



Pressure Pulsation and Pipeline Vibration Damping with the Use of 3D Printed Nozzles

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Abstract. Manifold vibrations in volumetric compressors systems are often the result of pressure pulsations and flow characteristics as well as compressor-generated mechanical vibrations. Standard methods of damping pressure pulsations in compressor installations using Helmholtz resonators focus on damping the main pulsation frequency resulting from compressor operation. Currently, in both refrigeration and industrial compressors, continuous operation with variable rotational speed of the compressor drive shaft is becoming a standard. As a result, the compressor, while working, generates pressure pulsations with different frequency values, which cannot be effectively suppressed using the standard method. In the works published in recent years, there are informations that shaped nozzles, introduced into the discharge manifold of compressor, can significantly affect the damping of pressure pulsations in a wide range of their frequencies. The production of damping nozzles using 3D printing techniques allows us to design unprecedented shapes. The article presents the effect of nozzles with complex shapes (impossible or difficult to produce using conventional methods) on the damping of pressure pulsations and pipeline vibrations.

Keywords: Pressure pulsations · 3D printing · Vibration · Damping · Compressors

1 Introduction

Pressure pulsations which occur in installations of displacement compressors are one of the main negative phenomena generated by the operation of the compressor. One of the effects of the occurrence of pressure pulsation is pipeline vibration. Due to the safety requirements (in industrial gas installations) and parameters related to the comfort of their use in cooling installations, this pipeline vibration should be limited.

The most popular method of damping pulsations are mounting Helmholtz resonators. The tuned mass dampers are used often to dampen pipeline vibrations. These technologies only work on the designed frequencies. The publications [1–3] proved the effectiveness of pulsation damping in a wide frequency range by shaped nozzles. However, in this paper the influence of elements with complex shapes (impossible or difficult to produce with the use of classical production techniques) is presented. In order to produce such

elements, 3D printing technologies were used. Currently, this type of approach seems to be more common in this type of research. In several papers different approach of 3D printing and usage of that elements was described. An unexpected acoustic absorption phenomenon in 3D printed Helmholtz resonators is described in paper [4]. The possibility to use 3D printed materials in high temperatures was described in paper [5]. Influence of different geometry in Tuned Sloshing Dampers on wave energy dissipation is presented in [6]. This paper shows that 3D printing can be used in a wide range of applications related to damping. From the very beginning of the use of displacement compressors the problem of pressure pulsations phenomena is very well known. Nevertheless, the current research topic is still widely described in scientific publications. The authors in paper [7] present the pressure pulsations in piping system and describe the damping characteristics. The influence of introducing flat orifice plate on the pressure pulsations is also presented in this paper.

Nonlinear vibrations of thin plate in pulsating flow are described and the theoretical approach is presented in [8]. The installation of multi-dimensional vibration isolation and mitigation device is described in Xu et al. [9]. The influence of the orifice on the decrease in the pressure pulsation level with the reduction of the orifice cross-sectional area was described by Rydlewicz et al. [10]. The usability of this element in piping systems to attenuate pressure pulsations was indicated. Effectiveness in damping pressure pulsations when applied to a resonant piping system by mechanism of a Herschel-Quincke (HQ) device was presented by Lato et al. [11]. In this paper, experimental investigations of the passive pressure pulsation and pipeline vibration damping with the use of 3D printed elements are described.

2 Damping Elements

During the research 12 different elements, made with 3D printing techniques were tested. Changes in static fluid pressure, flow velocity, and vortex characteristics are different for obstacles with different shape characteristics. Also the forces acting on different nozzles affect the pipeline differently and may amplify or dampen its vibrations. For this reason, the tests were carried out for nozzles of various shapes, classified into four groups. Elements of hyperboloidal shapes belong to the first group presented in Fig. 1. The effectiveness of these elements, in damping pressure pulsations, was presented in papers [1–3]. In presented research, different variations of hyperboloidal nozzle were examined. Shape A.1. is the simply hyperboloidal nozzle which allows to compare the effect of other shapes on the damping of pulsations and vibrations. Nozzles A.2., A.3. And A.5. Are twin hyperboloidal shapes, where A.5. is also shape used in previous investigation. Shapes A.2. And A.3. Had cylindrical holes in the material. In the case of A.2. The holes are larger and their arrangement is less frequent than in the A.3. Shape A.4. is a single hyperboloid shape with a void space between the outer diameter and a thin wall with a hyperboloidal profile. Additionally, the wall has openings with similar dimensions and arrangement as in the shape A.3.

The shapes of the second group are shapes that narrow the flow cross-section along the length of the nozzle similar as in the case of hyperboloid nozzles. These shapes are shown in Fig. 2. Shape B.1. is based on the shape of the mouthpiece for brass instruments. In the case of the instrument, the sound wave spreads evenly over the instrument, which may have a positive effect on the damping of pressure pulsations and maintaining flow consistency.

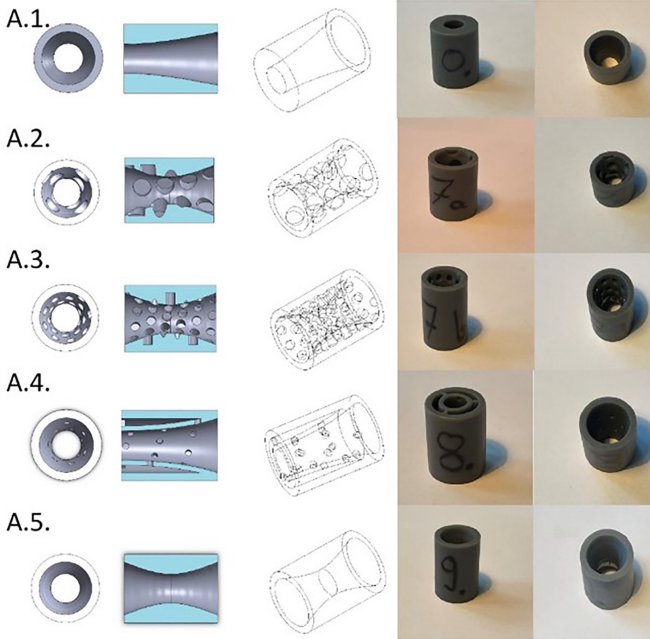


Fig. 1. Group A – hyperboloidal-type shapes

The concept B.2. is derived from a silencer for firearms, however, there is a narrowing of the inner diameter. The shape B.3. Consists of many helical ribs which have the effect of breaking up the flow around the circumference of the nozzle. Due to its complicated shape it is impossible to produce with subtractive methods.

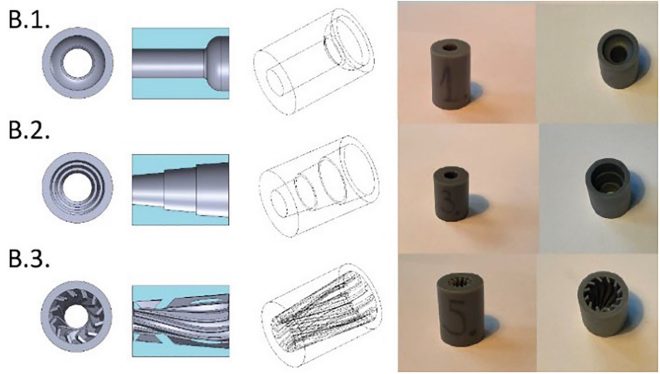


Fig. 2. Group B – narrowing shapes

Group three are non-standard nozzles with an irregular constriction. In Fig. 3 it can be seen that due to their shape, the flow through these elements is more irregular than in the previous groups.

A turbine-like element, shown in Fig. 4, was examined as the last one.

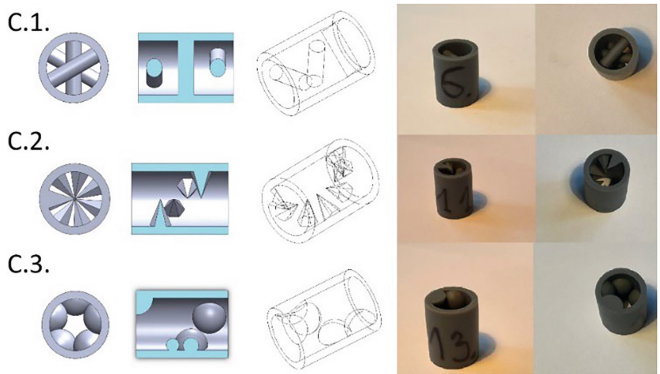


Fig. 3. Group C – irregular shapes

All elements were designed to meet a condition in which the change of the gas flow surface area in the passage is equal to 70% of the flow area of the pipe in which the elements are assembled.

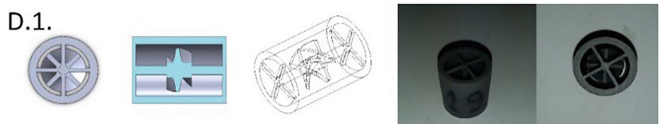


Fig. 4. Group D – turbine-like element

The point of reference for the results obtained for the presented shapes was the installation with an element maintaining the diameter of the pipeline, later described as an empty pipe. On the basis of previous tests, the large value of the narrowing used in the tests was selected, to emphasize the significant impact of the elements on the damping of pressure pulsations and on pipeline vibration.

3 Test Stand

The experimental investigations were performed in the discharge manifold of the two-cylinder reciprocating air compressor SAF-23 driven by an electric motor which is controlled by inverter. Test stand system is presented in Fig. 5.

The LabView/SignalExpress software was used to measure the pressure pulsation, while the DASYLab was used to measure the vibration signal.

For all measurements the pressure was set with a reducing valve at 1.5 bar. The temperature for the highest rotational speed stabilized each time at around 104 °C. While waiting for the compressor to reach a stable operating temperature, the temperature in the hall and the atmospheric pressure were recorded. After the parameters stabilized, measurements were taken. The duration of data recording for each measurement was approximately 5 s long. This amount of time was sufficient to catch the appropriate signal range. Due to the tracking the signal in real time, it was possible to detect incorrect readings caused by detaching the sensors during the measurement. In order to avoid random measurement errors, these measurements were repeated at 5 min intervals. After a series of measurements of the tested element, the compressor and all related devices were turned off.

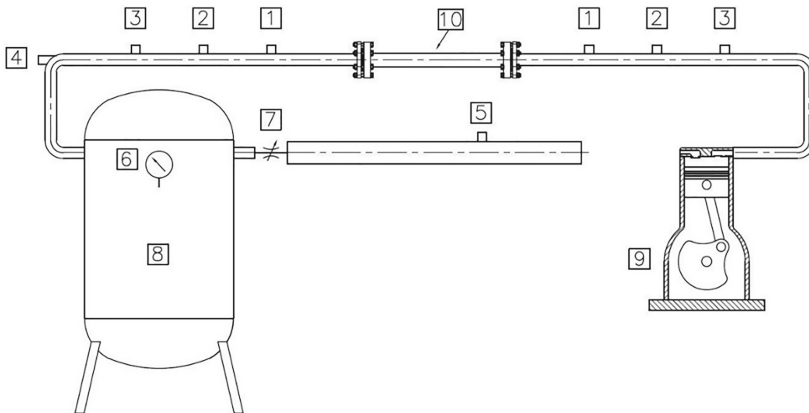


Fig. 5. The scheme of the test stand. 1 – Differential pressure measuring points, 2 – Dynamic pressure sensors, 3 – Thermocouples, 4 – Vibration sensor, 5 – Thermoanemometer, 6 – Manometer, 7 – Throttle valve, 8 – Compressed air tank, 9 – Compressor, 10 – Damping element mounted in the assembly part

4 Results

A series of experimental tests made it possible to determine the peak-to-peak value of the pressure pulsation amplitude for different values of the shaft rotational speed, and thus for different values of the pulsation frequency. The results obtained by the sensor behind nozzle mounting point for all investigated shapes for all pulsation frequencies are presented in the Fig. 6.

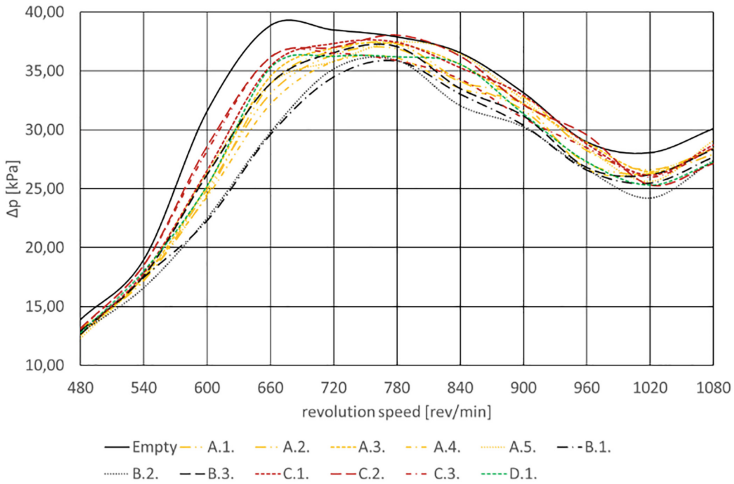


Fig. 6. Pressure pulsations peak-to-peak values for different shapes and different shaft revolution speed – pressure pulsation sensor located behind the nozzle mounting point

For all values the average pressure pulsation damping, for all frequencies, was calculated as a percentage damping related to empty installation as it is described in the Eq. (1):

$$\psi_{nozzle.avg} = 100\% - \frac{\Delta p_{nozzle.avg}}{\Delta p_{empty.avg}} \cdot 100\% \tag{1}$$

where:

$\psi_{nozzle.avg}$ – average nozzle pressure pulsation damping for wide range of frequencies [%],

$\Delta p_{nozzle.avg}$ – average pressure peak-to-peak value [kPa] with nozzle in the installation,

$\Delta p_{empty.avg}$ – average pressure peak-to-peak value [kPa] for straight pipe in the installation.

The calculated values of the average pulsation damping, measured in front and behind the nozzle for wide range of frequencies, are presented in Table 1.

Table 1. Pressure pulsation damping by different shapes.

No.		A.1.	A.2.	A.3.	A.4.	A.5.	B.1.	B.2.	B.3.	C.1.	C.2.	C.3.	D.1.
$\psi_{nozzle.avg}[\%]$	<i>In front</i>	3,0	4,5	3,8	5,0	4,9	2,6	3,8	4,5	3,8	3,5	2,9	3,0
	<i>Behind</i>	7,9	8,0	7,2	9,5	7,1	12,0	12,9	8,4	6,0	4,8	6,3	8,0

The average damping of pressure pulsations behind the damping element is the highest for elements from group B as it can be seen in the Table 1. Damping in front and behind the nozzles have different nature for different shapes. In the A group the A.4. Shape stands out as it suppresses the pulsation value the most, both in front of and behind the nozzle. For the shapes B.1. And B.2. Pulsation damping in front of the nozzle is very low – that suggests a significant wave reflection on the orifice.

As during the tests the level of longitudinal vibrations of the installation was also measured, Table 2 shows the average vibration damping of the first harmonic for the tested frequency range. For all values the average vibration acceleration damping for all frequencies was calculated as a percentage damping related to empty installation, as it is described in the Eq. (2):

$$\Theta_{nozzle.avg} = 100\% - \frac{\Delta a_{nozzle.avg}}{\Delta a_{empty.avg}} \cdot 100\% \quad (2)$$

where:

$\Theta_{nozzle.avg}$ – average nozzle acceleration damping for wide range of frequencies [%],

$\Delta a_{nozzle.avg}$ – average acceleration peak-to-peak value [$m \cdot s^{-2}$] with nozzle in the installation,

$\Delta a_{empty.avg}$ – average acceleration peak-to-peak value [$m \cdot s^{-2}$] for straight pipe in the installation.

Table 2. Longitudinal vibration damping by different shapes.

No.	A.1.	A.2.	A.3.	A.4.	A.5.	B.1.	B.2.	B.3.	C.1.	C.2.	C.3.	D.1.
$\Theta_{nozzle.avg}[\%]$	10,4	5,3	5,1	17,9	8,7	11,3	16,3	-2,0	0,4	3,3	-18,5	-4,2

As can be seen, the influence of different shapes on vibration damping is highly heterogeneous in different groups. It can be seen that for shapes A.2. and A.3., which are the same hyperboloidal shapes, but with different hole diameters, the influence on the vibration damping is similar. The same effect is for hyperboloidal shapes without holes. In this group, for the shape with openings and free cavity between the hyperboloid profile and the pipe vibrations damping reach highest value. Vibrations are not damped or are actually amplified in the nozzles, in which the pulsating flow can cause higher values of radial and oblique forces than axial ones. These shapes are distinguished by the fact that they do not constrict the flow in an axially symmetric manner.

5 Conclusions

Performed investigations of the influence of 3D printed elements on the pressure pulsation and pipeline vibration damping indicate that shape is a key factor and have big influence on the described phenomena. The article presents how different shapes influence these important phenomena and shows a linear relationship between pressure pulsation damping and vibration damping for shapes narrowing along the length of the nozzle which can be described as axially symmetrical (excluding the holes contained therein). What is very important, it has been proven that even very different shapes placed inside the pipeline suppress pulsations in a wide frequency range. Thanks to the conducted experimental research, it is possible to choose the further direction of shape development in this type of damper. The results of the conducted research suggest that the most effective may be shapes that narrow along the length of the nozzle. Shape A.4 turned out to be particularly effective in simultaneous damping of pressure pulsations and vibrations of the pipeline, as it combines an internal hyperboloidal profile with an empty void into which gas flows through holes made in the hyperboloidal profile. Further research will be carried out, to determine the influence of a given shape on the flow resistance. Future research will focus on optimization of the shapes of this type of damping inserts.

Acknowledgements. This research was funded by Polish National Centre for Research and Development, grant number LIDER/40/0140/L-11/19/NCBR/2020.

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