26th International Conference
ENGINEERING MECHANICS 2020
Brno, Czech Republic, November 24 – 25, 2020

COMPUTATIONAL SIMULATION OF CAVITATION BUBBLE COLLAPSE

Burda R.*, Rudolf P.**

Abstract: *Cavitation threatens lifetime of hydraulic machines, ship propellers or diesel injection nozzles, but can also serve as efficient way of pathogenic microorganisms eradication, water disinfection and chemical residuals removal. While classical Rayleigh-Plesset equation provides suitable 1D tool for description of the bubble behavior away from the wall, it suffers serious problems close to solid boundary due to its assumption of bubble sphericity during all stages of the bubble life. Therefore, a detail computational simulation based on RANS equations and multiphase Volume of Fluid approach was performed. Simulation was able to capture microjet, which deforms the bubble in solid wall vicinity, penetrates through bubble interior and is responsible for transformation from vapor bubble to vapor ring. It is important that numerical solution enabled detailed spatial description of the bubble evolution and allowed to distinguish between the pressure peaks caused by microjet impact on the wall and bubble collapse, thereby enhancing our understanding of the bubble collapse close to the solid boundary.*

Keywords: Cavitation bubble, Microjet, cavitation bubble collapse, Volume of fluid method, Impact pressure.

1. Introduction

Cavitation occurs when pressure in liquid drops below level of saturated vapor pressure at given temperature. Two most frequent ways of inducing cavitation are hydrodynamic (by local increasing of velocity, e.g. in Venturi tube (Rudolf et al., 2012)) and acoustic (by exposing the liquid to variable external pressure field, e.g. using ultrasonic generator). Cavitation bubble is growing from its equillibrium radius to its maximum size and then violently collapses. Collapse is accompanied by a pressure peak, generation of acoustic waves, chemical reactions (generation of hydrogen peroxide) and sonoluminescence. Abrupt pressure changes can be used for elimination of pathogenic microorganisms (e.g. cyanobacteria, (Zezulka et al., 2020)) or for degradation of chemical residuals in waste water (e.g. estrogens or pharmaceuticals (Zupanc et al., 2013)).

Behavior of the cavitation bubble driven by variable pressure field is described by Rayleigh-Plesset equation (Franc and Michel, 2006). However, this non-linear ordinary differential equation is derived for spherical bubble during its whole lifecycle. In case of real bubble close to the wall, bubble is losing its sphericity and phenomenon of microjet appears. Microjet is a very fast stream of liquid which penetrates the bubble and impacts onto the solid wall. Hence bubble changes from spherical shape into cavitating ring, which further collapses during a series of rebounds. Asymmetrical bubble collapse can be studied using computational fluid dynamics (CFD) tools (Minsier, 2010).

2. Method

In the present study, the bubble collapse near solid wall is simulated using axisymmetric calculation where the axis of symmetry is perpendicular to the solid wall (see Fig. 1). The bubble is subjected to external periodical pressure field which is driven by pressure boundary condition on the edge of the liquid domain. The boundary condition is described by equation (1). The initial pressure in the domain p_d is 200 kPa,

* Ing. Radim Burda: V. Kaplan Department of Fluid Engineering, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, radim.burda@vutbr.cz

** Assoc. Prof. Ing. Pavel Rudolf, PhD.: V. Kaplan Department of Fluid Engineering, Brno University of Technology, Technická 2896/2; 616 69, Brno; CZ, rudolf@fme.vutbr.cz

doi: 10.21495/5896-3-094

amplitude of the pressure function p_{amp} is 180 kPa and frequency f is 20 kHz. The initial temperature in the domain is 300 K and the radius of the bulk liquid domain R_{inf} is 165 times the value of the initial radius of the bubble which ensures that the bubble collapse is not affected by the boundaries of the liquid domain (Minsier, 2010).

$$p = p_d - p_{amp} sin(2\pi f t) \quad (1)$$

The bubble with initial radius $R_0 = 78.5$ µm is introduced into the domain after one period of sinusoidal pressure function to ensure well converged initial pressure field. The bubble is located in a standoff distance from the solid wall which is defined by non-dimensional parameter $\gamma = d/R_{max}$ where d is the distance between the center of the bubble and the solid wall and R_{max} is the maximum equivalent radius of the bubble during the simulation. The calculation is executed with 6 different values of γ, ranging from 0.76 to 2.66.

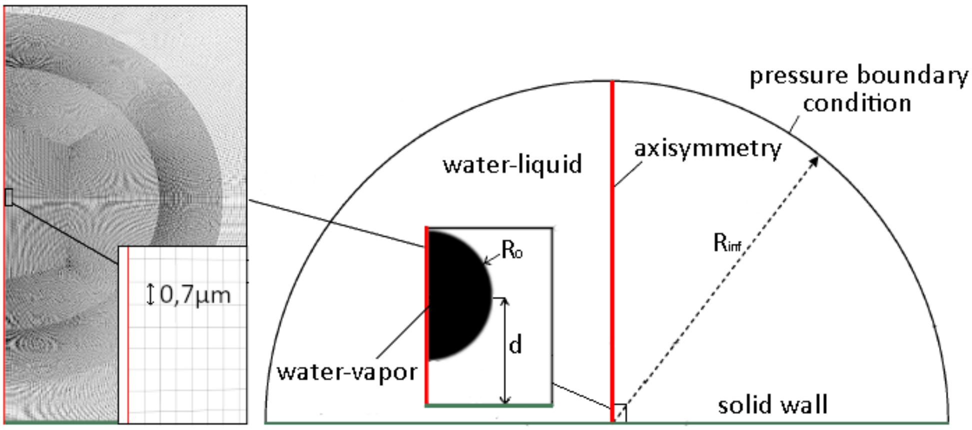

Fig. 1: Liquid domain with detail of quadrilateral mesh near solid wall (~360 000 cells).

Because the bubble collapse is considered to be a high-speed phenomenon with significant Mach values, the compressibility is primarily predominant and therefore both water vapor and liquid water are considered as compressible fluids. The water vapor inside the bubble is treated as ideal gas with specific heat defined by piecewise-polynomial function. The calculation is set as transient with variable timestep driven by Courant number in order to achieve sufficient timestep during the rapid bubble collapse. The pressure-based solver ANSYS Fluent 19 with double precision is used for the simulation.

The multiphase flow is simulated with explicit Volume of Fluid (VOF) model with sharp interface modeling. The VOF model uses volume fraction to identify the interface between liquid and gas phases. The cells containing pure liquid and pure gas phases are identified by volume fraction of 0, respectively 1. In this simulation the cells with the volume fraction greater than 0.5 are considered as water-vapor and are used for the calculation of bubble volume, respectively equivalent radius. The surface tension between phases is modeled by continuum surface force model with constant surface tension coefficient of 0.07 Nm^{-1}. The calculation is performed with SST k-omega model with PISO scheme for the pressure-velocity coupling.

As the cavitation is of hydrodynamic nature it is not possible to validate the simulation with experiment because we are unable to create a single bubble. The validation experiment is commonly conducted for laser-induced bubble collapse which is of different physical nature than hydrodynamic cavitation.

3. Results

Simulations were performed for several standoff distances. Typical evolution of the bubble collapse is depicted in Fig. 2, which clearly shows onset of the microjet, its impact onto the solid wall and disintegration of the originally spherical bubble. It should be stressed that the process is extremely fast and takes only hundredths of microsecond.

Fig. 3 summarizes different bubble behavior for different standoff distances and focuses on the microjet - phenomenon connected with bubble collapse close to the solid wall.

As for the bubble shape, gradual losing of the bubble sphericity is observed and when microjet penetrates the bubble, vortex ring is formed, which then collapses and further disintegrates. This development is imprinted on the vapor volume and pressure signal by so called rebounds.

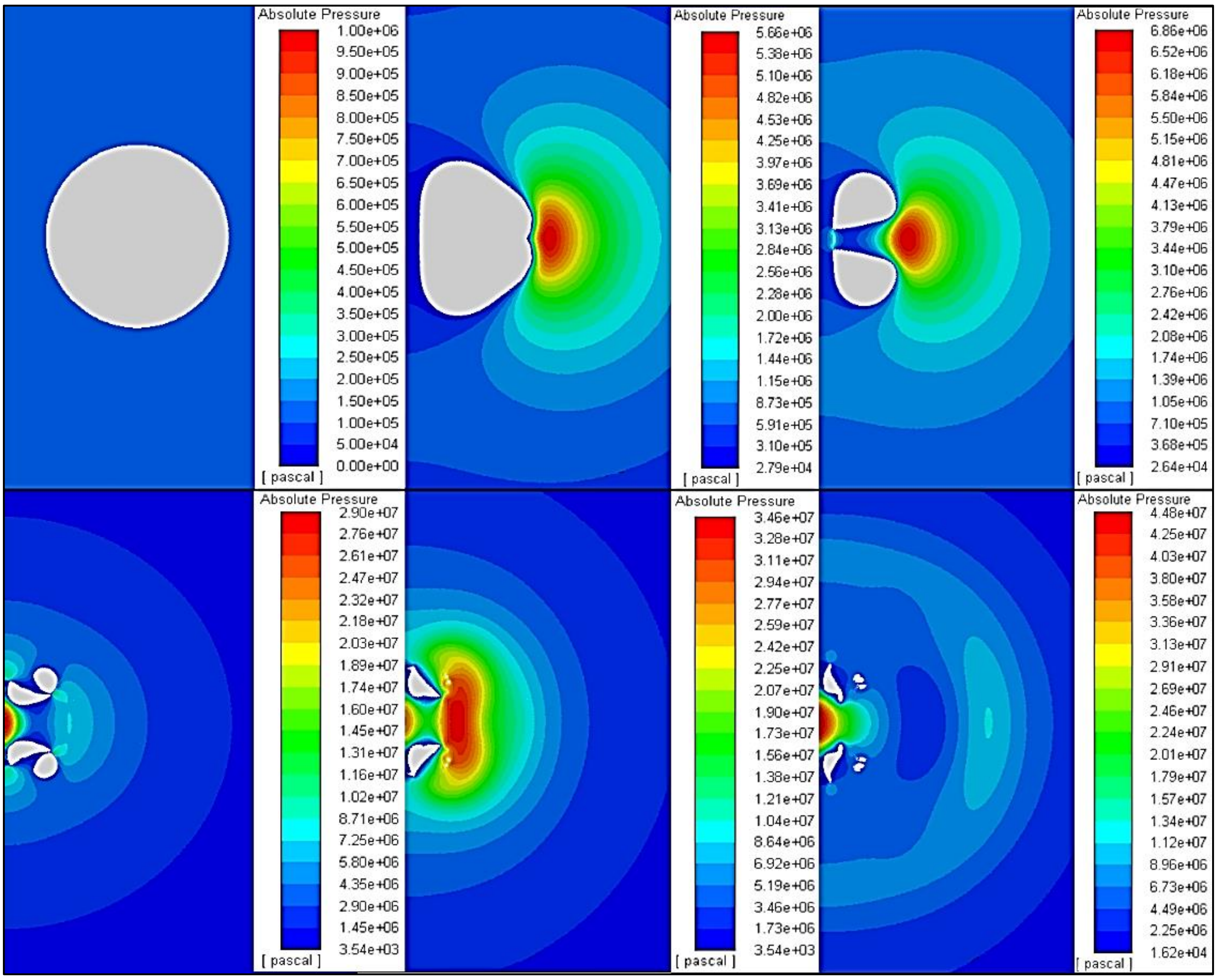

Fig. 2: Pressure contours at different stage of bubble collapse near solid wall (solid wall is on the left side of every picture). From left to right: initial bubble, start of the microjet intrusion, microjet impact, bubble splitting, bubble collapse, bubble collapse impact on solid wall, $\gamma = 0.76$.

It is very interesting that two distinct pressure peaks can be observed: the first one is associated with microjet hitting the wall and second one with collapse of the bubble itself, while the peak induced by microjet is higher. Investigation for different standoff distances γ revealed that the closer is the bubble to the wall the higher is the impact pressure. Velocities of the microjet are relatively high, reaching several hundred meters per second.

4. Conclusions

Cavitation bubble collapse induced by variable pressure field was successfully simulated using the Volume of Fluid approach. While utilizing the geometrical axisymmetry significantly decreased computational effort, it still remains a challenging problem due to requirements on very small time step size during the abrupt change of the bubble volume.

Simulation allowed to distinguish between the pressure peak induced by microjet impact and by cavitation bubble collapse, which is of great importance for understanding of the destruction mechanism of cavitation.

Further simulations will focus on response of the bubble to stepwise change of the pressure field, which is situation closer to hydrodynamic cavitation. Obtained pressure peaks will be correlated with mechanical properties of the microorganism's cell membranes.

Results obtained in this simulation can be also very helpful for development of a cavitation erosion model.

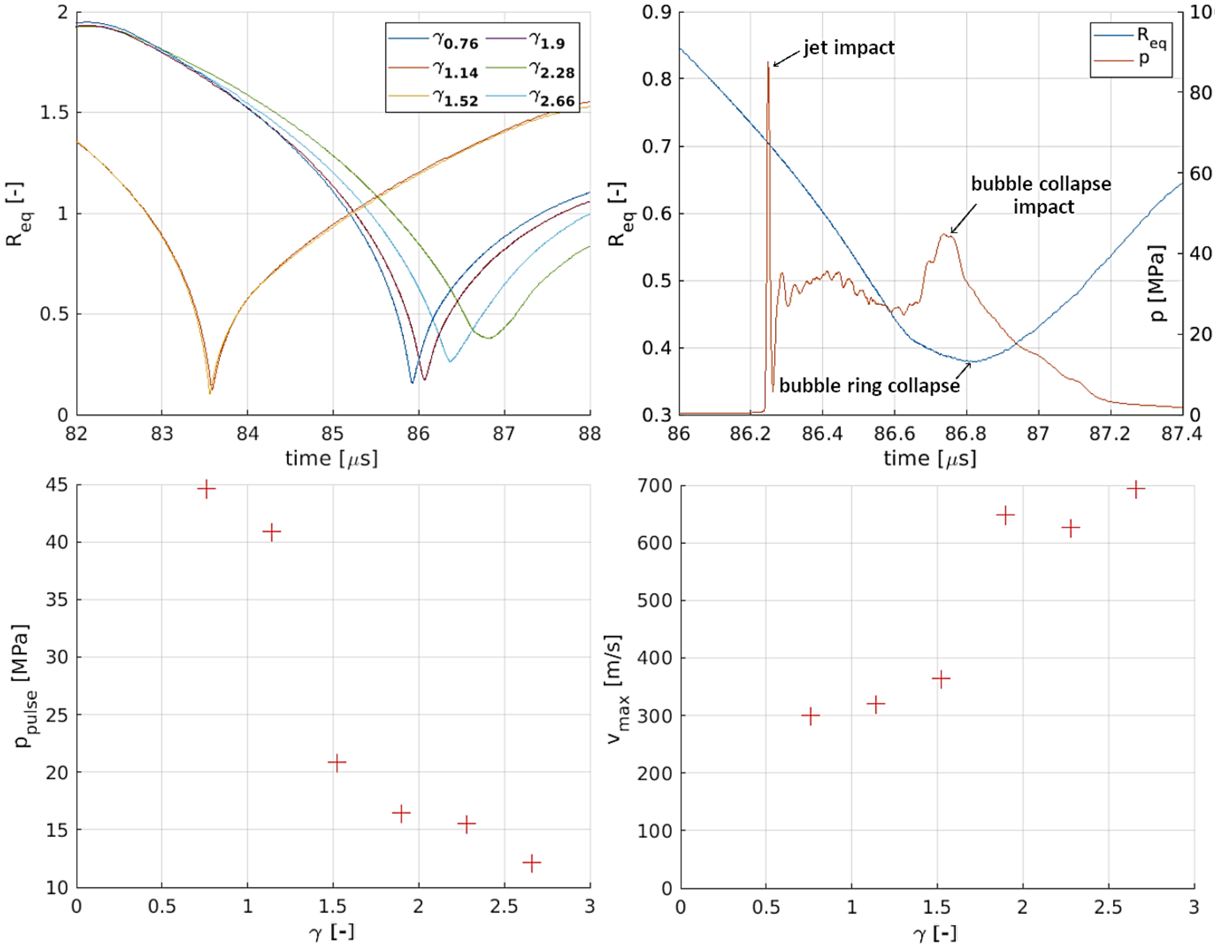

Fig. 3: From left to right: equivalent radius-time curves for different values of γ, pressure impact on the center of the solid wall and equivalent radius as a function of time ($\gamma_{0.76}$) , maximal bubble collapse impact pressure on the center of solid wall as a function of γ, maximal velocity on the axis (microjet) as a function of γ.

Acknowledgement

Czech Science Foundation is gratefully acknowledged for supporting the research under project 19-10660S “Removal of estrogens from waste water using hydrodynamic cavitation in combination with advanced oxidation processes”.

References

Franc, J.-P. and Michel, J.-M. (2006) Fundamentals of Cavitation. Springer.

Minsier, V. (2010) Numerical simulation of cavitation-induced bubble dynamics near a solid surface. PhD thesis.

Rudolf, P., Hudec, M., Zubík, P. and Štefan, D. (2012) Experimental measurement and numerical modeling of cavitating flow in converging-diverging nozzle. EPJ Web of Conferences (25) 01081

Zupanc, M., Kosjek, T., Petkovšek, M., Dular, M., Kompare, B., Širok, B., Blažeka, Ž. and Heath, E. (2013) Removal of pharmaceuticals from wastewater by biological processes, hydrodynamic cavitation and UV treatment. Ultrasonics Sonochemistry 20(4), pp. 1104-1112

Zezulka, Š., Maršálková, E., Pochylý, F., Rudolf, P., Hudec, M. and Maršálek, B. (2020) High-pressure jet-induced hydrodynamic cavitation as pre-treatment step for avoiding cyanobacterial contamination during water purification. Journal of Environmental Management, 255, pp. 1-7.