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SCIENTIFIC PAPER

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SUSTAINABLE DEVELOPMENT OF PRESSURE EQUIPMENT USING 3D DIGITAL IMAGE CORRELATION METHOD

Article Highlights

- Analytical, numerical and experimental investigation of globe valve is performed
- 3D experimental strain field on sphere/cylinder intersection is measured
- Analysis showed that valve housing is over-dimensioned
- Eco-friendliness in globe valve production can be achieved

Abstract

As pressure equipment is most commonly used in various industrial fields, making manufacturing processes eco-friendlier (e.g., mass reduction of the final product, material and energy savings, etc.) and transitioning to sustainable production by developing eco-innovative products will have a positive effect on the environment. The aim of this paper is to analyze globe valve housing exposed to internal pressure using full-field experimental 3D digital image correlation (3D-DIC) method and numerical strain and stress data in order to propose improvements for more sustainable development, with respect to practical engineering application of EN standards. The highest von Mises strain values around 0.03% were measured on the point of highest geometrical discontinuity, sphere/cylinder intersection. Stresses of the examined globe valve using numerical and theoretical approach are significantly below material yield limit and allowable stress for internal pressure values of 30 bar, that is significantly higher than nominal operating pressure of 6 bar, proving that structure is over-dimensioned and can be optimized. New experimental procedure development and application in full-field strain analysis contributes to increased valve housing reliability, mass reduction and material and energy savings during manufacturing which directly affects its eco-friendliness, lowers manufacturing price and increases market competitiveness.

Keywords: 3D digital image correlation method, environmental protection, globe valve housing, internal pressure, sustainable development.

Present-day environmental issues (*e.g.*, soil pollution, air pollution, climate change, water pollution, etc.) have begun to degrade the natural environment with human activities as one of the main factors in that process. Since the Industrial Revolution, humans have used technology that influenced degradation of the environment and the rapid depletion of non-renewable natural resources [1]. High production levels of goods and the overconsumption of resources are following technological progress. However, as a result of the EU environmental policy, companies must review their production processes to become “greener” or environmentally friendly, so the transition to sustainable production by developing eco-innovative products is of great importance [2].

The main sources of pollution are well known. The most important man-made sources are industrial, including thermal power plants, space heating and vehicular traffic [3]. Since pressure equipment is most commonly used in various industrial fields, making manufacturing processes eco-friendlier (*e.g.*, mass

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reduction of the final product, material and energy savings, etc.) will have a positive influence on the environment.

Globe valves are popular industrial valves. The globe valve has good regulation characteristics but high resistance because of the flow path [4]. Internal pressure is the primary loading of globe valves, with the valve housing as the main component exposed to the internal pressure [5].

Strength calculations are performed during the design of valve housings. A globe valve housing consists of a spherical body and a cylindrical branch, *i.e.*, a sphere/cylinder junction that can be approximated as a spherical pressure vessel with a radial nozzle. Previous studies of pressure vessels focused on its geometrical discontinuity, relying on analytical calculations based on membrane and shell bending (*i.e.*, plate components) theories, numerical calculations and conventional experimental methods.

Calculations in standards regarding pressure equipment (*e.g.*, EN 13445, EN 12516 etc.) are based on membrane and bending shell theories. Standard EN 12516-2:2004 [5] is used for strength calculation of the industrial valve housing. The wall thickness of valve housing composed of different geometric components has to be calculated in two steps. Galic *et al.* [6] showed that the wall thickness of a two-way globe valve housing in intersection areas according to [5] is calculated only in the symmetry plane. Finite element analysis (FEA) of the part revealed a critical location in the crotch area. However, this location is located away from both the symmetry plane and critical locations proposed for analysis by standard EN 12516-2 [5]. Therefore, these authors concluded that standard EN 12516-2 is not precise enough for a two-way globe valve housing design.

One of the landmark papers on sphere/cylinder junction is due to Leckie and Penny [7]. They calculated stress concentration factors (SCF) for a cylindrical nozzle positioned on spherical pressure vessels for four loading cases. Stresses in the spherical part were presented and stresses in nozzles were ignored. Typical results were plotted as diagrams. Nozzle stress results were presented later by Rodabaugh *et al.* [8] but clarification of the stresses in the vicinity of this geometrical continuity continue to be of interest. Other authors also analyzed sphere/cylinder junction in their papers [9-14] through various examples and geometry parameters. As one of the common conclusions in their investigations, the researchers emphasized the shortage of experimental data in the available literature, *i.e.*, the necessity for more experimental data in critical areas where precise determination of displacement, strain and stress is not possible using older, conventional methods for displacement and strain measurements – such as strain gauges, extensometers and LVDTs.

Conventional experimental methods have several limitations. First, conditions in the vicinity of predefined geometrical discontinuities in the tensile specimen were analyzed through tensile testing. Using the tensile testing results, SCFs were plotted on diagrams and later used to “solve” problems on geometrically complex structures. Since conventional methods provide localized results only for the specific tensile geometry being tested, this approach gives only approximate solutions that are not sufficiently precise or accurate for complex structures. Conventional methods provide only a localized result on a measured object. Secondly, conventional methods provide measurements in the vicinity of the geometrical discontinuity, without the possibility to measure the higher strain values nearer the actual intersection of geometrical shapes.

To improve understanding of local conditions in loaded, complex structures, the optical three-dimensional digital image correlation method (DIC) is used in these investigations. DIC methods [15] are non-contacting and can be used for 2D (2D-DIC) and 3D (3D-DIC or StereoDIC) [16] surface displacement and strain measurement (*e.g.*, material testing, structure testing, numerical model verification, fracture mechanics, etc.) [17-25]. As a part of a broader study, a globe valve housing was subjected to axial loading and analyzed in several papers [26,27]. A thorough search on relevant literature revealed very few publications that address the problem of full-field experimental analysis of sphere cylinder junction under internal pressure. Thus, the aim of this paper is to analyse globe valve housing exposed to internal pressure using full-field experimental 3D digital image correlation (3D-DIC or StereoDIC), along with theoretical and numerical strain and stress data in order to propose improvements the design of globe valve housing for more sustainable development.

EXPERIMENTAL

A study was conducted on globe valve DN32 PN6 in this work. The valve is made of cast iron EN GJL-250 (GG25) subjected to internal pressure. The globe valve housing dimensions are shown in Figure 1. Mechanical properties of material GG25 (EN GJL-250) are as follows: 0.1% proof stress is 165 MPa, tensile strength is 250 MPa and modulus of elasticity is 110 GPa.

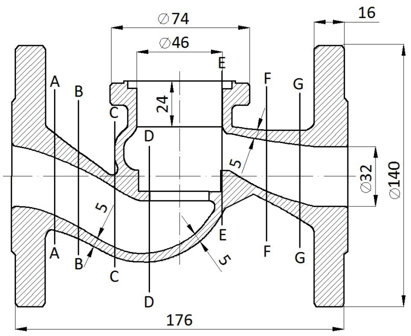

Figure 1. Globe valve housing dimensions and position of characteristic cross-sections.

Experimental analysis

Strain field experimental measurements were conducted using system Aramis 2M (GOM, Germany). Aramis 2M is based on the 3D-DIC method. Consistent with recently documented reporting guidelines for DIC measurements, the Aramis setup parameters are as follows:

- CCD cameras with resolution of 1600×1200 pixels
- 50 mm camera lenses
- Measuring volume of 105 mm×75 mm×55 mm
- Measuring distance (distance between camera support and centre of measuring volume) 800 mm
- Facet (subset) size 25×20 pixels
- Calibration standard point variability of 0.001 mm
- Camera pan angle 25.4°
- Calibration point variability of 0.024 pixels (for a correct calibration, the manufacturer states that calibration deviation may be between 0.01 and 0.04 pixels)
- The strain accuracy on the junction is 0.014%
- Custom-made LED lamp manufactured for specimen lighting.

The experimental setup is shown in Figure 2. In this experiment, valve housing was tested in the standardized pressure testing installation for industrial valves subjected to internal pressure. Within the Laboratory for Process Engineering at Faculty of Mechanical Engineering in Belgrade, globe valves hydrostatic research and testing showed that stresses during testing are significantly lower than standard stress values that are used for valve calculations. Based on this information, it has been assumed that the globe valve housing walls were thicker than required, *i.e.*, the valve thickness is considerably oversized. Experiments were conducted for the maximal internal pressure of 30 bar, as installation pressure limit is 30 bar and FEA showed that valve housing is in the safe zone for this pressure.

Areas on valve housing around upper flange were not taken into consideration, due to experimental method limitation.

Experimental procedure

Experiment was conducted according to the steps defined in [26]:

Sample preparation. The surface of the measuring object must have a pattern with good contrast in order to clearly allocate the pixels in camera images. Valve housing surface was cleaned and sprayed for experiment. White paint was sprayed as base colour. A nominally stochastic black dots pattern was applied for image correlation system analysis.

Selection of measuring volume. Measuring volume is selected based on sample size and the area of interest on the sample, providing sufficient spatial resolution for accurate digital image correlation. The average black dot size on the specimen is 6 pixels, which is larger than the minimum of 3×3 pixels^2 required to have sufficient sampling [15,28].

System calibration. Prior to experiment, system calibration was performed for the measuring volume using calibration panel CP 20/90/D07210 having coded and uncoded reference points and two calibration scale bar values (distance 1 of 83.159 mm and distance 1 of 83.159 mm). During calibration, each camera is calibrated, defining the external configuration and intrinsic imaging parameters [15].

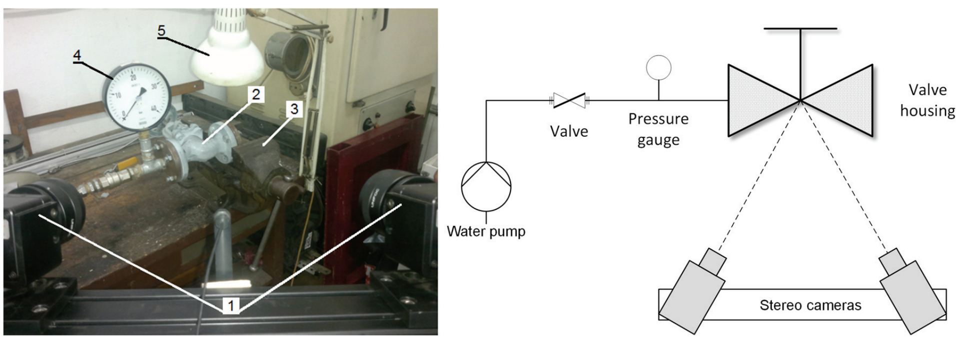

Figure 2. Experimental setup: 1 - stereo cameras; 2 - globe valve; 3 - clamp; 4 - pressure gauge; 5 - lighting.

Sample positioning. One valve flange was clamped to ensure there is no valve translation and the other flange was free, as shown in Figure 2.

Measurement. After successful calibration, measurement was performed. Pressure test procedure is done according to Test P10 defined in standard EN 12266-1 [29]. Pressure testing installation scheme is illustrated in Figure 2b. Test fluid was water at temperature of 20 °C. Maximal internal pressure was 30 bar. Digital images were recorded manually immediately before and every 5 bar during the loading. First recorded image (before the loading) is the reference image for data processing.

Data processing. Afterwards, computation was performed using Aramis software [30].

Finite element analysis

Pressure equipment finite element analysis [31] commonly includes stress and strain analysis, 2D and 3D linear elastic static [32] and dynamic analysis, local stresses, concentration factor studies [20,21] or vibration analysis. In order to evaluate and compare experimental and calculation results, numerical analysis of globe valve is performed using finite element method. Finite element analysis is performed using the software Abaqus.

Finite element model (Figure 3) consists of 6921 standard tetrahedral-type solids. Considering the symmetry of the model and loadings subjected to valve internal structure, one half of the model is analyzed. Boundary conditions [33] include restraining displacement in symmetrical plane in the transversal direction [12]. Furthermore, the valve model is simply supported by two nodes at model edges (Figure 4).

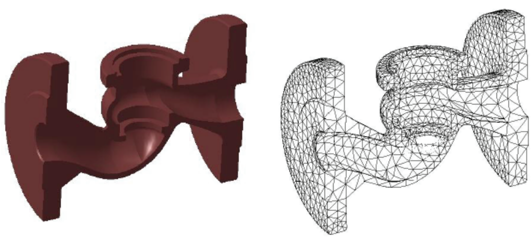

Figure 3. 3D and FE models of globe valve.

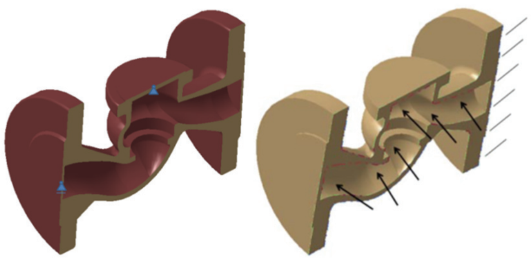

Figure 4. Constraints of the globe valve model.

Internal surface of the valve is subjected to maximal static pressure of 30 bar.

Analytical calculations

Standard EN 12516-2 [5] specifies the method for calculating the thickness of steel valve shells. The wall thickness of a valve body composed of different geometric components cannot be calculated directly. The calculation is a two-step procedure:

- the wall thickness calculation of the main body and the branches outside of the intersection or crotch area;
- the wall thickness calculation in the crotch area. As the first step, an assumption of a wall thickness in this area is made and this assumption can also be derived from the basic body wall thickness calculation. This assumed thickness is checked by considering the equilibrium of forces.

The globe valve body wall thickness is calculated for the characteristic cross-sections A-A to G-G, as shown in Figure 1.

RESULTS AND DISCUSSION

The results of the analytical calculations according to [5] are presented in Table 1. Calculated wall thicknesses of the globe valve housing for each cross-section are significantly lower than the actual wall thickness of 5 mm (manufacturer's data). The difference between calculated thickness and actual thickness is graphically presented in Figure 5. Light grey colour presents calculated wall thickness and dark grey colour the difference between calculated and actual wall thickness.

Table 1. Calculated wall thicknesses (mm) for characteristic cross-sections

Section	Shape					
	Rectangular, e_{c0}			Oval, e_{c0}		Cylindrical, e_c
A-A	-	-	-	1.45	1.61	1.11
B-B	-	-	-	1.54	1.74	1.12
C-C	-	-	-	1.62	1.85	1.13
D-D	1.67	1.96	1.75	-	-	1.13
E-E	1.8	2.21	1.87	-	-	-
F-F	-	-	-	1.63	1.86	-
G-G	-	-	-	1.38	1.52	-

The wall thickness difference can be contributed to the manufacturing technology of the globe valve. As the globe valve housing is cast, the casting process requires adding allowances; depending on the valve size, the difference can be up to several mm.

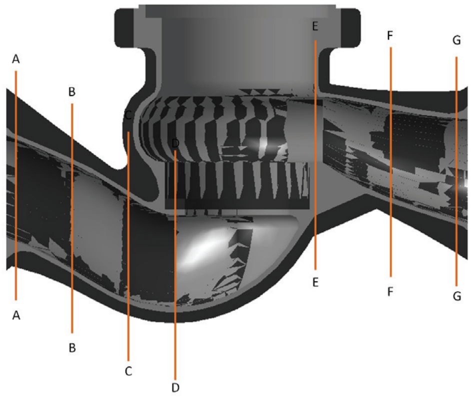

Figure 5. Difference between calculated wall thickness and the actual wall thickness of the globe valve housing.

The surface strain field was measured on the specimen near the sphere/cylinder intersection. The experimental von Mises strain field for 30 bar internal pressure is shown in Figure 6 with percentage strain value scale on the ordinate. The highest strain values, around 0.03% or 300 microstrain, are registered in the area of highest geometrical discontinuity, *i.e.* sphere/cylinder intersection. Mises strain values are up to 0.02% on valve housing the spherical and cylindrical parts.

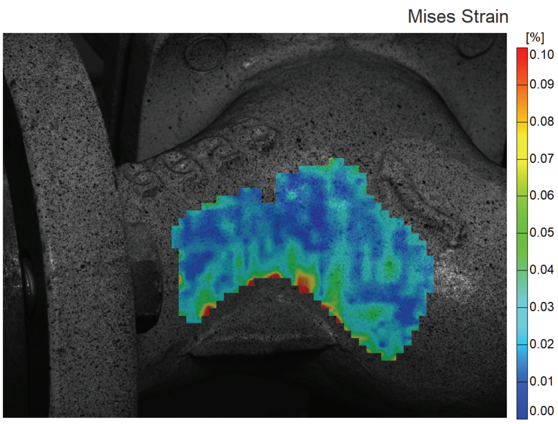

Figure 6. Experimental Mises strain field for internal pressure of 30 bar.

The 3D-DIC or StereoDIC method has some limitations [26]. As software analysis is based on pixels with the individual facet pattern seen with both cameras, strain computation is not possible on the edges of the sample. Therefore, extreme strain values (red colour) on the edge of the strain field are not taken into consideration due to this limitation. An additional limitation of this study was that it didn't take into consideration strain fields for operating conditions of globe valve, due to small strain results.

Numerical Mises strain field is presented in Figure 7 for internal pressure of 30 bar. Scale bar on the ordinate shows percentage values when multiplied by 100. Highest Mises strain values of around 0.014% were measured in the area of highest geometrical discontinuities, *e.g.*, on the sphere/cylinder intersection. Moving away from the reinforcement continually reduces the geometrical discontinuity and therefore the Mises strain values.

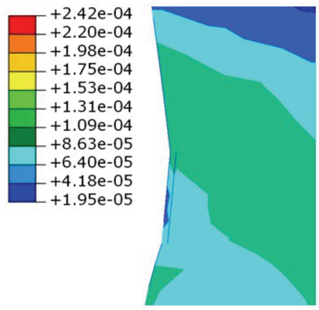

Figure 7. Numerical Mises strain field for internal pressure of 30 bar.

Numerical model was used for the analysis of the characteristic cross-sections defined in the theoretical analysis. Highest Mises stress and strain values on the upper and lower point of the cross-sections for internal pressure of 30 bar are presented in Table 2. The values in Figures 6 and 7 and Table 2 are obtained from different points on the valve housing surface. Values in Table 2 are from the sections defined by the standard and don't represent the highest strain values on housing.

Table 2. Results of the numerical analysis for internal pressure of 30 bar on the cross-sections

Cross-section	Mises strain, %		Mises stress, MPa	
	Upper	Lower	Upper	Lower
A-A	1.41E-02	9.44E-03	11.10	11.00
B-B	1.45E-02	1.4E-02	16.80	16.10
C-C	4.19E-02	2.33E-02	49.80	22.30
D-D	9.54E-03	1.87E-02	5.72	22.30
E-E	1.41E-02	9.44E-03	16.80	11.20
F-F	1.38E-02	9.40E-03	16.40	11.20
G-G	9.43E-03	4.26E-03	5.72	4.19

Stresses of the examined globe valve are significantly below material yield limit and allowable stress proving that the structure is over-dimensioned and can be optimized. Valve model calculated according to EN standard is in the safe zone. Nevertheless, their dimensions include safety factors considering production technique and calculation methodology drawbacks. It appears that the potential for optimization is great, assuming that the thicknesses of the valve structure can be reduced below the current requirements and thus making the valve a lot lighter.

Results presented in this paper are extending the findings of previous studies mentioned in the introduction. To our knowledge, this is one of the first papers showing full-field experimental results of sphere/cylinder intersection under internal pressure on the intersection itself. The developed procedure and method for application on complex structures presented in this paper can be also applied on other types of geometrical intersections, so it could be a solution to overcome the shortage of experimental data in the available literature faced by many researchers and engineers.

CONCLUSIONS

In this study, globe valve housing was analysed based on full-field experimental strain data, with respect to practical engineering application of EN standards. Experimental and numerical analysis showed that valve housing can withstand much higher internal pressure than nominal, *i.e.*, valve housing is over-dimensioned. Employing stereo cameras with StereoDIC in these types of problems has the potential to improve local measurements and speed up stress and strain analysis when compared to FEA method.

It is important to emphasize that the strain field was experimentally measured not only on the spherical and cylindrical parts of valve housing under internal pressure, but also on the sphere/cylinder intersection. To the authors' best knowledge, full-field experimental results for sphere/cylinder intersection under internal pressure are not available in the literature.

New experimental procedure development and application in full-field strain analysis contributes to increased valve housing reliability, mass reduction and material and energy savings during manufacturing, which directly affects its eco-friendliness, lowers manufacturing costs and increases market competitiveness.

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NAUČNI RAD

ODRŽIVI RAZVOJ OPREME POD PRITISKOM PRIMENOM METODE 3D KORELACIJE DIGITALNIH SLIKA

Kako se oprema pod pritiskom koristi u različitim oblastima industrije, razvoj ekološki prihvatljivijih proizvodnih procesa (npr. smanjenje mase finalnog proizvoda, uštede na materijalu i energiji i dr.) i prelazak na održivu proizvodnju razvojem ekološki inovativnih proizvoda će imati pozitivan uticaj na životnu sredinu. Cilj ovog rada je analiza kućišta ravnog zapornog ventila opterećenog unutrašnjim pritiskom primenom eksperimentalne metode 3D Korelacije Digitalnih Slika i numeričkih rezultata deformacija i napona kako bi se predložila poboljšanja za održivi razvoj, uzimajući u obzir i praktičnu inženjersku primenu EN standarda. Najveće vrednosti Mizesovih deformacija od oko 0,03 % su izmerene na mestu najvećeg geometrijskog diskontinuiteta, spoju sfere i cilindra. Naponi na ravnom zapornom ventilu dobijeni numeričkim i teoretskim pristupom su znatno manji u odnosu na granicu tečenja materijala i dozvoljeni napon za unutrašnji pritisak od 30 bar, što je značajno više od nominalnog radnog pritiska od 6 bar i što pokazuje da je kućište predimenzionisano i da može biti optimizovano. Razvoj i primena novih eksperimentalnih procedura u oblasti analize celih polja deformacija doprinosi većoj pouzdanosti kućišta ventila, smanjenju mase i uštedi materijala i energije u toku proizvodnje što direktno utiče na ekološku prihvatljivost, smanjuje cenu proizvodnje i povećava konkurentnost na tržištu.

Ključne reči: metoda 3D korelacije digitalnih slika, zaštita životne sredine, kućište ravnog zapornog ventila, održivi razvoj.