

# In-Line Sphere Arrays as Pressure Pulsation and Pipeline Vibration Dampers in Reciprocating Compressor Manifold



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**Abstract** Pressure pulsations and pipeline vibrations are unfavorable phenomena generated by the periodic operation of the volumetric compressors. The variable speed of the compressor shaft generates pulsations and vibrations of different frequencies, which means that Helmholtz resonators and tuned mass dampers are not the most effective devices to reduce these phenomena. One of the possibilities to dampen pulsations in a wide range of frequencies, is to place shaped nozzles in the compressor discharge manifold. However, the nozzles significantly affect the compression power by restricting the flow from the wall to the centre of the pipe. Therefore, the influence of elements placed on the axis of the pipeline with spherical shapes was investigated. In this research, 3D-printed nozzles with a different numbers of spheres were tested. Research shows how a number of spheres in the array influence the damping of pressure pulsation and pipeline vibration.

**Keywords** Damping · Nozzle flow · Pipeline vibration · Pressure pulsation · 3D printing

## 1 Introduction

The occurred unfavorable phenomenon of pressure pulsations in positive displacement compressor installations causes vibrations, energy loss, and valves wear are harmful to the installation and its components. The main methods currently used to dampen pressure pulsations are the installation of damping volumes on the suction lines or discharge lines of the compressor. Damping bottles are a very effective

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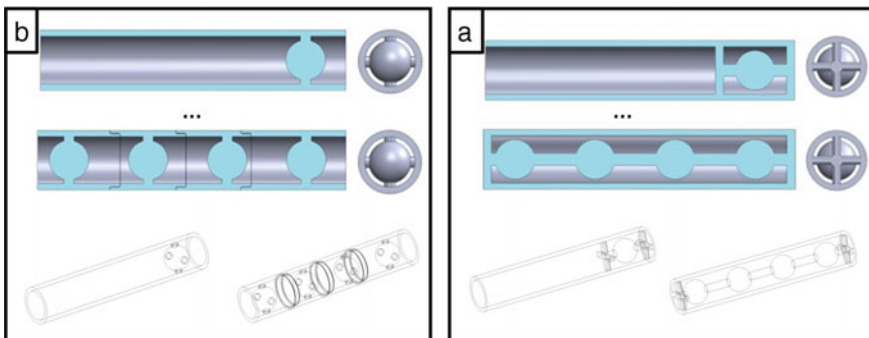
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solution for damping the main frequency of pressure pulsations. However, nowadays for better energy and flow control, of compressed refrigerant in the installation, compressors with adjustable drive shaft speeds are becoming more popular. This situation makes it necessary to dampen pulsations over a wide frequency range. The simplest method used in this case is the mounting of orifice plates in the compressor discharge pipeline but this solution have a significant impact on the compression energy efficiency value.

One of the proposed solution, which has been developed for several years [1], is the installation of shaped inserts in the compressor discharge manifold for pressure pulsation damping. It has already been shown that such inserts suppress pressure pulsations in a wide range of frequencies [2]. Article [3] proves that vortices generated on obstacles have a significant impact on damping of pressure pulsations. The choice of a spherical shape seems to be a proper way as a starting point for searching for solutions which will have a low impact on the compression power. In the literature, many articles can be found describing the phenomena related to the flow around a sphere [4] several spheres in a row [5] or other arrangements [6]. Therefore, the influence of the nozzles with different number of spheres on the damping of pressure pulsations in the piston compressor installation was investigated. The obtained results may also be useful in the design of other components fitted in the compressor discharge line, such as fluidic/vortex diodes, control valves, lube filters and other.

## 2 Design of the Nozzles

To compare the influence of different number of spheres introduced into the pipeline, on the pressure pulsations damping the appropriate nozzles were designed. Two conceptions in four variants (with one, two, three and four spheres) were designed. In Fig. 1 nozzles conceptions in two options are presented.



**Fig. 1** Nozzles with sphere conceptions: left: B-type with radial connectors, right: A-type with axially connectors

The diameters of the spheres were selected so that the spheres cover 70% of the cross-sectional area of the pipeline in the plane passing through the centre of the sphere. The distance between successive spheres was equal to the diameter of the spheres. All nozzles were printed from high-temperature resin in LFS 3D printing technology (a variant of SLA technology). The advantages and limitations of 3D printing technology had to be taken into account during the design process by selecting the appropriate tolerances of elements and the method of joining. In the A approach a cylinder placed in the axis of the element was used. Due to the significant peeling forces during printing, this cylinder had to be of high strength. In consequence, the gas flow in the muffler behind each ball is disturbed and cannot be treated as a free flow around the sphere. In the B variant of mounting the spheres, the idea was to eliminate the unwanted disturbed flow behind the spheres, therefore the spheres were mounted on cross elements attached to the walls of the nozzle. In this case, there is a necessity to use supports during printing and the necessity to remove them after printing. This implies that this type of nozzle had to be printed in parts. After the print and removal of the supports, the elements were precisely positioned and glued. Unfortunately also in this variant it is not possible to avoid the influence of the additional fastening elements on the flow around the sphere. However, testing these two cases allows one to compare the effect of different mounting methods on the damping of pressure pulsation.

### 3 Test Stand

Experimental investigations were carried out on a test stand consisting of the reciprocating oil-free compressor and specially designed test manifold. The nozzles were inserted into a specially prepared steel adapter and then the adapter with a nozzle was screwed onto the connectors in the installation.

Pressure pulsation measurement is carried out by two ICP Dynamic Pressure Sensors, with an accuracy of 7.232 (sensor 1) and 15.56 (sensor 2) mV/kPa. The vibration measurement was carried out with an ADXL 335 three-axis accelerometer with an output sensitivity of 300 mV/g. The cDAQ-9174 chassis was used to read and save the measured signals equipped with the NI 9215 measurement card with BNC connections—for the dynamic pressure signal and the NI 9205 with a spring terminal to connect the vibration measuring channels. A diagram of the measurement flow is shown in Fig. 2.

Measurements were made for all prepared nozzles. Measurements with the straight pipe shape (referred to as an empty case) introduced in the nozzle mounting point were performed as a reference point.

All measurements were carried out for constant pressure in the system of 5 bar. Measurements were made for three rotational speeds of the compressor drive shaft: 1100, 1600, and 2100 rev/min. Due to the work of the pistons (gas is pushed out every 90° of the drive shaft rotation and then 270° no gas is introduced into the installation),

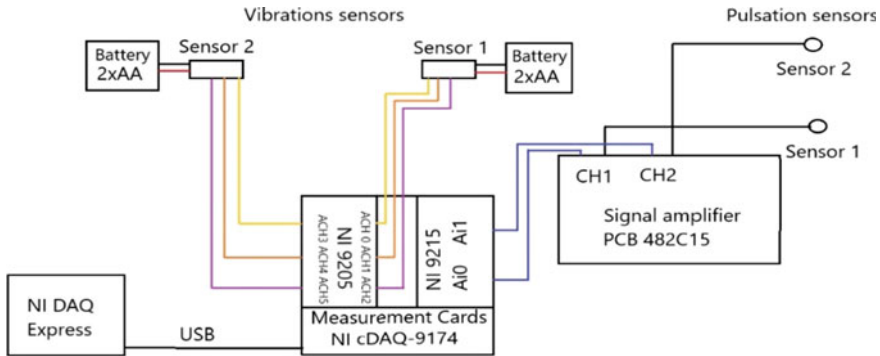


Fig. 2 Measurement circuit

the main pulsation frequency results directly from the value of the rotational speed of the drive shaft. Figure 3 shows a diagram of the test stand.

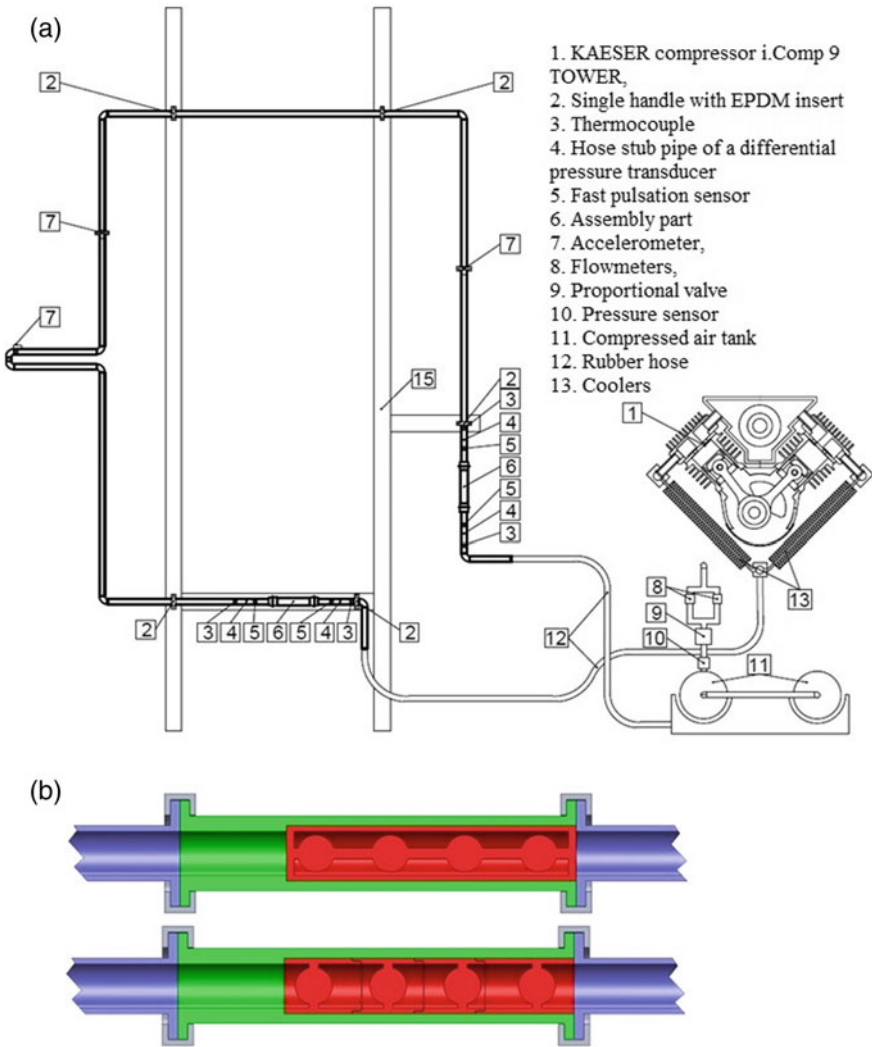
The research installation was designed to represent the real industrial system as much as possible. Therefore, various forces of the flow of compressed gas acted on different elements of the installation. Due to the connection of the installation and the compressor with rubber hoses, the impact of compressor vibrations on the vibrations of the test installation was minimised.

## 4 Results

The analyzes carried out on the test stand (described in Sect. 3) allowed to determine the effect of a different number of spheres in the nozzle on the damping of pressure pulsations and pipeline vibrations. The conducted research allows a better understanding of the effect of the series assembly of spheres on the damping of pressure pulsations in the pipeline. The vibration damping of the pipeline is mainly considered in this situation as a result of the decrease in the amplitude of the pressure pulsations, but in some cases, the interaction with the nozzle rigidly fixed in the pipeline may increase the vibration. This can be especially noticeable when the vortices generated by preceding sphere cause nonuniform distribution of flow forces on the next sphere.

Table 1 shows the measurement results for 8 nozzles and installations with a fixed pipe element.

As can be seen in Table 1, both the values of pressure pulsations and vibrations are significantly different for the nozzles used in the installation. In particular, a different nozzle effect for different pulsation frequencies can also be observed. In Table 1, in particular, the negative impact of the assembly of elements on the value of pressure pulsation in front of the nozzle can be observed. This phenomenon is particularly visible for the highest frequency of pressure pulsations. This is related to the throttling of the flow behind the sensor and in front of the nozzle.



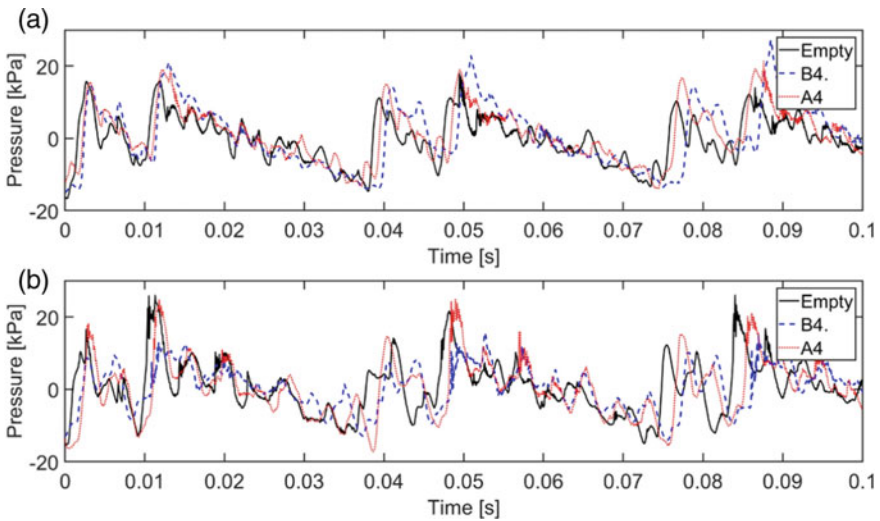
**Fig. 3** **a** A scheme of the test stand, **b** cross-section through the mounting element with mounted reducers where blue—pipeline, green—mounting element, red—tested nozzles

Figure 4 shows the waveforms of the measured signals for nozzles with four spheres and installations with a nozzle imitating an empty pipe.

Figure 4 shows a change in the character of the measured signal between the first and second measurement points in the installation. In particular, there is a significant decrease in the signal amplitude value for nozzle B4. Figure 5 shows the effect of the mounting of the nozzle on the damping of pressure pulsations and longitudinal vibrations of the pipeline. The main comparative factor for the tested nozzles with spheres is the dynamic pressure peak-to-peak value damping calculated for the sensor

**Table 1** Results of experimental investigations

		rev/ min	Nozzle								
			Empty	B1	B2	B3	B4	A1	A2	A3	A4
Pressure pulsations [kPa]	Sensor 1	2100	41.07	44.45	45.88	47.67	47.45	40.99	44.38	44.08	44.78
		1600	44.54	43.97	45.44	45.71	46.39	43.92	45.44	44.41	42.47
		1100	45.96	42.40	42.18	43.44	42.18	44.27	42.00	46.85	47.38
	Sensor 2	2100	42.18	40.60	38.00	37.96	38.25	41.35	42.18	41.44	40.41
		1600	52.26	46.88	42.11	41.12	39.02	48.63	50.94	51.62	50.35
		1100	46.52	41.10	41.34	40.59	38.22	45.09	43.60	45.35	45.34
Vibrations [m/s <sup>2</sup> ]	x-direction	2100	7.53	7.84	7.36	7.46	6.51	7.12	7.42	7.31	7.36
		1600	8.87	7.65	7.79	7.09	5.98	6.91	8.41	8.59	7.53
		1100	8.50	5.51	6.31	7.21	6.78	7.27	5.73	9.05	9.02

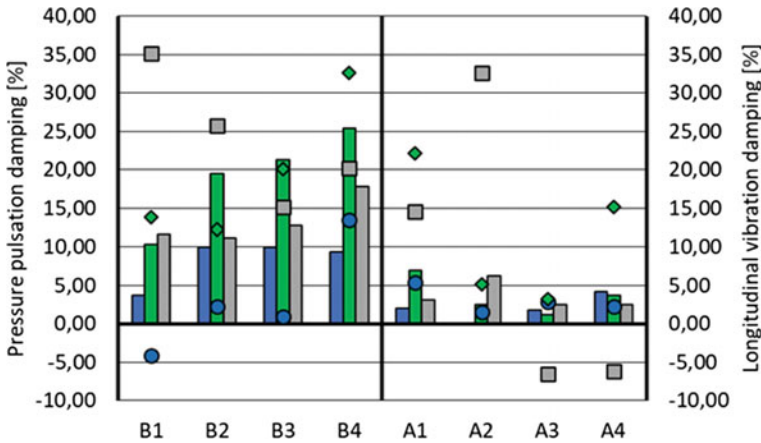


**Fig. 4** Pressure pulsation diagrams for three elements fixed in the installation: **a** sensor in front of the orifice, **b** sensor behind the orifice

behind the tested element. Damping values are calculated from the Eqs. (1) and (2):

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

where:  $\Delta p_{nozzle}$  is a pressure peak-to-peak value [kPa] with nozzle in the installation,  $\Delta p_{empty}$  is a pressure peak-to-peak value [kPa] with straight pipe print in the installation,  $\psi_{nozzle}$ —nozzle pressure pulsation damping.



**Fig. 5** The figure shows the percentage values of the pressure pulsation damping (left axis—bars) and longitudinal vibration damping (right axis—markers) for various rotational speeds: blue (circle)—2100 rev/min, green (diamond)—1600 rev/min, grey (square)—1100 rev/min

$$\zeta_{nozzle} = 100\% - \frac{\Delta a_{nozzle}}{\Delta a_{empty}} \cdot 100\% \tag{2}$$

where:  $\Delta a_{nozzle}$  is a vibration acceleration peak-to-peak value [m/s<sup>2</sup>] with nozzle in the installation,  $\Delta a_{empty}$  is a vibration acceleration peak-to-peak value [m/s<sup>2</sup>] with straight pipe print in the installation,  $\zeta_{nozzle}$ —longitudinal vibration damping with nozzle inserted in the pipeline.

As can be seen for the assembly of the spheres on the arms in the shape of a cross, the smallest pulsation damping occurs for a single sphere. The conducted research shows that in the case of pulsations with the highest frequency, a larger number of spheres does not significantly affect the damping effect. For the lowest value of the pulsation frequency, one, two and three spheres show very similar damping, and the increase occurs only for four spheres.

However, a clear trend is noticed for the middle of the tested frequencies. As the number of spheres increases, the damping value also increases. In this case, the damping of vibrations is similar, although there is a decrease in damping between one and two spheres. For the lowest pulsation frequency and thus for the lowest gas flow in the installation, the vibration damping value is independent of the pulsation damping value and decreases linearly with the increase in the number of spheres to three. This distinguishes the attenuation value compared to higher frequencies where the number of spheres tends to increase the attenuation.

In the case of spheres mounted on an axial rod, it is difficult to define clear trends. It can be noticed that the lack of generated vortices which are characteristic of aerodynamic spheres, causes lower values of damping pulsations. However, in this case, a higher correlation between pulsation and vibration damping is visible. This may be related to the limited possibility of generating vortices that are characteristic

of sphere streamlining and which may cause an uneven distribution of forces on subsequent spheres.

An important conclusion of the study is also the evaluation of the average pulsation and vibration damping of the different nozzles. Table 2 shows the average value of pulsation and vibration damping for all three speeds of the compressor drive shaft.

The average values of pressure pulsation damping for the sensor behind the mounting element show that in a wide frequency range, significant damping of pressure pulsations and longitudinal vibrations of pipelines for nozzles from group B is obtained. At the same time, it can be seen that the best damping occurs for 4 spheres in the array. It is hard to find any correlation in the case of group A nozzles. The only thing that can be said is that better vibration damping is achieved for the smallest number of spheres in this mounting option.

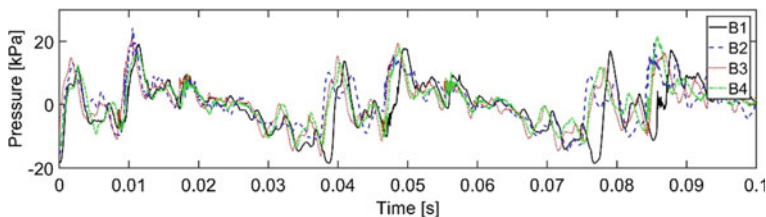
Figure 6 shows a comparison of the waveforms of the measured signals of type B spheres. The nature of the waveforms changes slightly with respect to the number of attached spheres. The decrease in the peak-to-peak value of an pressure with the increase in the number of spheres, especially in the low dynamic pressure phase, is noticeable.

Figure 7 shows the spectrum of signals obtained for the nozzles with the largest number of spheres and for an empty nozzle. It can be seen that multiple frequencies are important. However, the main frequency which results from the nature of the compressor work is dominant. This frequency is most dampened in the B4 option. Many harmonics are of great importance because of the unusual compressor work.

Harmonic analysis was used to compare the damping of the longitudinal vibrations of the pipeline. Figure 8 presents a comparison of the values of individual harmonics

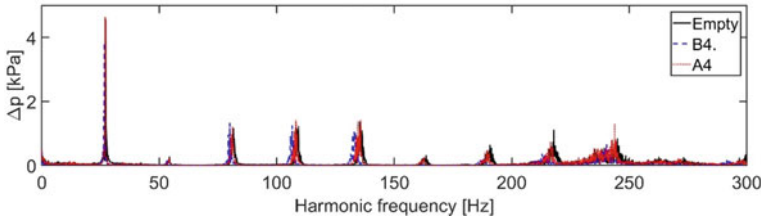
**Table 2** Averaged values of vibration and pulsation damping for three pulsation frequencies

		Nozzle							
		B1	B2	B3	B4	A1	A2	A3	A4
Pressure pulsations [kPa]	Sensor 1	0.26	- 1.84	- 4.40	- 3.82	1.75	- 0.50	- 2.99	- 2.50
	Sensor 2	8.57	13.49	14.69	17.50	4.00	2.94	1.83	3.47
Vibrations [m/s <sup>2</sup> ]	X direction	14.96	13.41	12.04	22.10	14.02	13.11	- 0.14	3.75

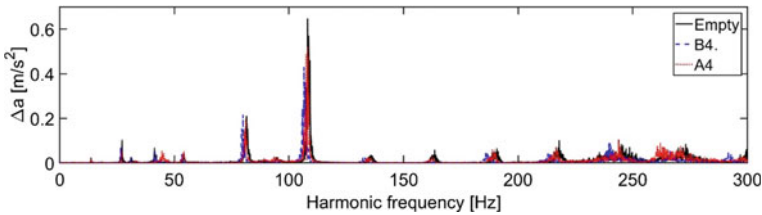


**Fig. 6** The signal of a sensor mounted behind the mounting element for four nozzles in group B





**Fig. 7** Harmonic analysis of pressure pulsation behind the mounting element for nozzles with four spheres in two connecting options



**Fig. 8** Harmonic analysis of longitudinal vibrations for nozzles with four spheres in two options

for pipeline vibration for the main pulsation frequency of approximately 27 Hz and nozzles with the largest number of spheres with an empty pipe.

As can be seen in Fig. 8, the frequency that is four times the excitation frequency of the pulsation has the greatest influence on the vibration of the pipeline.

## 5 Conclusions

The test results presented in this publication confirm the significant influence of flow vorticity on the damping of pressure pulsations. The vortex flow occurs in the case of cross-mounted spheres. Therefore, a stronger damping of pressure pulsations can be observed in the case of spheres mounted on crosses than spheres mounted on the shaft in the flow axis. It was also confirmed that nozzles of the appropriate shape dampen pressure pulsations and pipeline vibrations for different pulsation frequencies. Pipeline vibrations can be dampened as a result of pressure pulsation damping. However, in some cases, the uneven distribution of turbulence behind the mounted element can cause an increase in pipeline vibration damping despite damping pressure pulsations. The research presented in the article is the basis for further analysis to estimate the appropriate distribution of spheres and their shapes on the damping of pressure pulsations and pipeline vibrations. Research will also aim to estimate their impact on the increase in unit compression power in the installation.

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