

## DETERMINATION OF THE VOLUME OF THE TANK OF RAILWAY WAGON WITH RIBBING

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### ABSTRACT

This article is aimed at comparing the effectiveness of testing the dimensional parameters of a tank wagon with an internal ribbing with a nominal volume of 85 m<sup>3</sup> in a production plant. One of the used methods is the traditional volumetric method, ie measuring the volume of water with a pair of flowmeters when filling the vessel. The second method is a method of computer processing of data obtained by 3d scanning of the interior of the tank from several positions and the subsequent composition of the tank model and calculation of its volume using the PolyWorks program. Evaluation of both measurement methods revealed that despite the non-trivial internal division of the measured object, both methods are sufficiently accurate, and even in this case the scanning method provides the measurement result several times faster compared to the volumetric method. In the reported example, measurement time spent to achieve results for the scanning method was approximately one third comparing with that of the water filling.

**Keywords:** *volumetric method, water savings, 3D scanning, railway tank*

### INTRODUCTION

Sustainable modes of transport could help reduce the costs of road congestion, as they are expected to increase by 50% by 2050. According to the European Environment Agency, CO<sub>2</sub> emissions from rail transport are 3.5 times lower per tonne-kilometer than from road transport [1]. Therefore, sustainable modes of transport, especially rail, have become a key part of EU policy over the last 25 years. As early as 1992, the European Commission set the shift from road to rail as one of its main goals. In 2001, the Commission reaffirmed the importance of revitalizing rail transport, setting a target of maintaining the share of rail freight in the markets of Central and Eastern Europe at 35% by 2010. In 2011, it set a target of shifting up to 30% of road freight for distances exceeding 300 km for rail transport by 2030 and up to 50% by 2050 [2].

Tank wagons are used to transport gaseous and liquid substances. The tank wagon chosen for the measurement is manufactured by Tatravagónka Poprad and has a nominal volume of 85 m<sup>3</sup> ± 1% with a length of 11970 mm and a tank diameter of 3100 mm. Until now, the volumetric method of filling water and simultaneously measuring its volume with flow meters has been used in many production plants to control the volume of the tank [3], which is a lengthy method requiring a special workplace with powerful pumps. During the measurement, there is a large consumption of water, which is contaminated with impurities from production after



the measurement and it is necessary to ensure waste management for it. Electricity is used to drive the pumps during filling and draining and also to dry the tank after measurement. In recent years, an alternative optical scanning procedure has been used to reduce the environmental burden [4], [5]. In addition to the fact that the measurement can be performed without special requirements for workplace equipment, a significant benefit is also time-saving.

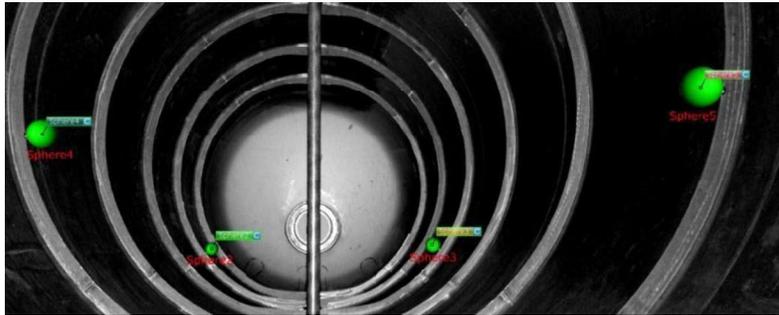
In the literature, analyzes of measurements of cylindrical vessels with a simple cylindrical surface [6], [7] are mostly described and there is a lack of studies with measurements of large vessels in which strengthening elements are used for stiffness reasons. The aim of this paper is to compare the measurement of the volume of such a tank by volumetric and scanning methods and to compare the accuracy and time efficiency of both procedures.

## EXPERIMENTAL SECTION

The FaroFocusS 150 3D scanner was used for non-contact measurement of the tank volume. During scanning, it emits an infrared laser beam into the centre of a rotating mirror, which further deflects it into space in the field of view of  $360^\circ \times 300^\circ$ . When it comes in contact with the object, it bounces back into the scanner. The distance from the scanner is determined by measuring the phase shifts of the laser radiation.

Measurements are processed on an HP Z840 Workstation Desktop containing 2x Intel Xeon CPU E5-2630 v4 @ 2.2 GHz with 128 GB RAM, 2x 4 TB LSI Logical Volume SCSI Disk Device and 1x 1 TB SSD, 2x NVIDIA Quadro P4000 64.0 GB graphics card. The software programs used are Polyworks Metrology Suite 2019 IR4 64-bit and Sceneversion 2019, API version. The highest quality scan of this system takes 118 min and 49 s, the lowest quality takes 1 min and 7 s.

Before scanning, the operator has to determine how many times the object will be scanned in order for 100% of the entire surface to be scanned. For some objects, one position is enough if it is scanned only locally, for others several dozen positions and relocations are necessary. Furthermore, reference balls need to be properly arranged to connect and register scans (Fig. 1). The balls are clamped on the place using a built-in magnet, so mounting them on steel parts is simple and stable. They have a precise spherical white reflecting surface and diameter  $\varnothing$  145 mm. To properly align two or more scans, the balls must be arranged in such a way that the scan of the space always contains at least three balls from each position.



*Fig. 1. Named reference balls (left side)*

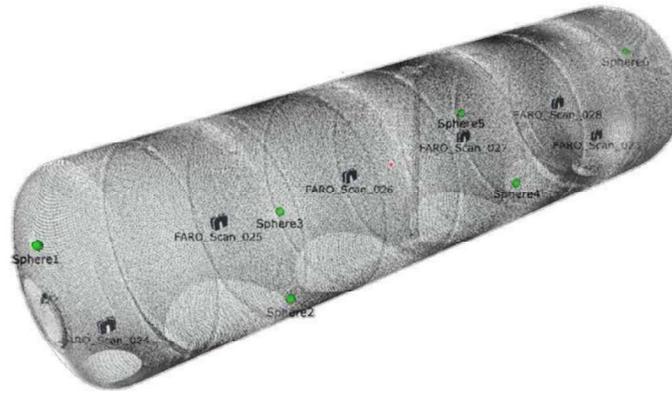
There are distributed 6 reference balls in the tank along the entire length of the tank and at different heights by using magnets. The entire tank was scanned for 6 positions, ie five relocations of the scanner. The first position was at the entrance hole and the last at the opposite end of the tank.

At the end of each scan, the scanner must be relocated between the other inner reinforcement ribs to be scanned from both sides. After each scan, it is necessary to enter the tank, relocate the scanner, turn the measurement on and get out. It takes about 20 seconds for the scanner to initialize and begin scanning after activating the next scan, so the operator has enough time to leave the measurement area. When selecting the All Scan profile, point density 1/4, repeating the measurement of each point 4x, scan size 10240 x 4267 points, measurement accuracy in the length of 10 m scattering of points 6.1 mm and scan duration 11 min 27 sec, the measurement took 75 min, respectively 105 min including the preparation.

In order to optimize the time and data load, the measurement was repeated with altered scanning and software parameters. Measurement at 6 positions with dot density 1/4 and repeated measurement of each point 2x, scan size 10240 x 4267 points, measurement accuracy in the length of 10 m scatter of points 6.1 mm result in scan duration 02 min 24 sec. The scanning of one tank was thus shortened to 15 minutes with preparation. The scans still need to be processed to measure the volume of the tank.

### **Data Processing**

Registration is the process of all scans aligning into one overall scan using a reference scan and data from the sensor such as position, direction and height. The most common and accurate way is registering using the beforementioned reference balls, which are arranged in the scanned space. Each ball must be named the same in each scan, as the software connects and overlaps the scans on the base of the same designation and position of the reference balls in the space.

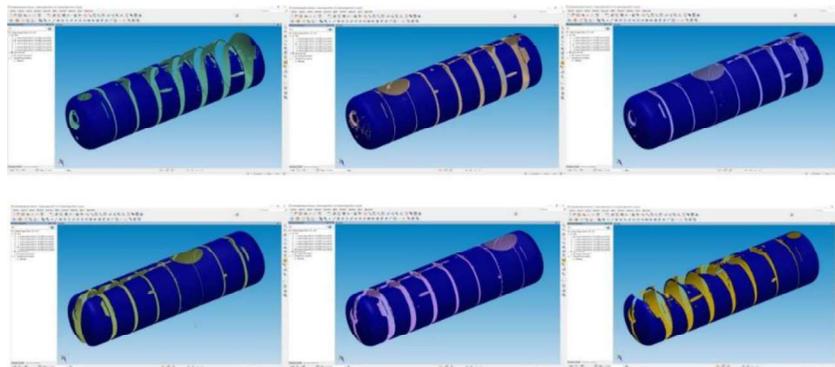


*Fig. 2. Reduced cloud of points*

After registration and alignment, a cloud of the contour points is ready for export. Fig. 2 presents a reduced cloud consisting of 459,000 dots, which is only 0.2% of the total scanned amount, to get semi-transparent picture showing the location of the individual scan device positions and reference points.

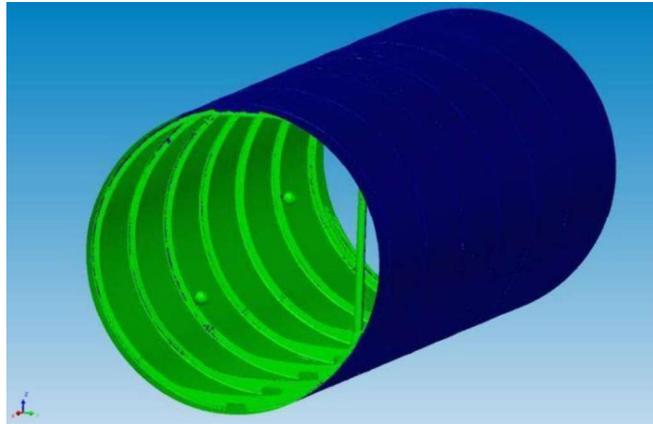
Data from the scanner are saved in a .fls file so that points are saved including the normal. Each point saved in this way contains six parameters: the coordinates  $x, y, z$  [mm] and the direction of the normal  $i, j, k$  [°].

In order to create the polygon model, PolyWorks software was used. When creating a polygonal model, the software always connects the two nearest points (vertices) into a vector. When three vectors are connected, a triangle - polygon is created. This procedure is repeated until all polygons are gradually connected and so polygonal model is created. The denser the points are, the more detailed and better dimensionally descriptive is the model. This is a procedure that lasts about 10 minutes.



*Fig. 3. Polygonal models evaluated after partial scans - the upper left model corresponds to the location of the scanner in the left part of the tank, the scanner is gradually relocated to the right*

Fig. 3 presents a serie of six partial models after each scan, from which an overall polygonal model is created. This is an illustration of how the system is not able to scan the areas behind the ribs (or whatever obstacle) from individual scanning positions, so it is necessary to perform relocated scans to ensure measurement of the elements allowing to model 100% of the surface necessary for the calculation.



*Fig. 4. Reference balls and spacer bar inside the tank*

Before one can perform the calculation of the tank volume, it is necessary to clean the object from unwanted elements that could affect the result of the calculation of the total volume. In this case, in addition to small dirt and radiation reflections from dust particles that form kind of noise that is to be cut-out, there are six reference balls inside the tank, which would reduce the actual volume of the tank with their volume, as well as the middle spacer bar, which serves to pump the gas out of the tank and at the same time prevents deformation of the tank in the middle (Fig. 4). Since it has a hollow shape and also serves as a pipeline, there are two ways to regard it in the calculation. The first option is to keep it in, calculate its internal volume and add it to the total volume of the tank. The second option is to erase the rod and not to modify the calculation, because its thin wall negligibly affects the volume calculation comparing to the size of the tolerance limit. The second method was chosen as faster and more practical.

It is also necessary to set the Cartesian coordinate system in the data model. Since the basic elements for inserting a coordinate system are not predefined, namely: plane, vector and point, it is necessary to define them. The vector is also the axis of the cylinder, it is possible to create it in two ways:

1. By defining a nominal CAD model and then extracting it as a data element
2. By defining a data model and creating an average cylinder from the measured elements.

To calculate the volume, it is still necessary to determine the reference plane, contour, direction and sampling step.



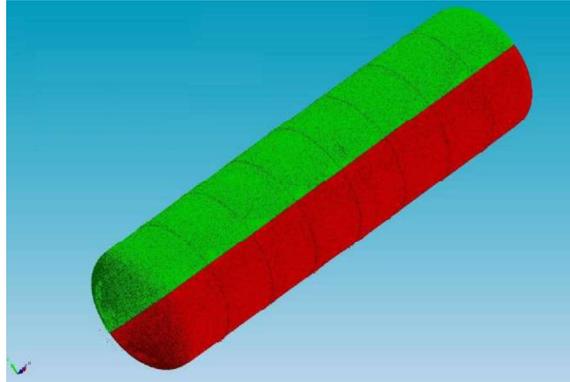
According to the Reference plane, the perpendicular direction of the orientation of individual intervals (sampling) of volume integrals (cubature) to the reference plane is determined. It must pass through the object in such a way that the integrals count through the entire volume of the body. Its orientation must be determined according to the coordinate system in the XY, YZ or ZX directions. In our case, the ZX direction was chosen to avoid undercutting the data behind the ribs inside the tanks.

Each data point is projected to a reference plane to determine which grid the square belongs to. Each data point in the grid square is calculated as the intersection of the vector starting at the centre of the grid element and the plane passing through the point containing the normal.

The sampling step are intervals (cross-sections) of integrals that fill the entire volume of the object. A value of 1.00 mm means that it is a square in cross-section with sides 1 mm x 1 mm. In general, the smaller the value, the more accurate the volume measurement result, but also the longer the calculation time, which increases exponentially with decreasing sampling step size. It is also necessary to create intersections with the side lids on the tank, so that the data object can be fitted on the CAD model in the longitudinal axis. Since the side lids have the shape of a spherical surface, they can be defined as a round cut with a certain diameter.

The total volume is the sum of the positive and negative volume as presented at Fig. 5 and Table 1. The two values are not the same because the tank is unevenly deformed and also depends on the position of the reference plane, which does not pass exactly through the central X-axis. Ultimately, this does not affect the accuracy of the tank volume calculation.

To determine the actual value of the tank volume, the following procedure for processing measurements for individual sampling parameters was chosen: a polygonal model is created from the processed scans, subsequently, it is possible to calculate the volume, which e.g. it takes 40 min with a selected sampling size of 0.5 mm. When sampling is changed to 0.45 mm, the calculation takes 2 hours, which is not very efficient in time, because the value of the total volume has changed by only 10 dm<sup>3</sup>, which is a negligible value in terms of the permissible tolerance of the tank volume. Anyway, in order to calculate the actual volume, 14 calculations of volumes were evaluated from sampling 100 mm x 100 mm descending to 0.45 mm x 0.45 mm. A graphical dependence and a linear trend line were created from the calculated volume measurements - see Fig. 6. The intersection of the linear regression line and the zero vertical axes represents the extrapolated theoretical actual value of the tank volume.



**Fig. 5.** Calculated tank volume with a nominal volume of 85 m<sup>3</sup>

**Table 1.** Integrated parts of the total volume

Volume measurement results	Tank with nominal volume 85 m <sup>3</sup>
Positive volume (green) [m <sup>3</sup> ]	42.5637
Negative volume (red) [m <sup>3</sup> ]	42.5709
Total volume [m <sup>3</sup> ]	85.1346

**Fig. 6** Displayed measured values of volumes depending on the sampling step with regression line

The graph shows the trend of the calculated volume depending on the step, corresponding to the linear function

$$f(\text{volume}) = -247.2 * \text{step} + 85430$$

After substituting the zero value of the step, it is possible to determine the theoretical value of the total volume of the tank, which corresponds to the position of the intersection of the values trend line with the vertical y-axis. That means that the calculated actual value of the tank volume is 85,430 dm<sup>3</sup>. The difference between the theoretically calculated value and that measured at 0.5 mm sampling is 123 dm<sup>3</sup>, which is an acceptable value from the point of view of tolerance  $\pm 850$  dm<sup>3</sup>. Therefore, it is not necessary to use the calculation of the extrapolated value in the paragraph when checking the volume of the measuring tank, but it is possible to use that procedure if the result needs to be refined.

Based on the evaluation of the measurement, the value for the reduction of points was adjusted from 1/4 to 1/24, the parameter for creating a polygonal model was optimized and the sampling step for the volume calculation was adjusted from 0.5 mm to 1 mm. The evaluation time was thus reduced from 90 minutes to 21 minutes, which is 36 minutes altogether with the scanning time. The reported time of 15-20 minutes referred in the literature [4], [8] was achieved by measuring simpler objects without ribbing. From this point of view, we consider the achieved result to be satisfactory. If further optimization is required, other reductions are



possible with respect to the measurement parameters and the calibration recalculation of the result based on trend extrapolation.

The determination of the volume for the given parameters is characterized by the uncertainty of determining the result  $\pm 101 \text{ dm}^3$ , which is an acceptable value from the point of view of tolerance  $\pm 850 \text{ dm}^3$ , as even the most unfavourable value of the measurement result falls within the given interval.

### **Comparison of Tank Volume Measurement by Scanning and Flow Meters**

In the production of wagon tanks, the technological process of production also includes the measurement of the internal volume, for which two measuring flow meters operating simultaneously were used in practice:

- MID 2-25/16-F/St-PT-MEL/HC-St M10AR with maximum flow  $4.5 \text{ m}^3/\text{hod}$
- MID 2-100/16-F/St-HG-ML/HC-St M20AM with maximum flow  $70 \text{ m}^3/\text{hod}$

Filling time:  $t_i = 68 \text{ min } 28 \text{ s}$

Emptying time:  $t_o = 45 \text{ min}$

Total time:  $t_{i+o} = 113 \text{ min } 28 \text{ s}$

Measured volume of water  $85\,075 \text{ m}^3 \pm 84 \text{ m}^3$

According to the calibration sheet, the MID 2-25 / 16 flowmeter has an uncertainty of the measurement result  $\pm 0.05\%$  and the MID 2-10 / 16 flowmeter under the same conditions the uncertainty of the measurement result  $\pm 0.105\%$ .

These results show that the actual volume of the tank meets the nominal requirements within the prescribed tolerance as measured by both methods, while the scanning method is more time-efficient and at the same time more environmentally friendly. Testing the tank for leaks and resistance to mechanical stress remains the advantage of the volumetric method over scanning.

### **CONCLUSION**

The aim of this work was to verify the effectiveness of measuring the internal volume of the railway tank with ribbing using a 3D scanner Faro FocusS150, as a reference measurement was used the currently used system of measuring volume flow meters MID 2-25 / 16-F and MID 2-100 / 16-F.

By comparing the two measurements in terms of accuracy, method of design and time, it can be stated that both methods of measurement are suitable for volume measurement and their accuracy meets the technical requirements for tank volume tolerance. From the point of view of time, the measurement with the FaroFocusS spatial scanner is more advantageous, because the measurement of the tank (observing the prescribed deviation of the volume tolerance) lasts altogether with the evaluation 36 minutes, ie it is 3x faster than the measurement with flow meters (113.5 min.). Another benefit of measuring with a scanner is the acquisition of data enabling the creation of an object model for other measurement possibilities along

with significant water and electricity savings. As for the possibilities of further streamlining of measurements, in the case of the volumetric method, it is possible to use higher flows, but the total amount of water and energy consumed will not change. In the case of 3D scanning, there could be tested another option to adjust the data processing process, however, related to the calculation accuracy.

This work fulfilled the original intention to use the FaroFocusS exterior scanner to measure the volume of tanks in the production process in a practical way. It is, therefore, possible to recommend this method of measurement and incorporate it into the technological method of production, respectively control of tank volumes in practice.

### ACKNOWLEDGEMENTS

The authors would like to thank the VEGA grant agency for supporting presented research work within the project VEGA 1/0205/19.

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