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Numerical analysis of the cavitation effect occurring on the surface of steel constructional elements

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ABSTRACT

Purpose: The aim of the work is to present the results of own investigations concerning the geometric optimisation of constructional elements working in the environment of cavitation wear together with a computer numerical analysis. The engineering material used for constructional elements working in the environment of cavitation wear is steel, commonly used for pressure devices working at elevated temperatures, P265GH, acc. to PN-EN 10028:2010.

Design/methodology/approach: SOLID EDGE ST 7 software, for synchronous designing, was used for the parametrisation of the shape, distribution, configuration and size of openings in constructional elements. Five models, with a different spacing and number of openings, were proposed for the optimisation of internal geometry of the cavitation generator and for the investigations; the models were then subjected to a numerical analysis using specialised software, ANSYS FLUENT v.16, employed for modelling the effects associated with fluid mechanics (Computational Fluid Dynamics - CFD). The data was implemented for this purpose in the software used, such as: density, yield point, tensile strength, heat conductivity coefficient for steel P265GH, material surface roughness, medium (water) flow rate, constant pressure loss of medium, pressure of steam saturation in a medium; and such data was called boundary conditions.

Findings: The authors' principal accomplishment is the optimisation of the shape, the selection of the most appropriate geometry of a constructional element generating the maximum number of cavity implosions in the environment of a flowing medium (water), with the use of computer tools dedicated to engineering design: a 3D and numerical computer analysis of fluid mechanics, CFD. Moreover, an attempt was made in this work to develop a methodology for characterisation of the phenomena accompanying the environment of cavitation wear.

Practical implications: A possibility of examining the phenomena and a process of wear of a constructional element made of P265GH grade steel for pressure devices working at elevated temperatures. The demonstration and presentation of potential places, areas and sizes of erosion existing on constructional elements working in the environment of cavitation wear.

Keywords: Cavitation wear; Cavitation erosion; Computer materials science; Cavitation generator; Computer simulation

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Cavitation erosion is one of the most popular phenomena of destruction of materials working in water conditions and in any kinds of liquids. The cavitation effect is defined as a physical effect, induced by a variable field of liquid pressures, where bubbles or other voids (caverns) – containing steams of a given liquid, gas or a steam-gas mixture – are formed, expanded and disappearing. This aspect is commonly known; however, it can be expressly said that knowledge in this field is quite scarce and is not systematically ordered. In an attempt to establish the framework, within which we often come across the effect of cavitation, two fields can be easily proposed. The first field are "generators", i.e. sources of cavitation (in particular turbine and pump blades, ship screws and any changes to geometry of constructional and technological parts in flow devices). The other field are cavitation "receivers", namely, among others, surfaces and edges of constructional elements such as, e.g. pipelines, energy fittings, heat distribution and water supply fittings, flow apparatuses and devices used in industry, exposed to turbulent flow of liquid (medium) transporting air bubbles which – when imploding – greatly accelerate the wear of constructional materials. If cavitation erosion phenomena are better recognised, this promotes more effectively the informed, thought-through design and usage of elements working in the conditions of complex wear in such industries as: river and sea transport, machining and cutting of hard metals, surface cleaning of various materials, chemical and petrochemical processes of, e.g. emulsification or depolymerisation; liquid sterilisation processes, processes used in aesthetic medicine or in heating engineering, where cavitation processes are at the stage of initial investigations [1-12].

The authors make an effort to find an answer to a number of questions associated with designing, construction optimisation and numerical analysis of constructional elements used in the environment of cavitation wear.

A thesis is put forward in the work that cavitation wear, taking place on the surface of constructional elements, has a dominant effect on designing, selection and operation of industrial constructions. It is worth stressing that one of the most popular techniques of protecting the surface of materials against wear is the use of all kinds of coatings and surface layers. Such techniques allow to use materials with worse strength and functional properties, however, with significantly improved surface. Because the majority of elements undergo destruction mainly on the surface, surface engineering technologies are an excellent reference point for protection of materials exposed to any kind of wear, including cavitation wear. It was the authors' intention to produce a cavitation generator with optimum geometry, i.e. such ensuring the biggest number of cavity implosions, presented as the content of steam on constructional elements. The so developed construction will allow to identify precisely the maximum possible cavitation wear for the set boundary conditions prevailing in the actual stream and cavitation device.

It is planned to employ PVD techniques in the next step of the experiment, which will substantially minimise the destructive impact of the cavitation environment on constructional parts used for constructing flow machines.

2. Material

Steel, commonly used for pressure devices working at elevated temperatures, P265GH, with a ferritic-pearlitic structure, was used for the optimisation of dimensions and shape of the cavitation generator. P265GH steel – due to its unlimited availability and attractive, low market prices – is used for constructing heat distribution devices and heating devices, and for less important constructional parts [13]. The chemical composition of the applied P265GH steel is shown in Table 1, and selected mechanical properties and physical values – important for numerical model optimisation – are shown in Table 2.

3. Methodology

Five constructional solutions of cavitation generators with variable geometry, number and shape of openings, marked for this publication with symbols A-E (Figs. 1-5), were proposed for this work. Computer models were prepared in SOLID EDGE ST.7 software, supporting the synchronous design technology [14].

Table 1.
The chemical composition of the applied P265GH structural steel [mass fraction], [%] acc. to PN-EN 10028:2010 [15]

Chemical composition		C, %	Mn, %	Si, %	Al, %	Cr, %	Ni, %	Cu, %	Ti, %	N, %	S, %	P, %
P265GH	max	-	-	0.4	-	0.3	0.3	0.3	0.03	0.012	-	-
		0.16	0.99	0.23	0.047	0.027	0.013	0.026	0.001	0.003	0.008	0.019

Table 2.
Selected mechanical properties and physical properties of the applied structural steel, P265GH

Mechanical properties	R_{eH} min, MPa	R_m min, MPa	A_5, %	heat conductivity coefficient, W/m*K
P265GH	265	410-570	23	58

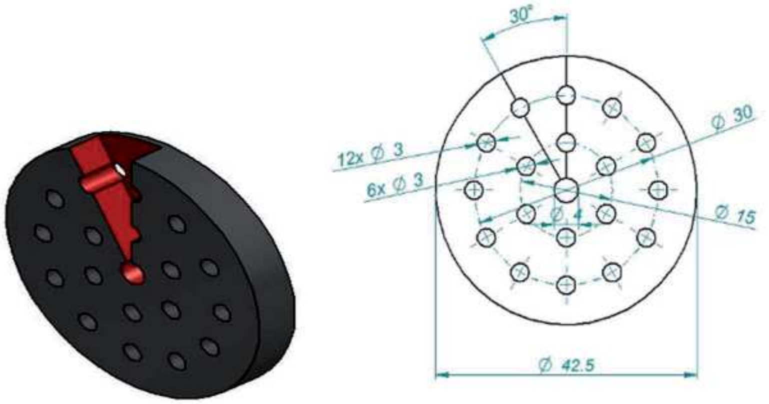

Fig. 1. View of computer cavitation generator together with dimensions, model designation – symbol A; generator thickness: 5 mm, relative clearance Pp=11.1%

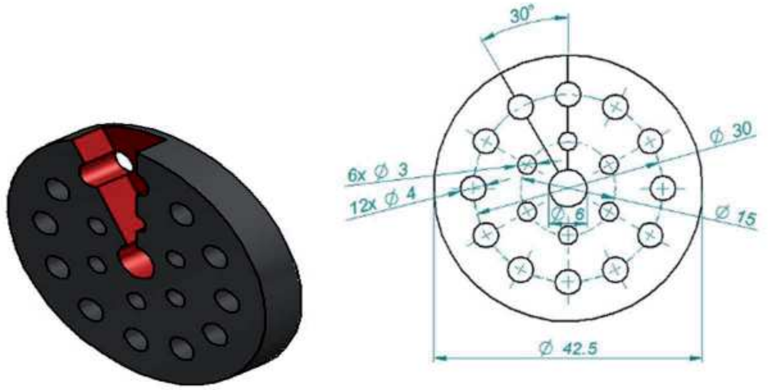

Fig. 2. View of computer cavitation generator together with dimensions, model designation – symbol B; generator thickness: 5 mm, relative clearance Pp=17.6%

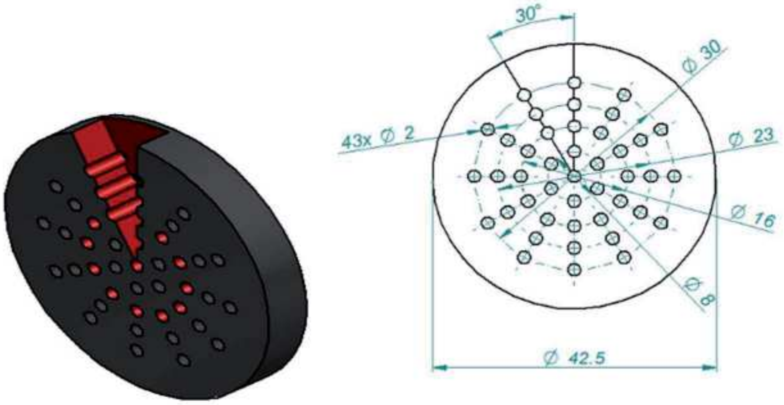

Fig. 3. View of computer cavitation generator together with dimensions, model designation – symbol C; generator thickness: 5 mm, relative clearance Pp=10.7%

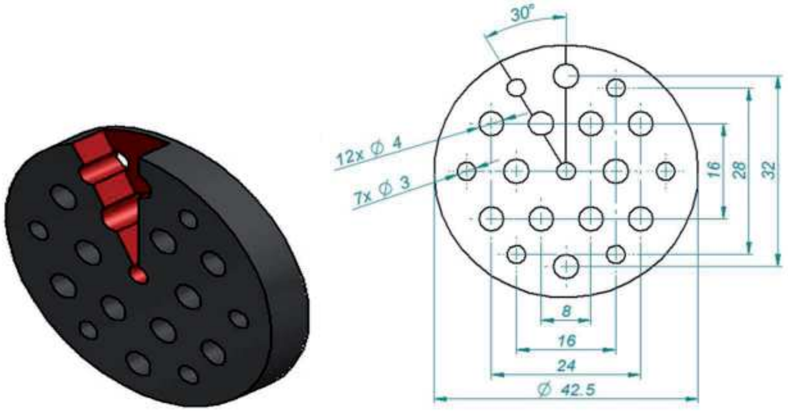

Fig. 4. View of computer cavitation generator together with dimensions, model designation – symbol D; generator thickness: 5 mm, relative clearance Pp=15.9%

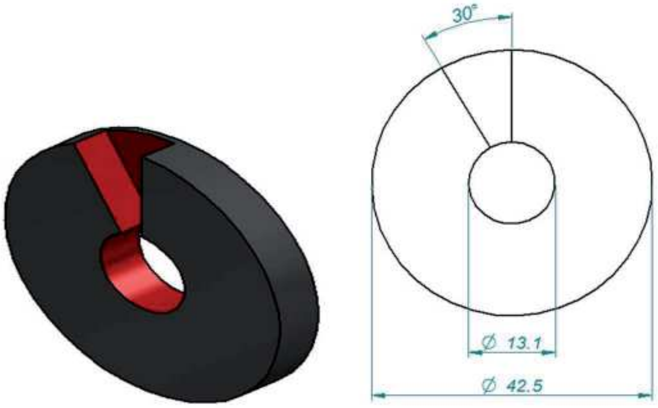

Fig. 5. View of computer cavitation generator together with dimensions, model designation – symbol E; generator thickness: 5 mm, relative clearance Pp=10.7%

The purpose of parametrisation of the shape, distribution and size of openings of cavitation generators was to indicate the most optimum geometry of a constructional element, generating the greatest number of cavitation implosions. In the next stage of the investigations, the authors – using a specially designed, personally prepared test stand based on the author's solution shown in Figure 6 and Table 3 – are verifying the simulations performed. It is a flow stream and cavitation device working in a closed cycle.

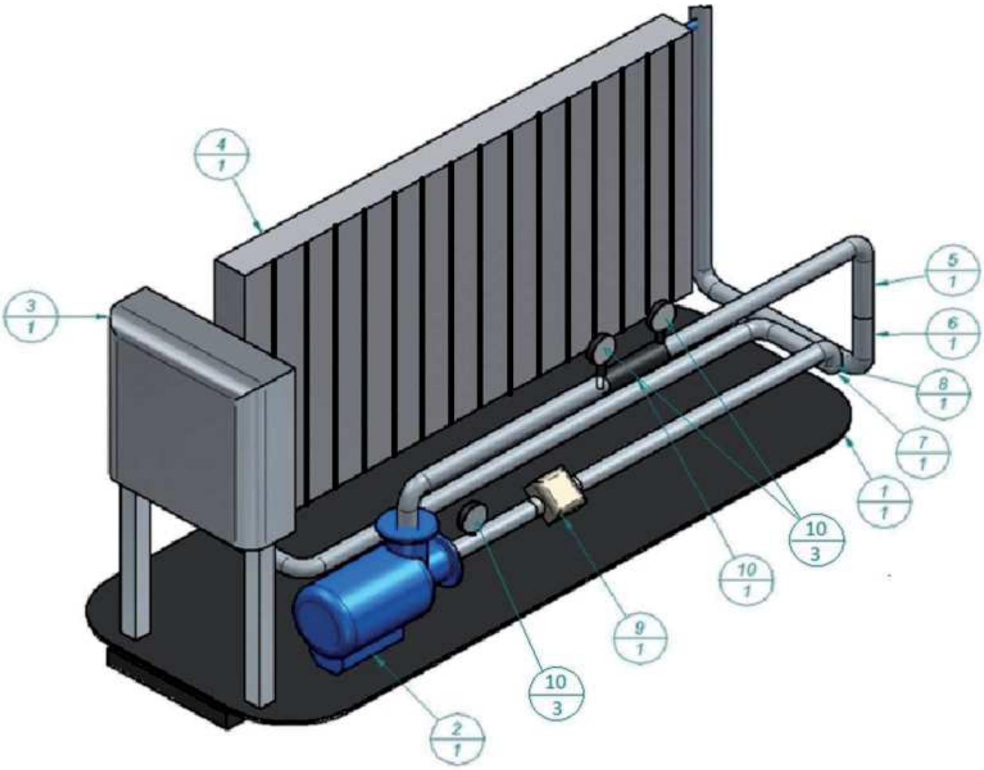

Fig. 6. Isometric diagram of the stream and cavitation device with the flow character of work, a test and measuring device

Table 3.
List of devices and apparatuses in the testing and measuring device

Element device	Name of apparatus	Technical description
1	test device base	S355J2G3 #8x800x2500 mm steel sheet, load-carrying structure
2	forcing pump Centrifugal	power=4 kW; material 316L Q=10-30 m^3/h
3	C&I control cabinet	Control and Measurement and Automatics apparatuses electricity meter
4	heat receiver	plate heater; Power=2 kW
5	pressure pipeline	P235TR1 ø=48.3x5 pipe; Joined with 141 method
6	compensation pipeline	P235TR1 ø=48.3x5 pipe; Joined with 141 method
7	return pipeline	P235TR1 ø=48.3x5 pipe; Joined with 141 method
8	suction pipeline	P235TR1 ø=48.3x5 pipe; Joined with 141 method
9	flow meter	flow dynamics qi/qp 1:50 (for qp=1.5 and 2.5 m^3/h)
10	Generator's cavitation medium	P235TR1 ø=48.3x5 mm pipe necked mounting socket for the cavitation generator (A-E) ø 42.5 mm 3 pcs. of manometers 63 mm G1/2”

The computer models of cavitation generators shown in Figures 1-5 (A-E) differ in the quantity, size, distribution and geometry of openings in a constructional element, hence with relative clearance.

Relative clearance was determined according to the formula (1):

$$\mathbf{P_p} = \sum Po / _{Pc} * 100\ [\%] \qquad (1)$$

where: Pp – relative clearance of generator, Po – sum of field areas of openings, Pc– field area of generator.

Software for numerically aided CFD (Computational Fluid Dynamics) was employed for the optimisation of the size, spacing and number of openings in the cavitation generator. The generators (Figs. 1-5) were each time positioned in the same place, i.e. perpendicular to the medium (water) flow direction (Fig. 7) in a specially prepared point of the pressure pipeline in the distance of 10 diameters (ø) of the straight section of the pipeline before and behind a constructional element. It was necessary, during numerical simulations, to assign permanent values, resulting from properties and requirements of the software used and from the basic theoretical assumptions and laws effective when solving the issues, associated with fluid mechanics, including: medium (water) velocity V at the inlet expressed with [m/s], medium pressure loss at the inlet, described as ΔP, and pressure of steam saturation P for water with temperature of 40°C, marked as [P].

The most efficient computational tool applied in the simulation of fluid mechanics phenomena (Computational Fluid Dynamics), called ANSYS FLUENT v.16, was used to model correctly and accurately the phenomena occurring during the flow of a medium (water). A computational analysis was performed to determine a potential place of implosion and cavitation wear in particular areas, including, especially, on any kinds of edges and discontinuities of the generator profile [16,17].

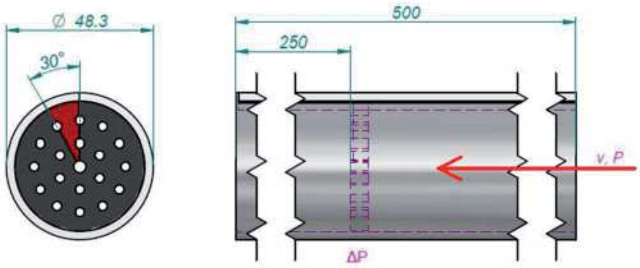

Fig. 7. Simplified computer model with a section of a generator for CFD analysis and its position with the marked flow direction of medium (water)

A section of the generator was only used for the simulation, to considerably reduce the time of computation, i.e. a one-twelfth part of the field area (30°), while observing at the same time all the principles associated with flow processes in computational models (Fig. 7).

The parameters of the medium flow process, for a simplified computer model shown in Fig. 7, were selected based on the literature data used for similar constructional solutions and based on general principles connected with fluid mechanics. A numerical analysis, conducted with the use of ANSYS FLUENT software for the set boundary conditions (Table 4), enabled to simulate cavitation implosions (content of steam), and to identify the places most exposed to cavitation wear, as well as its occurrence intensity for the particular designed cavitation generators.

Boundary conditions of the simulations performed in ANSYS FLUENT v.16 software for P265GH steel was presented in Table 4.

Table 4.
Boundary conditions of simulations in ANSYS FLUENT software for P265GH steel

Boundary conditions	Density	Yield point	Tensile strength	Heat conductivity coefficient	Surface roughness surface	Medium velocity at inlet	Pressure loss of medium at outlet	Pressure of steam saturation of medium for 40°C
P265GH	kg/m^3	MPa	MPa	W/m*K	μm	m/s	Pa	Pa
	7850	265	450	58	0.3	1.5	50 000	10 000

4. Results and discussion

In the first stage of the investigations performed, a construction was chosen of a cavitation generator producing the maximum number of cavitation (steam) implosions, characterised by variable shape, geometry, configuration, distribution, size and section area of straight-through openings. It was necessary to perform a numerical computer simulation, which enabled to indicate an optimum generator construction, permitting to produce the maximum number of cavitation implosions as a result of stream-like flow of water (medium). The value, distribution and pressure gradient P [Pa] of the medium at the cavitation generator inlet, and the number of cavitation implosions (steam) on a constructional element, were established based on CFD simulation results. Table 5 lists the detailed results and boundary conditions of the computer simulations performed in ANSYS FLUENT software.

Figures 8-12 present the distribution of pressure P [Pa] of a medium (water) before a cavitation generator, resulting from the water flow rate of 1.5 m/s in the section of the pipe with a diameter of 48.3 mm.

Table 5.
List of boundary conditions and results obtained for selected cavitation generators with symbols A-E; (Figs. 1-5) subjected to numerical simulation in ANSYS FLUENT v.16 CFD software

Type of cavitation generator used	Pp=Po/Pc Relative clearance x 100%	V Velocity of of medium at inlet	P * Pressure of medium at inlet	ΔP Pressure loss of medium at outlet	P_{40} Pressure of steam saturation of medium for 40°C	Cavitation * Cavitation number (content of steam in medium)
	%	m/s	Pa	Pa	Pa	%
A	11.1	1.5	**244 000**	50 000	10 000	**0.98**
B	17.6	1.5	107 500	50 000	10 000	0.39
C	10.7	1.5	**273 250**	50 000	10 000	**0.98**
D	15.9	1.5	136 700	50 000	10 000	0.39
E	10.7	1.5	263 500	50 000	10 000	0.39

* – average values.

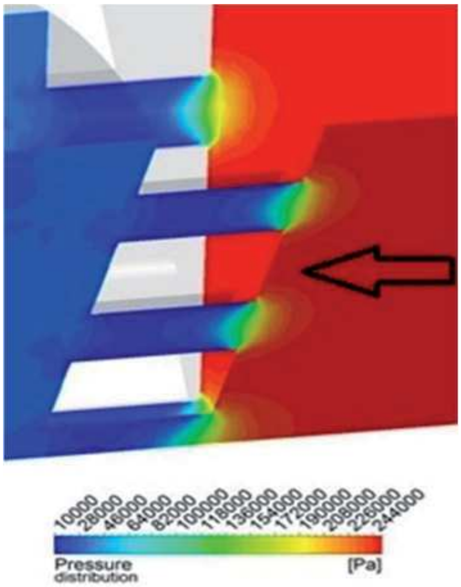

Fig. 8. Pressure distribution of flowing medium (water) on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol A (Fig. 1)

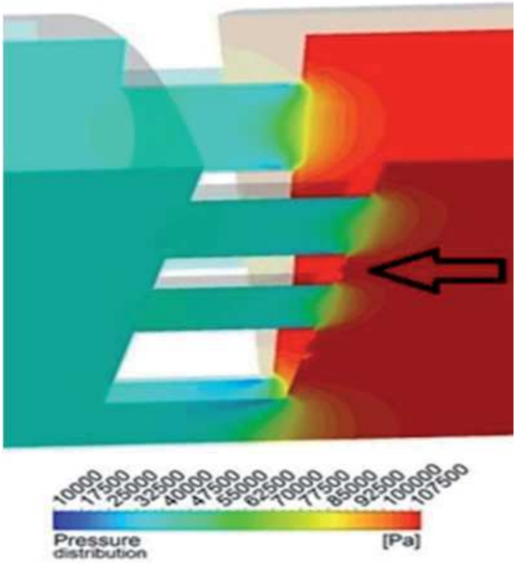

Fig. 9. Pressure distribution of flowing medium (water) on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol B (Fig. 2)

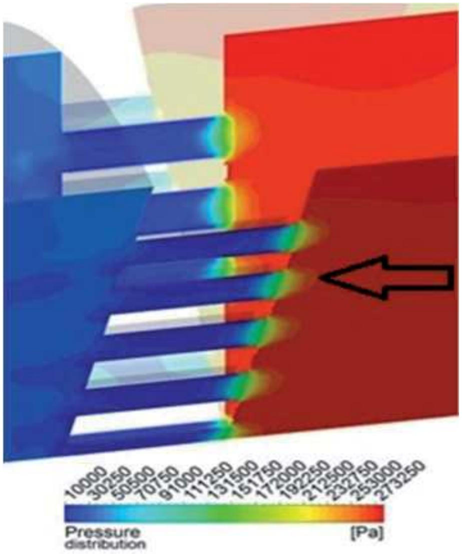

Fig. 10. Pressure distribution of flowing medium (water) on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol C (Fig. 3)

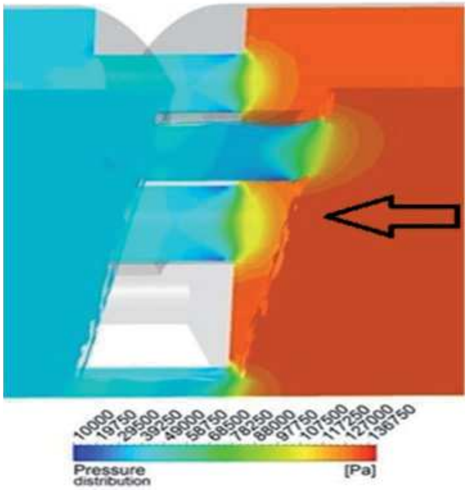

Fig. 11. Pressure distribution of flowing medium (water) on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol D (Fig. 4)

Figures 13-17 present the results of a simulation, based on which it was found in what areas, and with what intensity, cavitation implosion occurs (content of steam) and which areas, and in particular which edges and areas of the designed computer models, marked with symbols A-E, are most susceptible to cavitation wear.

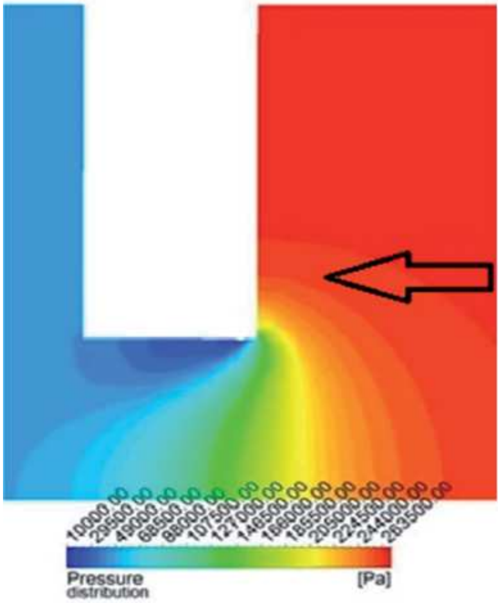

Fig. 12. Pressure distribution of flowing medium (water) on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol E (Fig. 5)

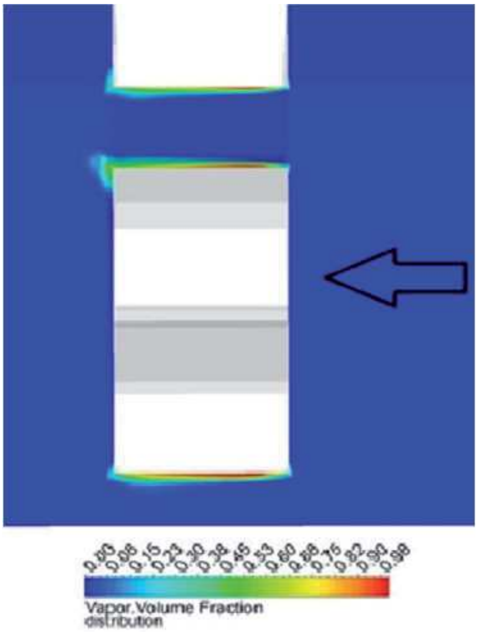

Fig. 13. Implosion distribution in form of content of steam on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol A (Fig. 8)

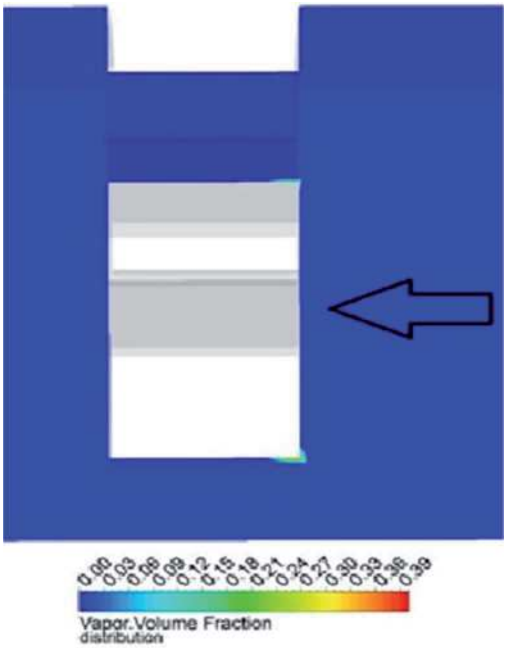

Fig. 14. Implosion distribution in form of content of steam on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol B (Fig. 9)

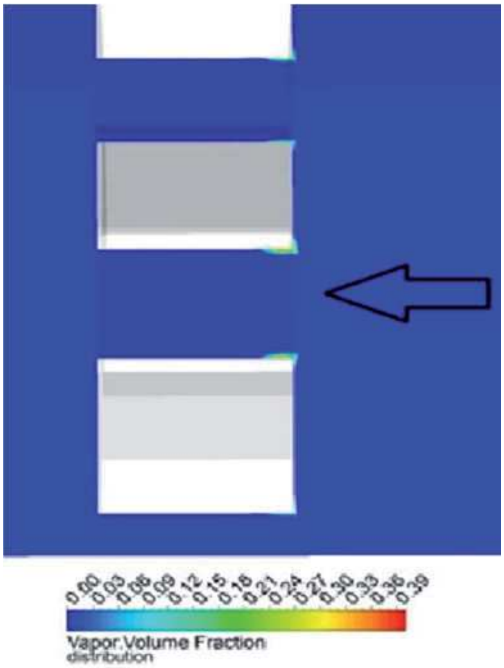

Fig. 16. Implosion distribution in form of content of steam on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol D (Fig. 11)

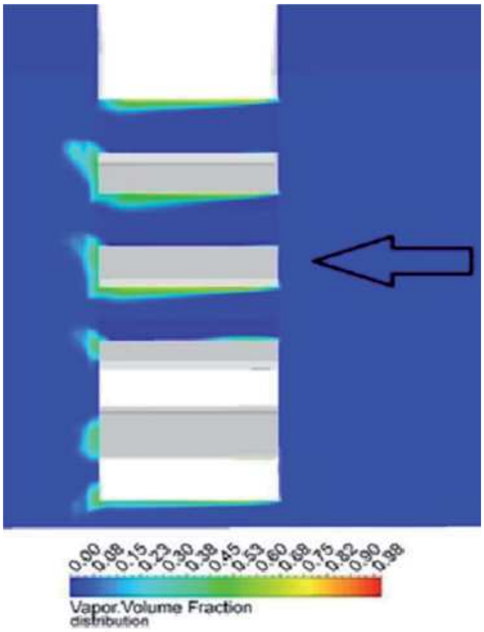

Fig. 15. Implosion distribution in form of content of steam on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol C (Fig. 10)

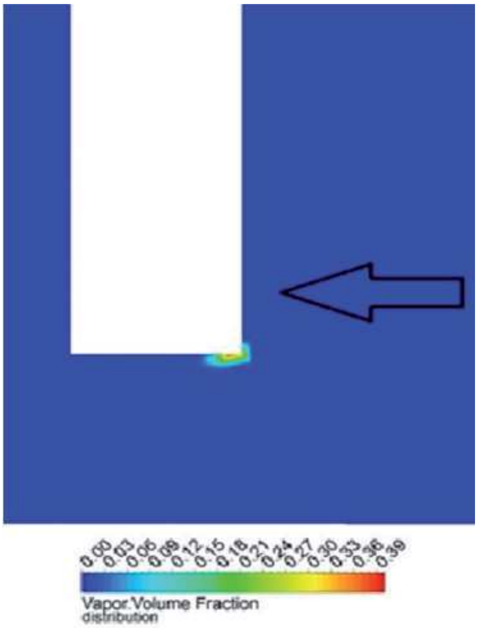

Fig. 17. Implosion distribution in form of content of steam on the one-twelfth (30°) section of the field area of model of constructional element marked with symbol E (Fig. 12)

It was established, according to the results of the numerical simulations listed in Table 5, that for a cavitation generator marked with symbol A, characterised by the relative clearance Pp of 11.1%, medium pressure at the inlet of 244 000 Pa was reached, for the number of cavitations (content of steam) of 0.98%, as shown in Fig. 8. The cavitation generator (Fig. 9), marked with symbol B, with the relative clearance of Pp = 17.6%, was characterised by water pressure at the inlet of 107 500 Pa; with the steam content of 0.39%, this element reached the water pressure and steam content values lower than the generator marked with symbol A, which has a smaller relative clearance of the construction. The third generator, analysed with the CFD method, was a constructional element marked as C, illustrated in Fig. 10. Values were obtained for this generator, very similar to those for a construction marked A, including: medium flow pressure of 273 250 Pa and the number of cavitations (content of steam) of 0.98% for the relative clearance of Pp=10.7% (Fig. 8). Another solution, subject to a computer simulation, was a generator marked D, with relative clearance Pp of 15.9%, for which medium pressure at the inlet of 136 700 Pa was reached, with the steam content of 0.39%. The results obtained for a cavitation generator marked D (Fig. 11), were similar to those established for a cavitation generator marked B (Fig. 9), having a similar relative clearance. The last construction analysed in ANSYS FLUENT software was a cavitation generator marked as E, shown in Fig. 12. This construction featured the simplest geometry with the relative clearance of 10.7%. For this reason, high water pressure, of 263 500 Pa, was reached for such a construction at the inlet, for a low number of cavitations of 0.39%. A constructional element marked E (Fig. 12) had a very similar relative clearance and water pressure at the inlet, but a proportionally lower content of steam in relation to the constructional elements A and C.

The investigations performed by the Authors have allowed to formulate additional conclusions, by analysing the places and areas of potential occurrence of the wear of a constructional element working in the cavitation environment. When two cases of the generators used are analysed together, i.e. A and C (Fig. 13 and Fig. 15), one can observe a considerable content of cavitation steam with very high intensity along the straight-through openings of the element and potential places of wear (cavitation smudges) on the rear outlet wall, when looking at the direction of the flowing medium (water). The other three constructions of cavitation generators, marked B, D and E (Fig. 14; Fig. 16 and Fig. 17), had very similar potential cavitation wear, visible only on the inlet edges of straight-through openings of the constructional element.

5. Conclusions

It can be concluded based on the outcomes of the numerical simulations attained in ANSYS FLUENT software that cavitation implosions (content of steam) simulating wear, are occurring to a high degree mainly before a cavitation generator, and especially on the inlet edges and along the straight-through openings of a constructional element. Relative clearance, expressed in per cents, is a very important constructional parameter, having decisive influence on the content of cavitation implosions formed (steam content). It can be easily said that a smaller cavitation clearance contributes to the larger content of cavitation steam in the investigated model, working in the cavitation environment. The results of a numerical simulation showed a comparable value of the relative clearance Pp and pressure distribution [P] for generators marked with symbols C and E, which did not translate into a comparable value of the number of cavitation implosions (steam content). The cavitation generator models marked with symbols A and C have the optimum construction, geometry, shape and distribution of openings. Those generators, for the same boundary conditions and the set material parameters, are characterised by the highest content of steam and generate the maximum number of cavitation implosions. A generator marked A, due to a larger, relative clearance of 11.1% than the relative clearance of a generator marked C, generates minimally smaller medium (water) flow resistance than a generator marked with symbol C (10.7%), in relation to the highest content of the generated cavity steams. An additional weighty conclusion is the fact that a generator marked A, whilst generating smaller water (medium) flow losses, is thus causing smaller consumption of electricity of the circulating pump as compared to the losses created in a generator marked C. It should also be emphasised that the highest efficiency in the designed measuring and testing system was achieved by using a cavitation generator marked A.

Necessary and helpful information was assembled, in the performed computer simulations and based on the numerical results of medium (water) flow at a temperature of around 40°C, for the set boundary conditions (Table 4), for a given computer model. A cavitation generator could be selected, based on such information, with the most optimum working parameters and dedicated to further investigations in the real configuration.

The most optimum construction, meeting all design and process requirements, was identified and confirmed on the basis of computer simulations made using professional aiding tools. It should be clearly underlined that a generator marked with symbol A, featuring the flow character of work (Fig. 6), and working in the real configuration, was chosen for further investigations in a stream and cavitation device.

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