**Univerzitet u Beogradu**
**Mašinski fakultet**

**Sanja S. Milivojević**

# HIDRAULIČKI UDAR U DVOFAZNOM SISTEMU

**Beograd, 2019**

Doc. dr Sanja S. Milivojević

HIDRAULIČKI UDAR U DVOFAZNOM SISTEMU

Prvo izdanje

Recenzenti:
Prof. dr Vladimir Stevanović, redovni professor, Mašinski fakultet, Univerzitet u Beogradu
Dr Milan Rajković, naučni savetnik, Institut za nuklearne nauke “Vinča”
Dr Milada Pezo, viši naučni saradnik, Institut za nuklearne nauke “Vinča”

Izdavač:
Mašinski fakultet, Univerzitet u Beogradu
Kraljice Marije 16, 11120 Beograd 35, Srbija
Tel: +381 (0)11 3370 350; Fax: +381 (0)11 3370 364

Za izdavača:
Dekan Prof. dr Radivoje Mitrović

Urednik:
Prof. dr Milan Lečić

Tiraž: 10 primeraka

Štampa:
PLANETA PRINT, Ruzveltova 10, 11 000 Beograd, Srbija

ISBN 978-86-6060-015-0

## PREDGOVOR

Direktan kontakt parne faze i pothlađene tečne faze u cevi ili posudi pod pritiskom vodi do intenzivne kondenzacije pare praćene padom pritiska u zapremini pare i ubrzavanja okolne mase tečnosti ka zapremini koju je ispunjavala para, što dovodi do nastanka hidrauličkog udara i može izazvati teška oštećenja postrojenja. Ovaj fenomen se naziva hidraulički udar izazvan kondenzacijom pare, (eng. Condensation Induced Water Hammer). Razvijen je jednofluidni model za predviđanje prostiranja talasa pritiska tokom hidrauličkog udara. Pokazano je da pouzdano predviđanje prostiranja talasa pritiska veoma zavisi od određivanja brzine kondenzacije, nestacionarnog trenja i praćenja kretanja razdelne površine tečne i parne faze. Primenjen je novi pristup rešavanju problema uvođenjem modela koji prati kretanje razdelne površine i uzima u obzir nestacionarni karakter promene brzine kondenzacije. Poređenjem rezultata dobijenih primenom jednofluidnog modela na predviđanje prostiranja talasa pritiska sa izmerenim podacima na eksperimentalnim aparaturama za proučavanje hidrauličkog udara izazvanog kondenzacijom pare dostupnim u literaturi dobijeno je zadovoljavajuće slaganje. Primećeno je značajno rasipanje podataka dobijenih eksperimentalnim putem pri istim uslovima eksperimenta, koje je posledica brzine kondenzacije i njene zavisnosti od zahvaćenih kapljica - koncentracije razdelne površine parne i tečne faze u blizini čela stuba tečnosti.

Većina objavljenih rezultata je rezultat rada na projektu "Napredne analitičke, numeričke i metode analize primenjene mehanike fluida i kompleksnih sistema" (2010) finansiranom od strane Ministarstva za nauku i tehnološki razvoj Republike Srbije (sada Ministarstvo prosvete, nauke i tehnološkog razvoja) u okviru Programa osnovnih istraživanja za naučnu oblast Matematika, kompjuterske nauke i mehanika, broj projekta (ON714014). Autor se zahvaljuje kolegama koji su doprineli zajedničkim radovima citiranim u ovoj monografiji, kao i recenzentima.

**SADRŽAJ:**

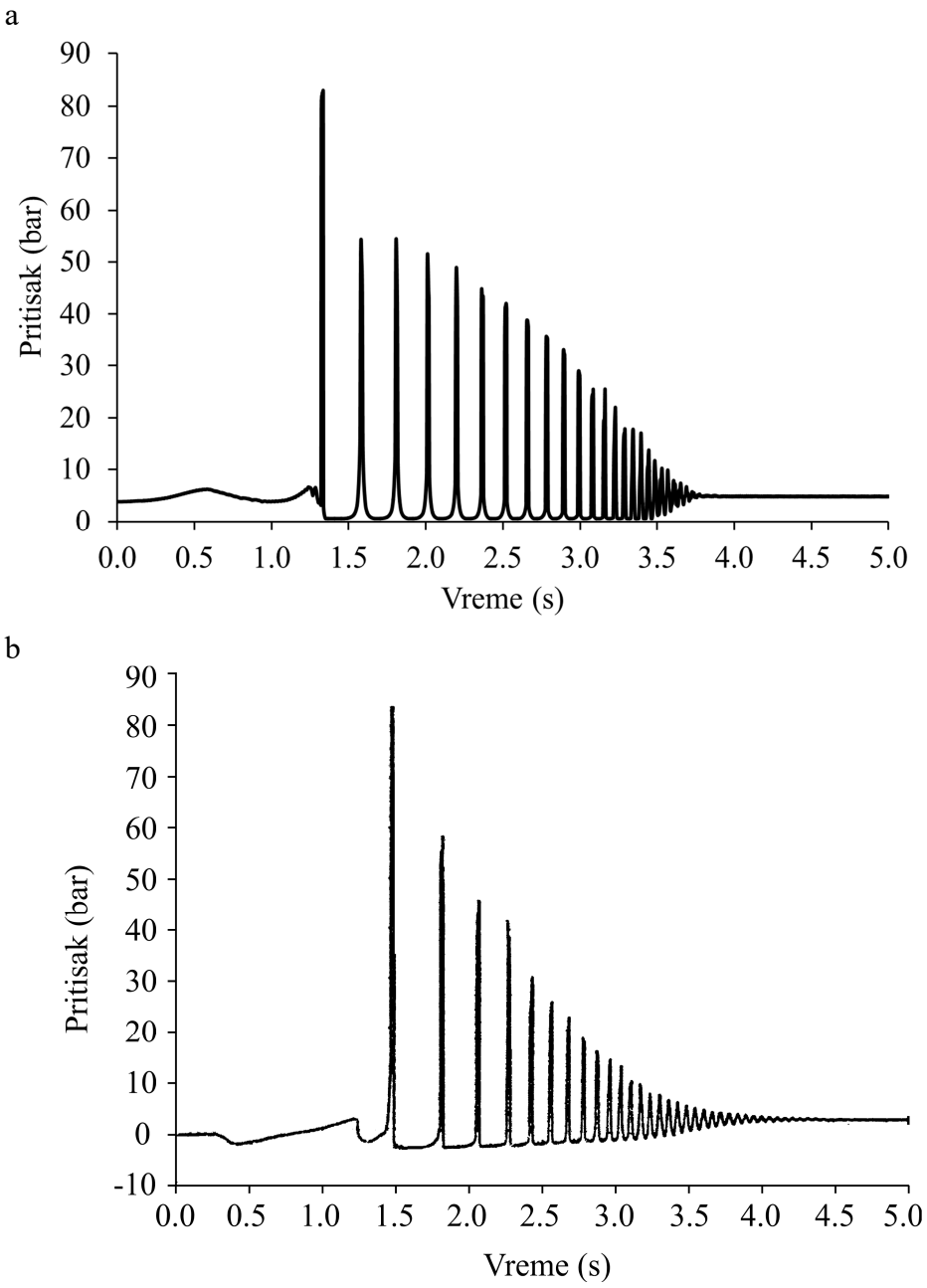
## LITERATURA


1. Barna, I.F., Inre, A.R., Baranyai, G., Ezsol, G., Experimental and Theoretical Study of Steam Condensation Induced Water Hammer Phenomena, Nuclear Engineering and Design, 240, 2010, str. 146-150.
2. Beuthe, T.G., Review of Two-Phase Water Hammer, Proceedings of the 18th Annual Canadian Nuclear Society Conference, Toronto, Canada, 1997.
3. Bjorge, R.W., Griffith, P., Initiation of Water Hammer in Horizontal and Nearly Horizontal Pipes Containing Steam and Subcooled Water, ASME J. Heat Trans., 106, 1984, str. 835-840.
4. Blömeling, F., Neuhaus, T., Schaffrath, A., Development and Validation of DYVRO for the Simulation of Condensation Induced Water Hammer: Comparison with a Two-Phase Slug Model and with Experimental Data of the Water Cannon Experiment, The 15th International Topical Meeting on Nuclear Reactor Thermal - Hydraulics (NURETH-15), Pisa, Italy, May 12-17, 2013, NURETH15-307
5. Choi, D.K., PIPES – A Computer Code for Analysis of Dynamic Hydraulic Response in Plant Piping Systems, Windsor, 1983.
6. Chun, M.H., Yu, S.O., A Parametric Study and a Guide Chart to Avoid Condensation/Induced Water Hammer in a Horizontal Pipe, Nuclear Engineering and Design, 201, 2000, str. 239-257.
7. Demidovitch, B., Maron, I., Elements de calcul numerique, Editions Mir, Moscou, 1987.
8. de Vries, M., Simon, A., Suction Effects on Feedpump Performance: A Literature Survey, Sulzer Brothers Limited, EPRI Report CS-4204, Palo Alto, USA, 1985.
9. Dittus, F.W., Boelter, L.M.K., Heat Transfer in Automobile Radiators of the Turbulent Type. University of California Publications, Vol. 2, 1930, str. 443-461.
10. Ghiaasiaan, S.M., Two-phase flow, boiling, and condensation. Cambridge University Press, 2008, str. 482.
11. Gruel, R. L., Huber, P. W., Hurwitz, W. M., Piping Response to Steam-Generated Water Hammer, Journal of Pressure Vessel Technology, Vol. 103, August 1981, str. 219-225.
12. Joukowsky, N., Water Hammer. Transleted by O. Simon, Proc. American Water Works Association, 1904, str. 24.
13. Jovanović, M., Jocić, Lj., Instalacija i postupak za sprečavanje hidrauličkog udara u postrojenju pumpe za napajanje vodom generatora pare, Patent br. 47840, Zavod za intelektualnu svojinu, Beograd, 1996.
14. Kirsner, W., Waterhammer, HPAC Heating/Piping/Air/Conditioning, January 1999, str. 113-122.

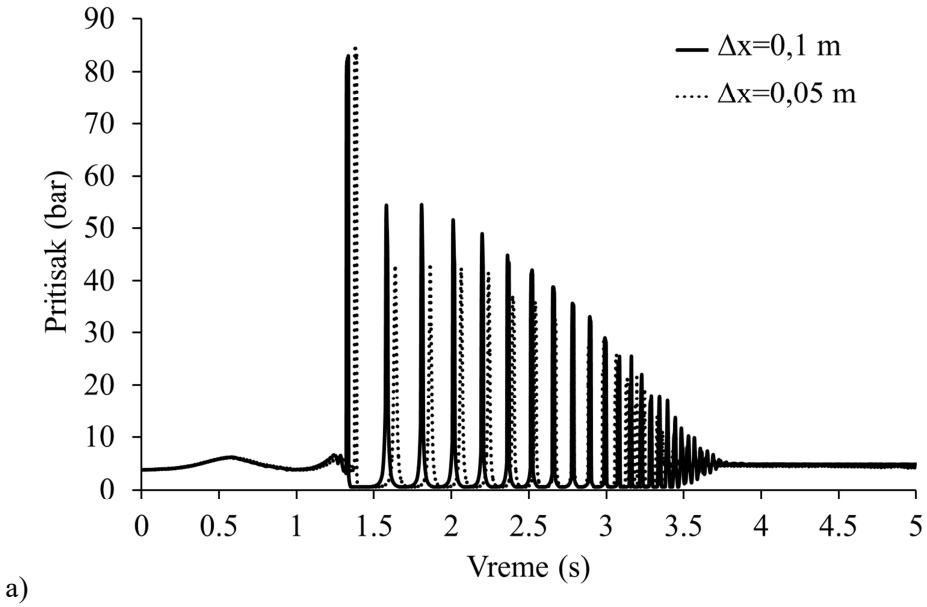
15. Kronig, R., Brink, J.C., On the theory of extraction from falling droplets. Applied Science Research, A2, 1950, str. 142-154.
16. Kucienska, B., Seynhaeve, J.M., Giot, M., Friction relaxation model for fast transient flows application to water hammer in two-phase flow – the WAHA code. International Journal of Multiphase Flow 34, 2008, str. 188–205.
17. Kuznecov, Y.N., Heat transfer in safety problems of nuclear reactors, Energoatomizdat, Moskva, 1989, str. 67.
18. Liu, W.S., Tahir, A., Zaltsgendler, E., Kelly, W., Leung, R.K., Development Status of TUF Code, Proceedings of the 17th Annual CNS Conference, Canadian Nuclear Society, Fredericton, Canada, 1996.
19. Liu, W.S., Hanna, B., Zaltsgendler, E., Advances in Modelling of Condensation Phenomena, Proceedings of the Annual Meeting of the Nuclear Society, Toronto, Canada, 1997.
20. Martin, C.S., Condensation – Induced Water Hammer in a Horizontal Pipe, Proceedings of the 3rd IAHR International Meeting of the Workgroup on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, Brno, Czech Republic, 2009, str. 397-407.
21. Milivojevic, S., Stevanovic, V., Maslovaric, B., Condensation Induced Water Hammer: Numerical prediction, Journal of Fluids and Structures, 50, 2014, str. 416-436.
22. Milivojevic, S., Stevanovic, V., Maslovaric, B., Numerical Simulation of Condensation Induced Water Hammer, The 15th International Topical Meeting on Nuclear Reactor Thermal - Hydraulics (NURETH-15), Pisa, Italy, May 12-17, 2013, NURETH15-171.
23. Neuhaus, T., Dudlik, A., Experiments and Comparing Calculations On Thermohydraulic Pressure Surges in Pipes, Proceedings of the Eleventh International Topical Meeting on Nuclear Reactor Thermal-Hydraulics (NURETH-11), Avignon, France, October 2-6, 2005, Paper: 540.
24. Prica, S., Stevanović, V., Maslovarić, B., Numerical simulation of condensation induced waterhammer, Proceedings of the 12th International Conference on Nuclear Engineering, Arlington, Virginia USA, April 25-29, 2004, ICONE12-49404.
25. Prica, S., Numerička simulacija hidrauličkog udara izazvanog kondenzacijom pare, Magistarski rad, Mašinski fakultet, Beograd, 2006.
26. Prica, S., Stevanović, V., Maslovarić, B., Numerical Simulation of Condensation Induced Water Hammer, FME TRANSACTIONS, New Series, Vol. 36, No. 1, 2008, str. 21-26.
27. Prica, S., Stevanović, V., Maslovarić, B., Vapour-Liquid Interface Tracking And Condensation Induced Water Hammer Predictions, 2nd International Congress of Serbian Society of Mechanics, Palić, Srbija, June 1-5, 2009.

28. Saito, T., Hughes, D. D., Carbon, M. W., Multi-fluid modeling of annular two-phase flow, Nuclear Engineering and Design, 50, 1978, str. 225-271.
29. Seo, J. S., Bankoff, S. G., "Entrainment and Condensation Effects in the Upward Acceleration of a Liquid Column", Proc. 3rd International Topical Meeting on Nuclear Power Plant Thermal Hydraulics and Operations, Seoul, Korea, 1988.
30. Serkiz, A.W., An Evaluation of Water Hammer in Nuclear Power Plants, Proceedings of the 2nd International Topical Meeting on Nuclear Reactor Thermalhydraulics, Santa Barbara, California, USA, 1983.
31. Shu, J., Modelling Vaporous Cavitation on Fluid Transients, International Journal of Pressure Vessels and Piping 80, 2003, str. 187-195.
32. Spalding, D. B., Jun, L., Qin, H., Radosavljevic, D., Taylor, K., Villasenor, F., Walsh, M. C., Wu, Z., "Problem Specifications and Collated Solutions of the Two-phase Numerical Benchmark Exercise 1986-7", Imperial College of Science and Technology, Report No. CFD/87/1, London, UK, 1987.
33. Stevanović, V., Numeričko rešavanje prostiranja talasa pritiska u sistemu fluida i strukture termoenergetskih postrojenja, Magistarski rad, Mašinski fakultet, Beograd, 1986.
34. Stevanovic, V., Studovic, M., Bratic, A., Simulation and Analysis of a Main Steam Line Transient with Isolation Valves Closure and subsequent Pipe Break, International Journal of Numerical Methods for Heat & Fluid Flow, Vol. 4, No. 5, 1994, str. 387-398.
35. Stevanovic, V., Jovanovic, M., Prica, S., Maslovaric, B., Condensation induced water hammer in thermal plants, Proceedings of the 11th International Conference on Multiphase Flow in Industrial Plants, Palermo, Italy, September 7-10, 2008, str. 783-790.
36. Stevanovic, V., Prica, S., Maslovaric, Waterhammer in Pipelines of Steam Boilers, Proceedings of the 4th IAHR International Meeting on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems, Belgrade, Serbia, October 26-28, 2011, str. 57-65.
37. Stoop, P.M., Van der Bogaard, J.P.A., Koning, H., CHARME-01, A Thermo- Hydraulic Code for The Calculation of Fast Transients Inside Piping System, 8th Int. Conf. on Structural Mechanics in Reactor Technology, Brussels, 1985.
38. Streeter, V.L., Wylie, E.B., Hydraulic Transients, McGraw Hill, New York, 1967.
39. Studović, M., Stevanović, V., Nedeljković, S., Ilić, M., Analiza uzroka havarije u kotlarnici TEC-2 Kliničkog centra Srbije, Mašinski fakultet, Beograd, 1997.
40. Tong, L.S., Weisman, J., Thermal Analysis of Pressurized Water Reactors, ANS monograph, 1979.

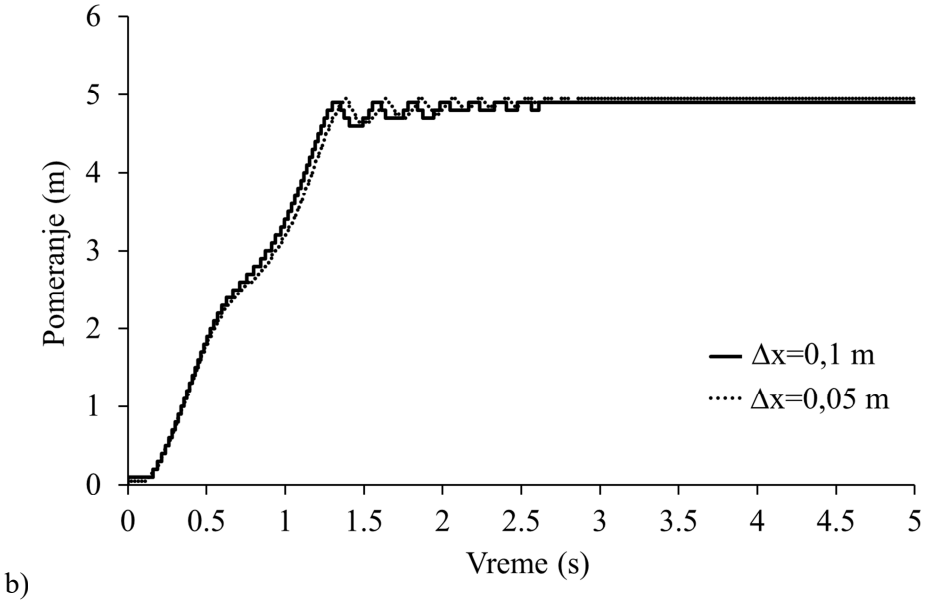
41. Vardy, A.E., Brown, J.M.B., Transient Turbulent Friction In Smooth Pipe Flows, Journal Of Sound And Vibration, 259(5), 2003, str. 1011–1036.
42. Wagner, W., Kretzschmar, H.J., International Steam Tables, Springer-Verlag, Berlin, 2007.
43. Wulff, W., Computational Methods for multiphase flow, A Review prepared for the Second International Workshop on Two-Phase Flow Fundamentals, Rensselaer Polytechnic Institute Troy, New York, USA, 1987, str. 38-42.
44. Yeung, W.S., Wu, J., Fernandez, R.T., Sundaram, R.K., RELAP5/MOD3 Simulation of the Water Cannon Phenomenon, Nuclear Technology, Vol. 101, Feb. 1993, str. 244-251.
45. Zaltsgendler, E., Tahir, A., Leung, R.K., Condensation-Induced Waterhammer in a Vertical Upfill Pipe, Transactions of the American Nuclear Society, 74, 1996, str. 346.
46. Živanović, Šijački-Žeravcić, Stevanović, V., et al., 2007, "Investigation of the break of the main steam isolation valve in the boiler unit of the HPK Chemical corn treatment – Draksenic", Faculty of Mechanical Engineering, Belgrade, Serbia.




Slika 6.6 Sračunata (gore) i izmerena (dole) promena pritiska u toku vremena u blizini zatvorenog kraja vertikalne cevi u aparaturi za simulaciju hidrauličkog udara (Milivojević i dr., 2014).



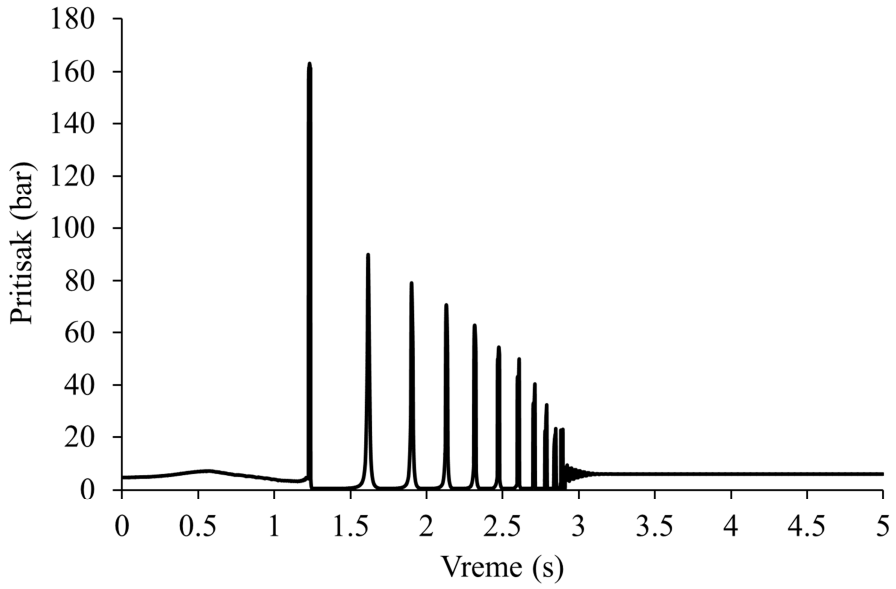

a)



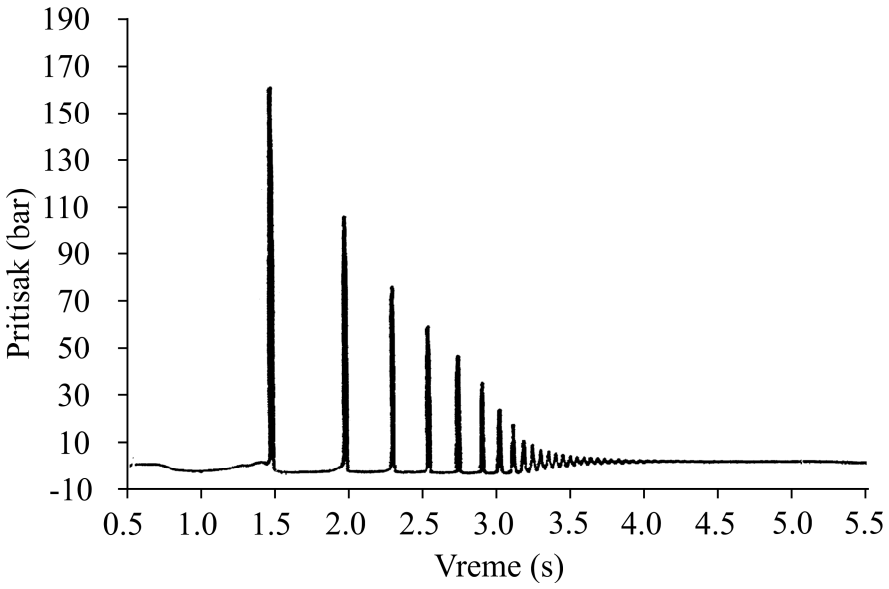

b)

Slika 6.15 Promena pritiska (gore) i pomeranje položaja razdelne površine (dole) u toku vremena u blizini zatvorenog kraja vertikalne cevi u aparaturi za simulaciju hidrauličkog udara dobijene za različite vrednosti prostornog koraka numeričke mreže (Milivojević i dr., 2014).

a




b




Slika 6.16 Sračunata (gore) (Milivojević i dr., 2014) i izmerena (dole) promena pritiska u toku vremena u blizini zatvorenog kraja vertikalne cevi u aparaturi za simulaciju hidrauličkog udara. Početni pritisak vode je 6,54 bar.