	$\lambda^{1/6}$
- hitrost, čas	$\lambda^{1/2}$
- Reynoldsovo število	$\lambda^{3/2}$
- pretok	$\lambda^{5/2}$

valve with a “sudden expansion” exit ([6] and [7]), see Fig. 2. The valve opening was adjusted continually between 10% and 100% for various pressure heads.

Experimental results were available for a model scaled down by a factor of $\lambda = 14$. The following scale factors resulting from Froude’s similarity law should hold:

- length, pressure	λ
- cross sectional area	λ^2
- volume, mass, forces	λ^3
- pipe wall roughness	$\lambda^{1/6}$
- velocity, time	$\lambda^{1/2}$
- Reynolds number	$\lambda^{3/2}$
- discharge	$\lambda^{5/2}$



Sl. 2. *Iglasti zasun*
Fig 2. *Needle valve*

2 METODA

Uporabljeno je bilo računalniško simuliranje toka s programsko kodo ICCM-Comet enačbah [8], ki temelji na Reynolds-povprečenih Navier-Stokesovih (RPNS) enačbah [9]. Predpostavljen je bil viskozen in turbulenten tok. Sistem enačb RPNS je bil sklenjen z znanim modelom k-ε. Geometrijski model, kakor tudi diskretizacija, sta bila pripravljena s programskim orodjem I-DEAS [10], ki je bil poleg tega uporabljen še za trdnostno analizo zasuna in posode.

Računsko območje smo razdelili v več podobmočij, kar je omogočilo izdelavo blok-strukturirane mreže kontrolnih prostornin (elementov, celic) kvadraste oblike, ki jo je bilo mogoče uporabiti za pripravo izračuna v različnih izračunalnikih toka. Kombinirali smo večje število O in H topoloških shem ter število kontrolnih prostornin postopoma povečevali, da smo dosegli neodvisnost rezultatov od topologije in gostote mreže [9]. Tipično število elementov, nad katerim opazovane količine niso več bile odvisne od gostote mreže, je bilo 100.000 za celoten sistem.

Zaradi velikih vibracij plašča umirjevalne posode, ki je bila predmet meritev, smo se odločili za časovno odvisno (neustaljeno) simuliranje. Kadar curek vode zapusti cev z nenadno razširitvijo, se lahko pojavijo samovzbujana nihanja ([11] in [12]). Pri meritvah smo opazovali statični tlak na več značilnih mestih v posodi (na vrhu, na cilindrični steni, na dnu). Najbolj značilne rezultate smo dobili v merilnih točkah na dnu posode.

3 NUMERIČNI REZULTATI

3.1 Višina posode

Višino posode smo spreminjali, da bi našli najboljšo vrednost glede na največjo moč disipacije pri še sprejemljivih amplitudah nihanja tlaka. Nihanje statičnega tlaka v osi na dnu posode za različne višine posode prikazuje slika 3.

Slika 4 prikazuje odvisnost razlike statičnega tlaka »od vrha do vrha« glede na višino posode. Poudariti je treba, da se dinamična komponenta tlaka $p_{dyn}=\rho v^2/2$ v vseh merilnih točkah ni kaj dosti spreminjala v času, torej je bila glavna nihajoča količina statični tlak.

Količnik disipacije je bil definiran kot razmerje med disipirano močjo in vstopno močjo. Izkazalo se je, da se je 93 ± 0,2% vstopne moči (0,2% je v glavnem posledica nihanja) sipalo neodvisno od višine posode. Presenetljivo se je izkazalo, da je rezultat postal odvisen od začetnih pogojev pri višinah pod 11 m. Ta pojav bo predmet prihodnjih raziskav.

2 METHOD

CFD calculations were performed using ICCM-Comet computer codes [8] based on Reynolds averaged Navier-Stokes (RANS) equations [9]. The flow was assumed to be viscous and turbulent. The system of RANS equations was closed using the well-known k-ε turbulence model. Geometry modeling and grid generation were performed using SDRC I-DEAS software [10], which was also used for additional structural investigations of the mechanical valve and chamber properties.

The computational domain was divided into several sub-domains to enable block-structured hexahedral grid generation, which could easily be input to various fluid flow solver computer codes. A variety of different combinations of O and H topology types of grids were combined and the number of control volumes gradually increased to achieve independence of the results on grid density and the chosen combination of grid topology [9]. The typical number of elements above which the results of interest were not sensitive to the grid density was 100 000 for the entire system.

Due to excessive vibrations of the chamber used in the experiment we decided to perform transient calculations. When a water jet exits a pipe with sudden expansion, self-sustaining oscillations can be expected ([11] and [12]). The static pressure was observed both in numerical and laboratory experiments at several characteristic locations inside the chamber (top, cylindrical wall, bottom). The most representative results were obtained at the measuring points at the bottom of the chamber.

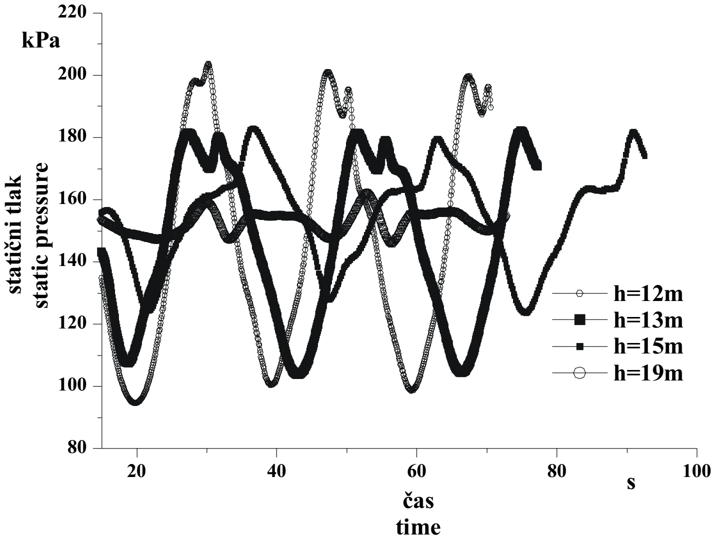
3 NUMERICAL RESULTS

3.1 Height of the chamber

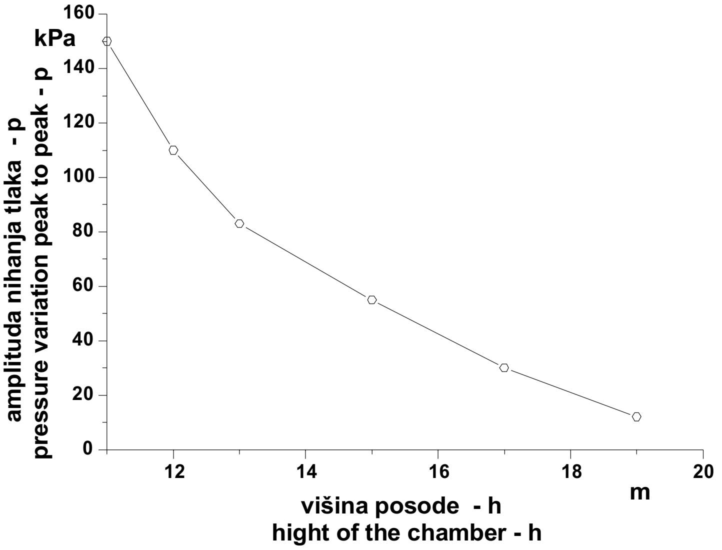
The chamber height was varied in order to find an optimum value that gives maximum power dissipation at an acceptable amplitude of pressure oscillations. The static pressure oscillations at the bottom of the chamber for different chamber heights are shown in Fig 3.

Figure 4 shows the dependence of peak to peak pressure variation as a function of chamber height. It should be pointed out that the dynamic component of the pressure $p_{dyn}=\rho v^2/2$ at any diagnostic point inside the chamber did not change considerably over time, i.e., the main oscillating quantity was the static pressure.

Calculation of the dissipation rate was defined as the ratio of dissipated power over input power. It turned out that 93 ± 0.2% of the inflow energy (the ± 0.2% was mainly related to the oscillations when present) was dissipated independently of the height of the chamber. This conclusion holds in the range 7 to 19 m of the chamber height. However, for heights below 11m the solution became sensitive to initial conditions. This phenomenon will be the subject of future studies.



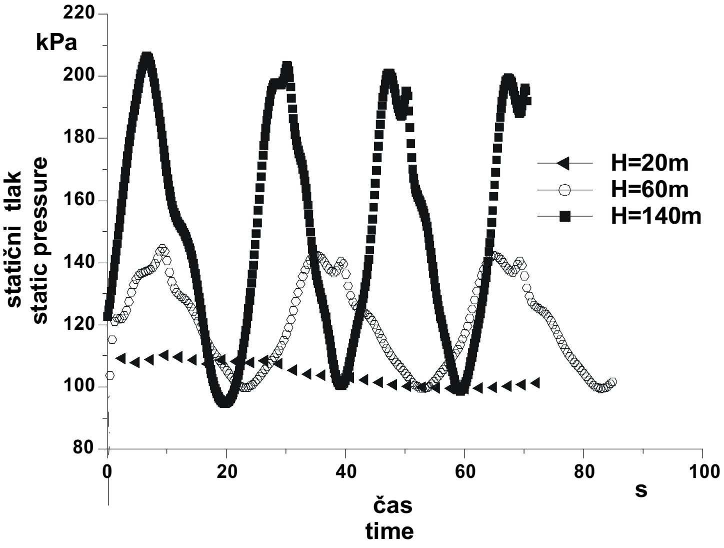
Sl. 3. *Nihanje statičnega tlaka na dnu posode za različne višine posode*
Fig. 3. *Oscillation of static pressure at the bottom of the chamber for different chamber heights*



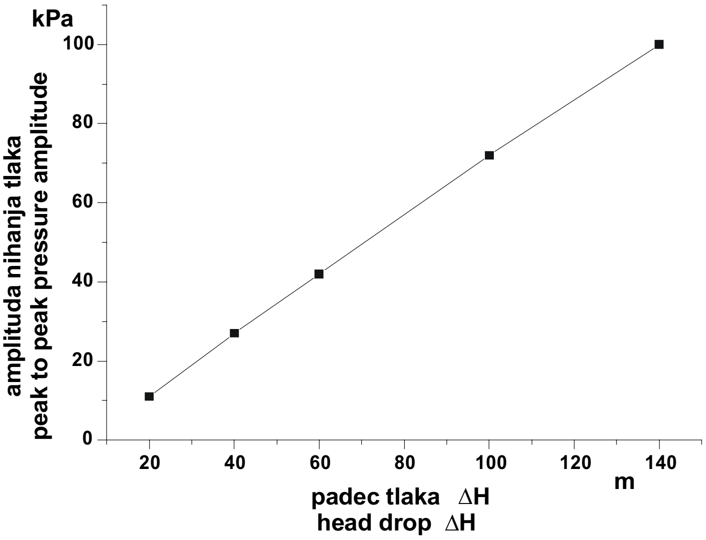
Sl. 4. *Razlika statičnega tlaka »od vrha do vrha« v odvisnosti od višine posode*
Fig. 4. *Peak to peak pressure variation as a function of chamber height*

Iz inženirskega vidika je bilo treba določiti višino, nad katero se niso več pojavile velike mehanske obremenitve. Osredotočili smo se na ugotavljanje veljavnosti podobnostnih zakonov pri neustaljenem stanju. Zato smo raziskali tokovna polja pri tistih višinah posod, pri katerih so se pojavljala nihanja. Ugotavljali smo tudi povezavo med amplitudami nihanj ter padcem tlaka med vstopom in izstopom, izraženim v obliki $\Delta H=\Delta p_{tot}/\rho g$ (Δp_{tot} pomeni razliko totalnega tlaka ($p_{tot}=p+p_{dyn}$) med vstopom in izstopom, ρ je gostota vode in g je težnostni pospešek). Slika 5 ponazarja nihanje tlaka na dnu posode pri različnih padcih tlaka med vstopom in izstopom za izbrano višino posode h = 12 m. Slika 6 pa prikazuje razliko tlaka od vrha do vrha v odvisnosti od padca tlaka ΔH med vstopom in izstopom.

From the engineering point of view it was important to determine the chamber height above which there were no excessive mechanical loads. We focused our attention on the validation of similarity laws under transient conditions. Therefore we investigated chamber heights with expressed oscillations. We also determined the relation between oscillation amplitudes and the pressure head $\Delta H=\Delta p_{tot}/\rho g$ (where Δp_{tot} is the difference of the total pressure ($p_{tot} = p+p_{dyn}$) between the inlet and outlet, ρ is the water density and g represents acceleration due to gravity). In Figure 5 the time dependence of the chamber pressure for different head drops is illustrated for the case of constant chamber height h = 12m. Figure 6 shows the quantitative dependence of peak to peak pressure variation on the pressure drop ΔH for the same chamber height.



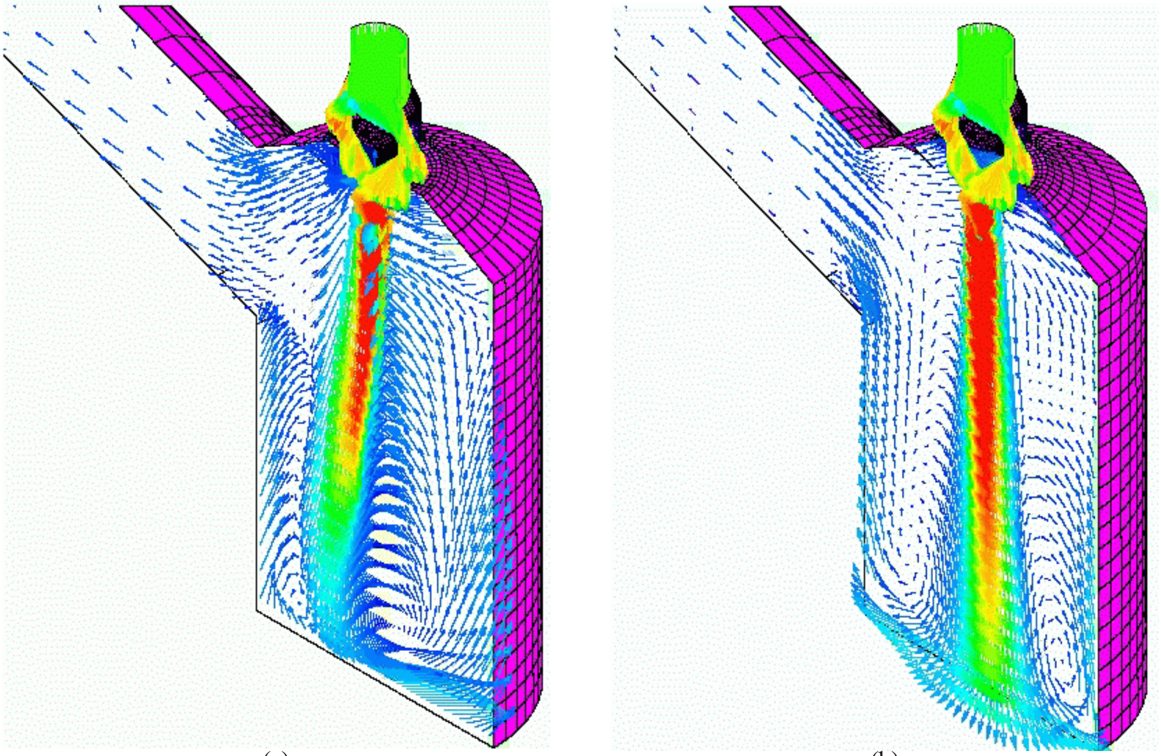
Sl. 5. *Časovna odvisnost tlaka v merilni točki za različne padce tlaka med vstopom in izstopom ΔH*
Fig. 5. *Time dependence of the chamber pressure for different system pressure drops ΔH*



Sl. 6. *Odvisnost razlike tlaka »od vrha do vrha« v odvisnosti od padca tlaka med vstopom in izstopom ΔH*
Fig. 6. *Dependence of peak to peak pressure variation on system pressure drop ΔH*

Podlaga za fizikalni pojav opaženih nihanj je povezana s povratnim učinkom ujetja in posledično nastajanje področij recirkulacij znotraj posode. Čeprav je celotni pretok nihal le za nekaj odstotkov, je mogoče na podlagi slik 7a in 7b sklepati, da je šlo za večje kakovostne spremembe v hitrostnem polju. Vodni curek je periodično spreminjal smer. Njegova kinetična energija je bila disipirana v celoti znotraj posode, medtem ko je bila dinamična komponenta tlaka znotraj izstopne cevi zanemarljiva. Velike kakovostne spremembe hitrosti so se pojavile ne začetku izstopne cevi, kjer so vektorji hitrosti spreminjali svojo velikost in smer za 360 stopinj. Z animacijo je mogoče prepoznati nastanek recirkulacijskih področij (celic). Animacijo z boljšim vpogledom v spreminjanje tlačnega in hitrostnega polja je mogoče najti na naslovu http://www.lecad.uni-lj.si/~jelic/anima.

The underlying physics of the observed oscillations is related to the feedback effect of confinement and the consequent formation of recirculation water zones inside the chamber. Although the total discharge rate oscillated by only several percent, it can be seen in Figs. 7a and 7b that the velocity field distribution qualitatively exhibited large changes over time. The water jet periodically changed direction. Its energy was dissipated exclusively inside the chamber while the dynamic component of the pressure inside the outflow pipe was negligible. Prominent qualitative changes of velocity occurred at the start of the outflow pipe, where velocity vectors change their magnitude and direction by 360 degrees. With the help of animation, the formation of recirculation zones (cells) could be recognized. Animation of the described behavior with more details, including both pressure and velocity fields, can be found at http://www.lecad.uni-lj.si/~jelic/anima.


(a) (b)

Sl. 7. *Hitrostno tokovno polje na simetrijski ravnini za h = 12 m, ΔH = 60 m pri dveh različnih časih t = 22 s (a) in t = 35 s (b)*

Fig. 7. *Velocity distribution at the symmetry plane for h = 12 m, ΔH = 60 m at two different times t = 22 s (a) and t = 35 s (b)*

Glede na dobljene rezultate smo se odločili, da bomo opazovali tok pri višini posode $h = 12$ m, kjer so bila nihanja dobro izražena in neodvisna od začetnih pogojev.

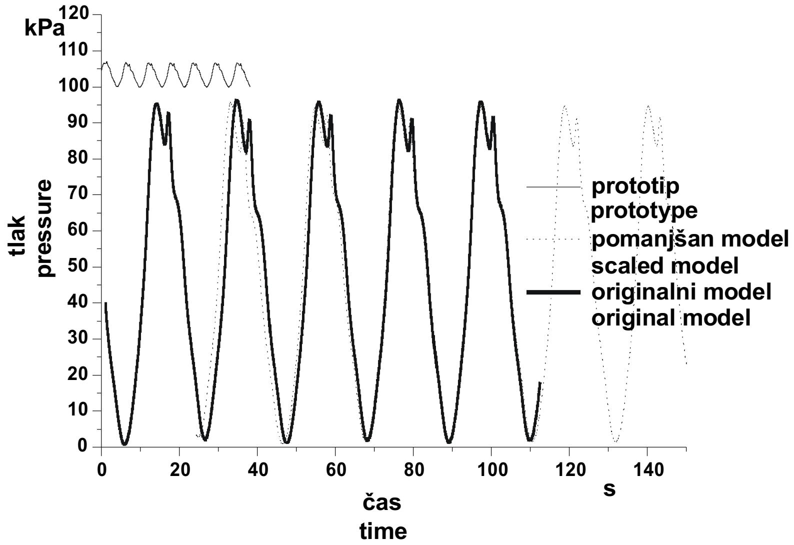
3.2 Podobnost

Raziskovali smo podobnost toka v prototipu in modelu. Linearno pomanjšanje z $\lambda = 14$ je bilo primerno za gradnjo modela kakor tudi za merjenje načrtovanega totalnega tlaka. Opazovali in primerjali smo časovno odvisno hitrostno in tlačno polje za model in prototip. Kakovostno obnašanje je bilo zelo podobno med obema sistemoma v času kakor tudi v prostoru, tj. gibanje vodnega curka je bilo pri obeh numeričnih modelih tako, kakor je prikazano na slikah 7a in 7b. Poleg tega smo primerjali kvantitativne rezultate v izbranih točkah, ki so se zdele značilne. Na sliki 8 predstavlja tanka črta rezultat izračuna na modelu in debela črta rezultat izračuna tlaka na prototipu v opazovani točki na dnu posode. Padec tlaka med vstopom in izstopom je bil $\Delta H = 70$ m za prototip in $\Delta H = 5$ m za model. Nato smo prenesli rezultat z modela glede na opisane podobnostne zakone, in sicer amplitudo tlaka za faktor $\lambda = 14$, čas pa za $\lambda = 14^{1/2} = 3{,}74$. Tako preslikano krivuljo ponazarja pikčasta črta na sliki 8. Očitno je, da je ujemanje med rezultati simuliranja

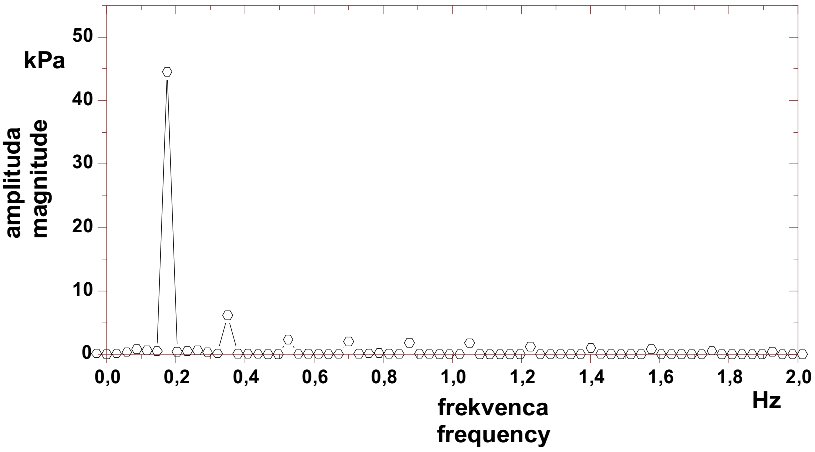
Considering the above results, we decided to focus our attention on the representative chamber length of 12 m where oscillations were well pronounced and were independent of the initial conditions.

3.2 Similarity rules

We investigated the similarity of the prototype to the model. Linear scaling at $\lambda = 14$ was determined to be appropriate for both building the experimental setup and measuring the estimated total pressure of the prototype at model scale. The velocity and pressure distribution over time were observed and compared for model and prototype. The qualitative behavior was very similar for both systems in time as well as in space, i.e., the motion of the water jet in the model was the same as demonstrated in Figs. 7a and 7b for the prototype. In addition, quantitative results were compared in particular locations that seemed to be representative. In Fig. 8 the thin line represents the results of the model and the thick line the results of the prototype obtained for the pressure at the bottom of the chamber. Pressure drop was ΔH=70m for the prototype, ΔH=5m for the model. However, we rescaled the results obtained on the model according to the above-mentioned similarity relations by multiplying the amplitude of the pressure by a factor of $\lambda = 14$ and by multiplying the time by $\lambda = 14^{1/2} = 3.74$. The resulting curve is shown in Fig. 8 by a dotted line. It can be seen



Sl. 8. *Primerjava statičnega tlaka na dnu posode za model in prototip*
Fig. 8. *Comparison of the static pressure obtained at the bottom of the chamber in model and prototype*



Sl. 9. *Amplitudni frekvenčni spekter nihanja tlaka iz izračuna na modelu*
Fig. 9. *Magnitude frequency spectrum of pressure oscillations obtained in model scale computations*

na modelu in rezultati simuliranja na prototipu odlično.

Pripadajoči frekvenčni spekter je prikazan na sliki 9. Sklepamo torej lahko, da je mogoče rezultate izračuna na modelu uporabiti na prototipu in nasprotno.

4 PRIMERJAVA NUMERIČNEGA IZRAČUNA NA MODELU Z EKSPERIMENTALNIMI MERITVAMI

4.1 Nihanja

Meritve na modelu so opravili na Inštitutu za hidravlične raziskave v Ljubljani. Opazili smo nihanja z osnovno frekvenco rahlo pod 0,2 Hz. Amplitudni frekvenčni spekter je prikazan na sliki 10. Amplituda glavnega vrha je nekoliko nad 10 kPa, toda celotna amplituda razlike tlaka “od vrha do vrha“, ki

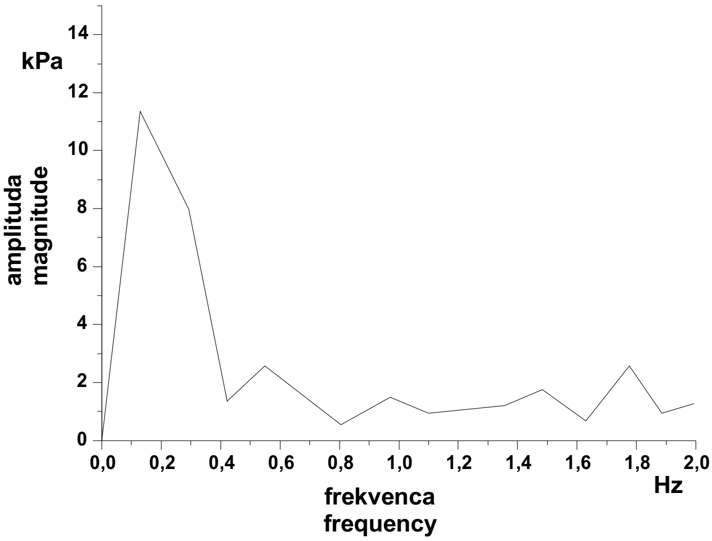
that agreement between the measured and computed curves is excellent.

The corresponding frequency spectrum is shown in Fig. 9. The above result means that it would be entirely acceptable to apply the results obtained on the model to the prototype, and vice versa.

4 COMPARISON OF MODEL SCALE COMPUTATIONAL RESULTS WITH LABORATORY EXPERIMENTAL RESULTS

4.1 Oscillations

Preliminary experiments were performed at model scale at the Institute of Hydraulic Research, Ljubljana, Slovenia. Oscillations were observed with a pronounced peak slightly below 0.2 Hz. The FFT spectrum is shown in Fig. 10. The amplitude of the main peak is slightly above 10 kPa but the total peak to peak amplitude of oscillations



Sl 10. *Amplitudni frekvenčni spekter nihanj, izmerjenih na modelu*
Fig 10. *Magnitude frequency spectrum of oscillations obtained in model scale experiment*

ima vir še v drugih frekvencah, je okoli 40 kPa. Na sliki 10 primerjamo te rezulate z numeričnimi rezultati s slike 8. V računalniškem izračunu je osnovna frekvenca pri 0,18 Hz, kar se dobro ujema z meritvami.

Pri računalniškem izračunu se pojavljajo dobro izražene višje harmonske glavnih frekvenc, medtem ko so pri preskusu višje harmonske dušene ter izražene še druge frekvence, kar lahko pripišemo povezanim mehanskim ter hidromehanskim nihanjem. Razlika tlaka »od vrha do vrha« je bila pri numerični raziskavi okoli 60 kPa, kar je primerljivo z eksperimentalnim rezultatom 40 kPa.

4.2 Pretočna karakteristika

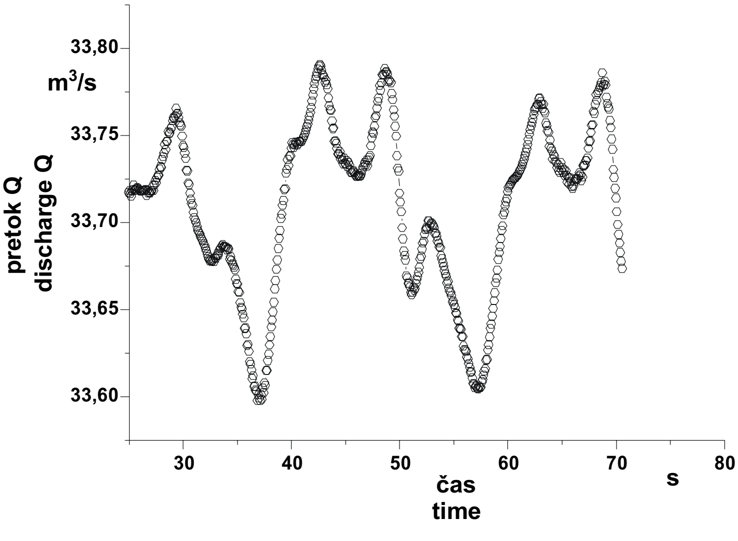
Pretok se s časom ni dosti spreminjal. Slika 11 prikazuje spreminjanje pretoka *Q(t)* pri prototipu

originating for other frequencies is about 40 kPa. In Fig 10 we compare these results with the numerical results from Fig 8. In a computational run the main frequency was about 0.18 Hz, which is in good agreement with the experiment.

In the numerical run there are well-defined harmonics of the main frequencies. In the experiment, due to coupled mechanical and hydrodynamic oscillations, higher harmonics were damped and other frequencies are also detected. The peak to peak pressure amplitude in numerical calculations was above 60 kPa, which is in fair agreement with the experimentally observed result of 40 kPa.

4.2 Discharge characteristics

The discharge did not greatly depend on time. Fig. 11 shows computed prototype discharge



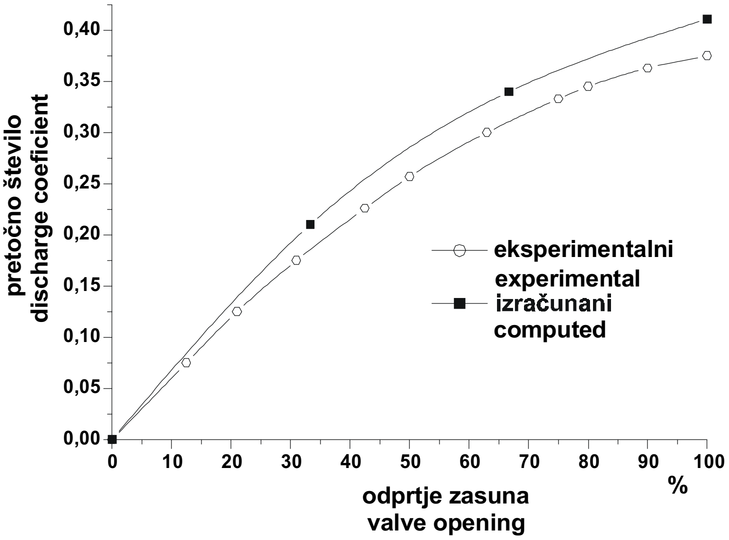
Sl. 11. *Odvisnost pretoka od časa*
Fig. 11. *Dependence of discharge on time*

pri pogojih, opisanih v poglavju 3.2. Padec tlaka med vstopom in izstopom ΔH je bil prav tako časovno neodvisen. Zato lahko štejemo, da je tudi pretočni koeficient $c_d=Q/A/(2g\Delta H)^{1/2}$ ustaljen.

Slika 12 prikazuje primerjavo med odvisnostjo pretočnega koeficienta od odprtja zasuna pri meritvah in simuliranju. Razvidno je, da je izračunani pretočni koeficient nekoliko precenjen (za okoli 8%). To lahko pripišemo podrobnostim geometrijskih oblik, ki niso bile del računalniškega modela (notranja rebra, ki nosijo telo igle, zmanjšajo vstopni prerez za okoli 5%). Poleg tega je mogoč vpliv težnosti na pretočno karakteristiko. Zato ugotavljamo, da so dobljeni rezultati v okviru pričakovanj in zanesljivosti.

variation $Q(t)$ under the same conditions as described in section 3.2. The pressure drop ΔH was also independent of time. Therefore the discharge coefficient $c_d=Q/A/(2g\Delta H)^{1/2}$ might be regarded as independent of time.

In Fig. 12 we present the discharge curve obtained by experiment as compared with the numerical results for the valve openings of 33, 67 and 100%. It can be seen that the computed discharge coefficient was slightly overestimated (by about 8%). This can be explained by geometric details that were not part of the numerical model (inner supports holding the valve and decreasing the inflow surface by about 5 %). In addition, we supposed that the gravity in a real system might slightly influence the discharge conditions as well. Therefore we assume that the obtained results are quite reasonable.



Sl. 12. *Primerjava izračunanega in eksperimentalnega pretočnega koeficienta*
Fig. 12. *Comparison of computed and experimental discharge coefficients*

5 SKLEP

Raziskali smo neustaljeni tok fluida v zapleteni geometrijski obliki z uporabo numeričnega simuliranja in potrdili rezultate z orientacijskimi meritvami. Geometrijska oblika je bila sestavljena iz navpičnega iglastega zasuna za ustvarjanje vodnega curka in posode za disipacijo kinetične energije. Neustaljenost toka je bila dobro izražena pri ustaljenih robnih pogojih.

Opazovali smo samovzbujana nihanja vodnega curka, ki so bila neodvisna od začetnih pogojev. Ugotovili smo, da sta frekvenca in amplituda nihanj odvisni od dimenzij posode (višina), pa tudi od padca tlaka med vstopom in izstopom. Medtem ko sta bili lokalno tlačno in hitrostno polje neustaljeni, so bile makroskopske količine (moč disipacije, pretok) skoraj nespremenjene.

Podobnost med pomanjšanim modelom in prototipom pri ustrezno izbranem pomanjševalnem razmerju je bila potrjena z veliko natančnostjo.

5 CONCLUSION

A study of a non-stationary flow in a complex fluid flow geometry was performed using numerical simulations and confirmed by preliminary experimental measurements. The geometry basically consists of a vertical needle valve for generating a water jet and a chamber for kinetic energy dissipation. A transient flow field was well expressed under the stationary boundary conditions imposed.

The self-sustaining oscillations of the water jet were observed independently of initial conditions. It has been shown that the frequency and amplitude of the oscillations depend on chamber dimensions (height) as well as on the system head. However, while the local pressure and velocity distribution were essentially functions of time, macroscopic parameters such as the discharge and power dissipation are rather constant.

Similarity between the model and prototype for a reasonable chosen scaling factor has been confirmed with a high accuracy. It has been shown that

Ugotovili smo, da je neustaljeno obnašanje prototipa mogoče napovedati tudi z modelom.

Rezultate numeričnega simuliranja smo primerjali z eksperimentalnimi. Pokazali smo dobro ujemanje frekvence in amplitude nihanj pa tudi časovno povprečenih makroskopskih veličin, kakršen je pretočni koeficient.

Nadaljnje raziskave bodo usmerjene v opazovanje sistema pri še manjših višinah posode, pri katerih postane sistem odvisen od začetnih pogojev.

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the transient behavior of the prototype can be predicted well by using the model scale.

The results of numerical simulations were compared with those obtained experimentally and good agreement was found concerning the frequency and amplitude of oscillation as well as concerning the time-averaged macroscopic quantities such as the discharge coefficient.

Further studies should be performed on shorter dissipation chambers for which the behavior of the system proved to be sensitive to initial conditions.

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Naslova avtorjev: dr. Nikola Jelić
doc.dr. Anton Bergant
Litostroj, E.I.
Litostrojska 40
1000 Ljubljana

mag. Tomaž Kolšek
prof.dr. Jože Duhovnik
Fakulteta za strojništvo
Univerze v Ljubljani
Aškerčeva 6
1000 Ljubljana

Aurhors' Addresses: Dr. Nikola Jelić
Doc.Dr. Anton Bergant
Litostroj, E.I.
Litostrojska 40
1000 Ljubljana, Slovenia

Mag. Tomaž Kolšek
Prof.Dr. Jože Duhovnik
Faculty of Mechanical Eng.
University of Ljubljana
Aškerčeva 6
1000 Ljubljana, Slovenia

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