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On Some Important Quantities Influencing Proper Functioning of the Differential Pneumatic Comparator

Back-pressure air gauging is an effective and practical way of controlling machine parts in large-scale production. It is a non-contact measuring technique based on the flapper-nozzle effect. The proper functioning of a differential pneumatic comparator depends on several geometric para–meters as well as flow conditions inside the device. The main problems of this controlling technique are the fouling of the measuring nozzle head and changes in the accuracy of the comparator. This paper examines the influence of the supply pressure, the diameter of the orifice in the measuring branch, and the axial distance in the flapper-nozzle area on pneumatic comparator performance. In a way, we are trying to optimize the performance of a given pneumatic comparator with respect to the tolerance field for which it is intended. The size, strength, and position of the vacuum in the flapper-nozzle area depend on the supply pressure and the axial distance between the measuring nozzle outlet cross-section and the workpiece surface. For a certain combination of these two parameters, we can influence the vacuum quantities. A pneumatic sensitivity of a comparator can be increased by increasing the supply pressure. The greater accuracy of the back pressure air gauge, the smaller the application range, i.e. the tolerance field that we can control with a given device.

Keywords: *back pressure air gauge, pressure, nozzle head fouling, flapper-nozzle area width, tolerance field.*

1. INTRODUCTION

Industrial production requires frequent measurements. In technical diagnostics, measurements are performed in order to determine the condition of technical systems. After the construction of a new product, the charac–teristics of the prototype solution are tested. Control and measurement are performed for the purpose of auto–matic process control. Systematic measurements with a known degree of uncertainty are the basis of Industrial quality management. Generally speaking, in most mo–dern industries, measurement costs make up 10-15% of total production costs.

Dimensional measurement sensors for quality control inspection of machined parts can be of contact and non-contact type. Within the later ones, there are optical, pneumatic, ultrasonic, and electrical techniques of dimensional control. The pneumatic dimensional control technique is applied for small dimensions con–trol, with an accuracy of up to ±0.025 µm [1]. We are all familiar with jet-impinging systems in engineering where the ratio of diameter to distance between nozzle front and flat surface is greater than one. We can find those in the heating or cooling of gas turbine blades [2] or different surfaces in experimental procedures [3] as well as in water jets [4-6]. In pneumatic control, this ratio is smaller than one. The main advantage of this technique is that the air flowing out of the measuring nozzle blows away impurities from the surface of the machined part [7]. According to the value of the supply pressure, pneumatic comparators are divided into low-pressure and high-pressure devices [8].

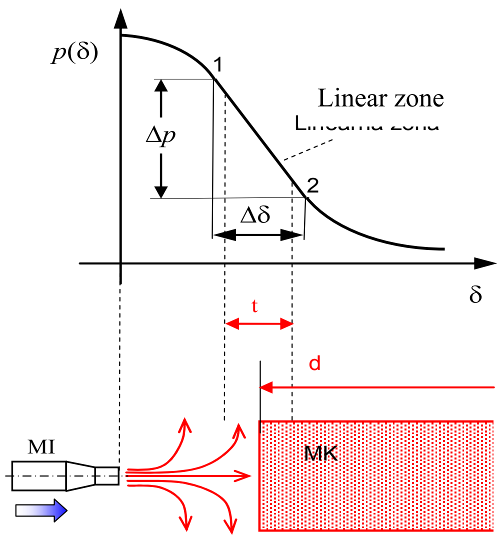

Figure 1. Dependence of the pressure on the surface of the workpiece and the distance between the nozzle and the workpiece, MK – workpiece, MI – outlet nozzle, [9].

Pressurized air from the differential pneumatic de–vice enters the outlet nozzle MI. It comes out and hits the

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surface of the workpiece MK whose dimensions are controlled, (see Fig. 1). The pressure p, which is measured on the surface of the workpiece MK depends on the supply pressure p_o, the diameter D of the orifice of the measuring branch, the geometric shape of the outlet nozzle MI, the radial coordinate r and the axial distance of the outlet nozzle from the surface of workpiece δ. By measuring the pressure depending on the vertical position δ of the outlet nozzle MI, the general diagram shown in Figure 1 is obtained. The pressure $p=p(\delta)$ on the surface of the workpiece has the highest value for the value of the axial position of the nozzle $\delta=0$, i.e. when the nozzle is in the initial position. The pressure value $p=p(\delta=0)$ is p_o. For small values of the distance δ, the diagram has the shape of a curved line, and the pressure on the surface of the workpiece gradually decreases and is lower than the supply pressure p_o. For higher values of δ, the pressure drops sharply. By increasing δ, a linear dependence $p(\delta)$ arises, the beginning of which depends on the degree of choking, i.e. on the diameter of the orifice Din the measuring chamber and supply pressure p_o. Further–more, with an increase in the value of δ, the pressure decreases, and the dependence is non-linear. Precisely, the straight part of the diagram $p(\delta)$, where the linear dependence of the pressure on the distance δ, i.e. piece dimension, is used in pneumatic metrology. The non-linear part of the diagram can also be used, but it was not used due to the need to introduce (know) the function $p(\delta)$.

All important aspects for the proper functioning of the differential pneumatic comparator can be classified into two main categories – accuracy and application range. These two are connected to the fouling of the measuring head and the instability of the measuring signal. Various authors have dealt with different ways to improve the performance of pneumatic comparators. The influence of the measuring nozzle tip geometry was the subject of [10-14]. It was shown in these papers that fouling of the measuring nozzle head can be reduced by altering the geometry of the nozzle head. Apart from the measuring nozzle geometry, in [15] the subject of research was the regulator diameter influence on the flow structure in back pressure air gauge systems. It is also demonstrated in [16] that an important parameter in air gauge pneumatic characteristic determination is the outer-to-inner nozzle diameter ratio. Skoko et al. [17] examined the influence of outlet nozzle inclination on the accuracy of the pneumatic comparator.

The present research aims to examine the influence of flow conditions in the comparator on its performance. In other words, for a single pneumatic comparator of a defined shape and diameter of a measuring nozzle, we will change the supply pressure p_o, orifice diameter D, and axial distance in the flapper-nozzle areaδ to see the influence of these parameters on the fouling of measuring nozzle head, the accuracy and application range of a back pressure air gauge in question.

2. EXPERIMENTAL RIG

The experimental equipment we used in this research is schematically shown in Figure 2. This is the same expe–rimental equipment that was used in the research pre–sented in [18]. A jet of compressed air flows through the measuring nozzle N_1 and hits the flat plate FP. Here, the pressure values in the axial $p(\delta)$ and radial $p(r)$ flow direction are measured. Nozzle N_1 is a so-called normal (standard) measuring nozzle with inner diameter d = 2 mm and outer diameter d_e = 4 mm. The position of the measuring nozzle relative to the flat plate FP changes the system for fine horizontal (DH) and vertical (DV) movement with an accuracy of 0.001 mm. Depending on the measurement series, the horizontal and vertical displacement steps (DH, DV) are 1 µm, 2 µm, and 10 µm. The maximum value of supply pressure used in this work is $p_{o,max}$ = 4 bar. Details of the equipment used are shown in Table 1.

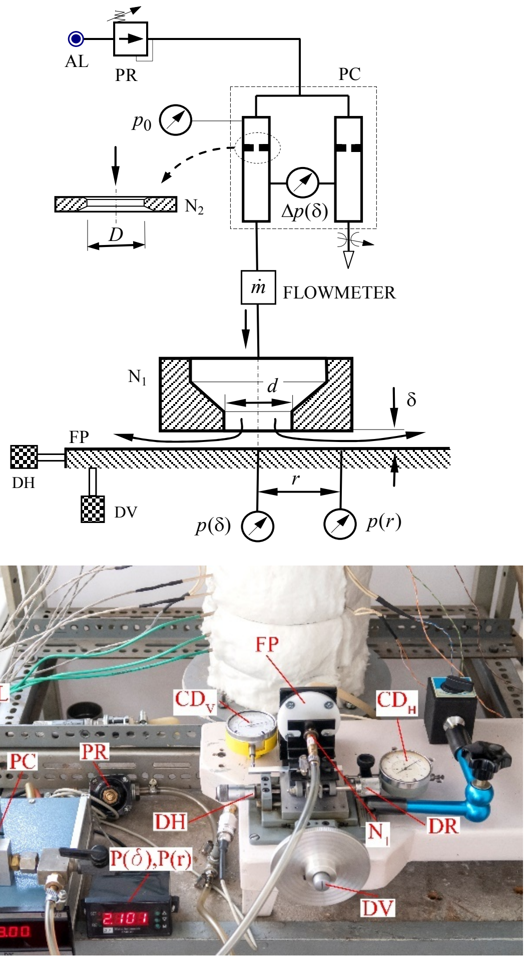

Figure 2. Schematic and photo of the experimental rig: AL – the source of pressurized gas (with pressure vessel); PR – pressure regulator; PC – pneumatic comparator; FP – flat plate; N_1 – measuring nozzle; N_2 – convergent-divergent nozzle in the measuring branch of the PC with orifice diameter D; DH, DV – system for fine displacement in horizontal and vertical directions, DR – system for fine rotation of measuring nozzle N_1 (not used in this research), CD_H, CD_V – mechanical comparators for control of vertical/axial displacement.

We have varied the values of supply pressure, orifice diameter in the measuring branch, and the axial distance between the measuring nozzle frontal surface and the workpiece surface i.e. the slot width in the flapper-nozzle area. The supply pressure was p_o = 1 bar, 2 bar, 3 bar, and 4 bar, and the diameter of the orifice in the measuring branch was D = 0.5 mm, 0.7 mm, 1.0 mm, 1.2 mm, 1.4 mm, 4.0 mm. The increment in the radial movement of the measuring nozzle is $\Delta r = 50$ µm, while the increment in axial movement of the nozzle, i.e. displacement in the direction of the nozzle axis $\Delta\delta = 10$ µm. The range of radial displacement of the measuring nozzle is -3000 µm $\leq r \leq$ 3000 µm, while the range of the axial displacement of the measuring nozzle is $0 \leq \delta \leq 1000$ µm.

Table 1. Technical specifications of the equipment used in experiments.

Compressible air source- Prva petoletka KAA 022, SRB	
Type	Reciprocating compressor
Max operating pressure	8 bar
Power of electric motor	2.2 kW
n	1430 min^{-1}
Pressure regulator – IMI NORGREN 11-818-981, CZ	
Max inlet pressure	4 bar
Pressure range	0.007 bar ... 4bar
Accuracy	0.001 bar for $p_o \leq 5$ bar
Flowmeter – Dwayer GFC-2106, USA	
Max inlet pressure	4 bar
Flow rate range	0 lit/min ... 500 lit/min
Accuracy	1 lit/min
Differential pressure gauge – KELLER EL-73, CH	
Pressure range	0 bar ... 5 bar
Accuracy	0.001 bar
Pressure gauge – DMI 104 P, SRB	
Pressure range	0 bar ... 5 bar
Accuracy	0.001 bar

3. RESULTS AND DISCUSSION

3.1 Quantities influencing the fouling of the measuring nozzle head

Due to the long-term operation of the differential pne–umatic comparator, dust particles are deposited on the front surface of the nozzle, which changes the geometry of the nozzle. The width of the flapper-nozzle area δ decreases and thus a measurement error occurs. This is a a consequence of a vacuum that is formed in the area between the front surface of the measuring nozzle and the flapper, i.e. the flat surface of the controlled work–piece. The position, size, and strength of the vacuum are defined by a radial distribution of pressure on the workpiece surface. The typical distribution of pressure on the workpiece surface in the radial direction is presented in Figure 3.

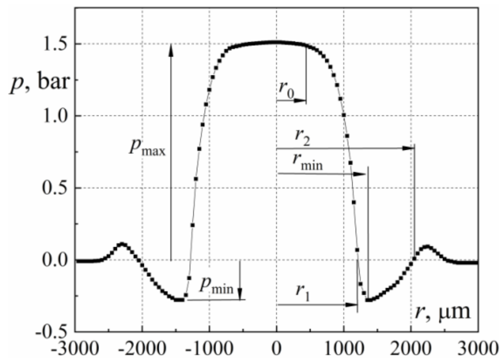

Figure 3. Typical pressure distribution in the radial direction.

Here one can see the zone of maximal pressure p_{max}, until the radial coordinate r_0. After that pressure sharply decreases towards the flapper-nozzle area. This is the place where it reaches its minimal value p_{min}. This minimal value of pressure is located between two radial coordinates (r_1 and r_2), where pressure changes its sign from positive to negative and vice versa, respectively. This is the vacuum area Δr, which is not desirable from the standpoint of pneumatic metrology usage.

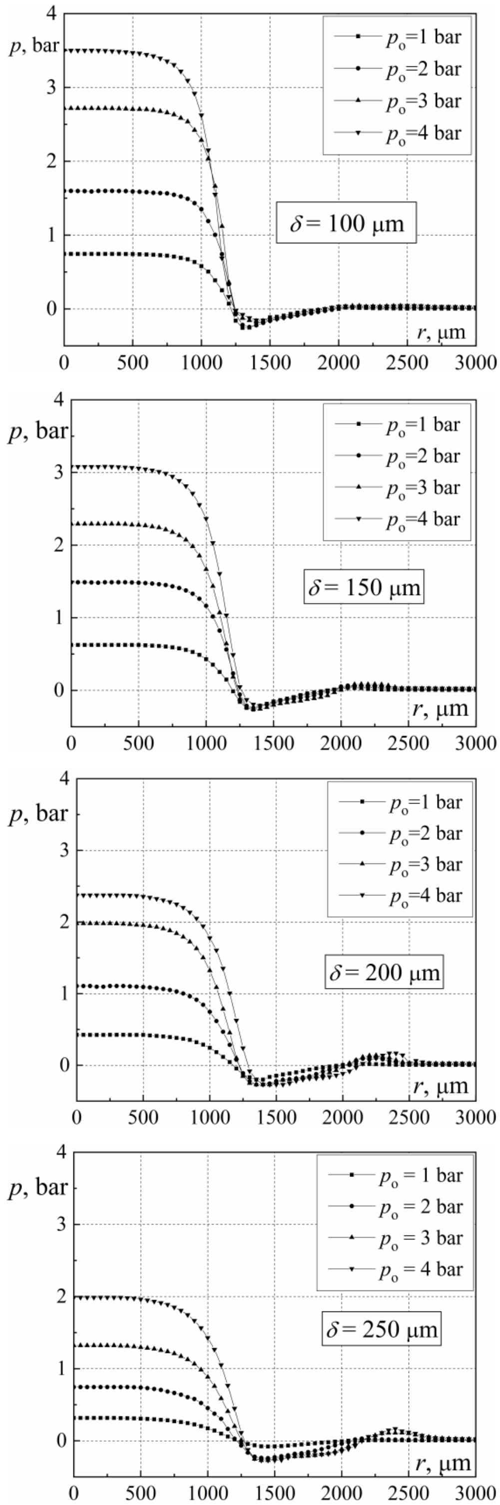

Figure 4. Influence of the axial distance from the workpiece on the pressure distribution in the radial direction for different values of supply pressure, *D* = 1 mm.

As stated before, it is the cause of measuring nozzle head fouling, i.e. accumulating of impurities. With the increase of radial coordinate beyond r_2, pressure rises and reaches its local maximum in the wall area, and then it decreases again till it reaches approximately zero value. In the following, we will examine how the size of the slot width affects the forming of the vacuum in the flapper-nozzle area.

Figure 4 shows the experimental results of pressure distribution in the radial direction when the axial distance between the measuring nozzle and the workpiece flat surface is δ = 100 µm, 150 µm, 200 µm and 250 µm for the supply pressure of p_o = 1 bar, 2 bar, 3 bar, and 4 bar. The highest pressure on the workpiece surface is obtained for the smallest slot width δ and highest supply pressure p_o, as expected. For a single supply pressure, the highest pressure in the stagnation zone (the zone of constant pressure) is for the smallest distance δ. This means that the highest gradient towards the wall area is for p_o = 4 bar and δ = 100 µm. It is noticed that with the increase of supply pressure, at the same axial distance between the outlet section of the nozzle and the flat surface, the length of maximum pressure r_0 decreases. Also, for δ = 100 µm, there is no local maximum in the wall area. For greater slot width δ a local maximum is observed only for higher values of the supply pressure.

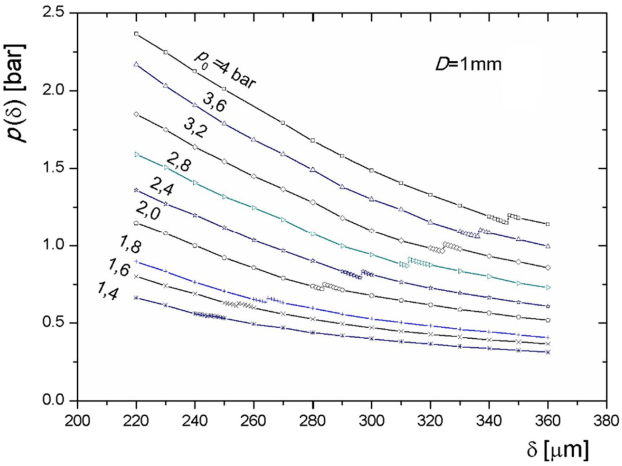

Figure 5. Pressure jump and signal instability [12].

Regardless of the supply pressure p_o and axial distance δ values, there is a vacuum in the flapper-nozzle area. However, there are some differences in the vacuum strength p_{min}, position $r_{min,}$ and size Δr for different supply pressures and distances δ. These are presented in Figure 6. As expected, the smallest vacuum is obtained for the smallest supply pressure p_o and greatest slot width δ. This is the vacuum that is acceptable in pneumatic metrology since it does not interfere with the normal work of a differential pneumatic comparator. A slightly higher vacuum is obtained for δ = 100 µm and supply pressures p_o = 3 bar and 4 bar, and this is also an acceptable value for proper operation of the pneumatic comparator. For smaller values of supply pressure (1 bar and 2 bar) the smallest value of pressure on the surface of the workpiece is moving away in a monotonous way (the r_{min} coordinate is monotonously rising) from the measuring nozzle axis (see Fig. 6b). This is also favorable from the pneumatic metrology application point of view. For two higher supply pressures, there is no obvious conclusion regarding the vacuum position. Contrary to this, with the increase in slot width δ, the vacuum Δr zone width gets bigger for higher supply pressures.

Since there are no clear rules about the behavior of the values of vacuum strength, size, and position, we have to make a compromise. If the criteria for decision is the lowest vacuum p_{min}, for slot width δ = 250 µm, one should use the supply pressure of p_o = 1 bar. However, for δ = 100 µm, it is better to use a supply pressure of 4 bar, since for that combination of values the vacuum strength is still acceptable for pneumatic comparator operation, and its size is the smallest compared to other supply pressures.

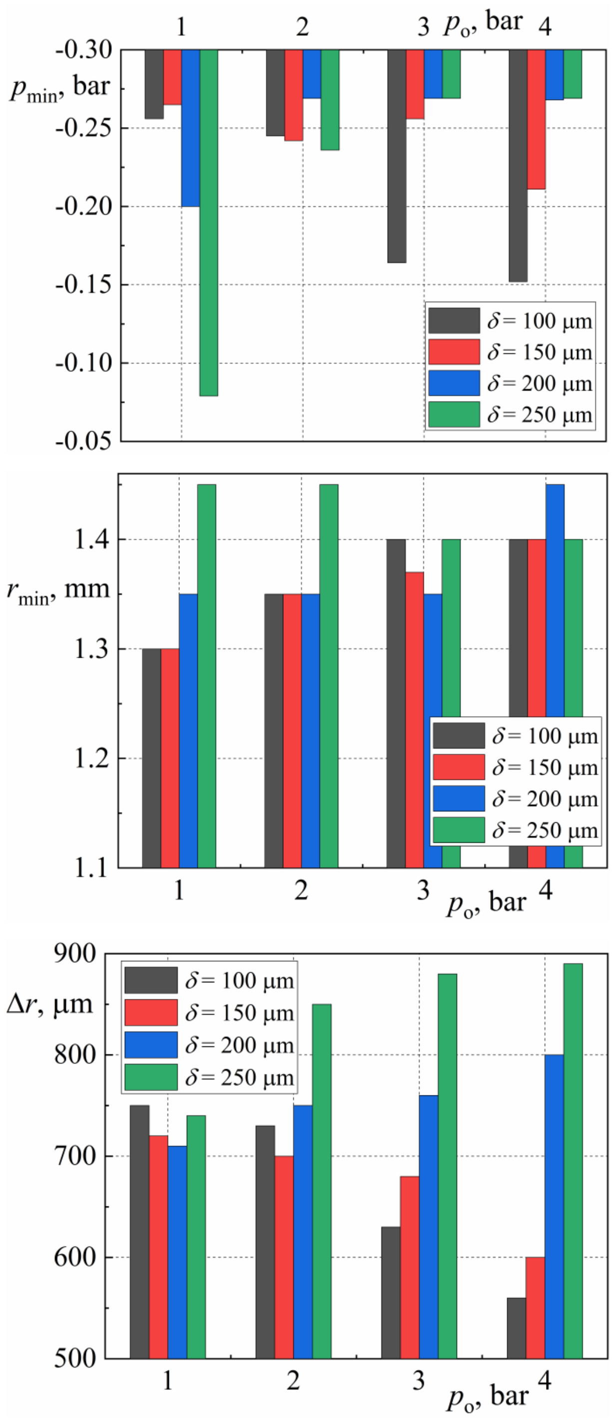

Figure 6. Strength p_{min}, position r_{min}, and size $\Delta r = r_2 - r_1$ of vacuum for different supply pressures and slot width.

Except in the case of the lowest supply pressure, the increase in slot width δ leads to an increase in the vacuum zone size Δr. One should be careful with greater δ values because there is a possibility of signal instability occurrence which leads to controlling error, (see Figure 5) [18-21].

We can say that for two lower and two higher values of the supply pressure, the behavior of the vacuum strength, position, and size is similar. For supply pres–sures $p_o = 1$ bar and $p_o = 2$ bar, there is no clear trend regarding the vacuum strength and size, while the position of the highest vacuum has inconclusive results for two higher values of the supply pressure ($p_o = 3$ bar and $p_o = 4$ bar). For smaller pairs of supply pressure values, the vacuum is moving away from the nozzle axis when the tolerance field is greater, i.e. when the slot width in the flapper-nozzle area is greater. For two higher values of the supply pressures, the vacuum is getting greater both in its strength $p_{\min}$ and its size Δr, which is not good. That means that for smaller tolerance field control it is better to use the supply pressures of 3 bar and 4 bar.

3.2 Quantities influencing the accuracy and application range of the comparator

Keeping the measuring nozzle head free of impurities is important from the standpoint of long-term usage of the pneumatic comparator without interruptions. The other parameter, also important for pneumatic comparator functioning is its accuracy. It is expressed through the quantity named pneumatic sensitivity S [18].

The pneumatic sensitivity is defined in the axial distribution of pressure on the surface of the controlled workpiece. This is the linear part of the curve $p(\delta)$, and its slope and length are dependent upon the supply pressure p_o and orifice diameter D in the measuring branch of the comparator. Another quantity that is connected to the linear part of the pressure distribution curve is the application range $\Delta\delta$ of the pneumatic comparator. This quantity tells us for what tolerance field we can use the back pressure air gauge in question, for a given combination of conditions, i.e. supply pressure and orifice diameter.

Figure 7 shows the distribution of pressure in the axial direction for different orifice diameters D and supply pressures p_o. It is evident that the supply pressure p_o significantly affects the position of the curve $p = p(\delta)$, the length of the linear part of the distribution $p(\delta)$, the length of the stagnation zone δ_0 in which $p = p_o =$ const, and the value of the initial pressure in the stagnation zone.

The results show that with the increase of the supply pressure p_o, all values in the pressure distribution in the axial direction on the flapper surface increase. The effect of the orifice diameter in the measuring branch is also evident. For lower values of the orifice diameter, i.e. greatest choking, the slope of the $p(\delta)$ curve is higher. This means that for these conditions the pneumatic sensitivity of the pneumatic comparator is higher. For a single orifice diameter, the greatest slope of the pressure distribution curve is for the highest supply pressure, as expected. Hence, if we have a pneumatic comparator of a predetermined geometry i.e. single measuring nozzle with one orifice diameter in a measuring branch, to increase the pneumatic sensitivity one has to increase the supply pressure.

The influence of the supply pressure rise on the pneumatic sensitivity of a comparator with a defined measuring nozzle is more pronounced for smaller values of the orifice diameter D (see Figure 7). The pressure value on the flapper approaches the asymptotic value for greater values of δ value, for all supply pressures and single orifice diameter. Asymptotic values for different supply pressures are closer together for smaller orifice diameter D, i.e. for greater choking in the measuring branch of the back pressure air gauge.

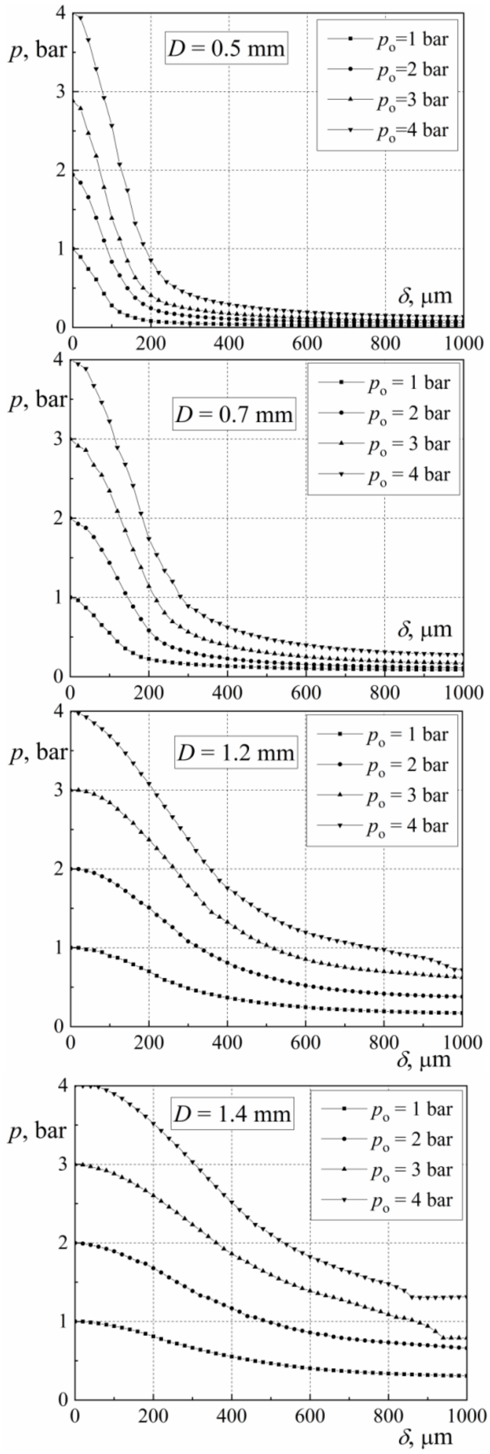

Figure 7. Influence of the orifice diameter D on the distribution of the pressure in the axial direction for four different supply pressures.

Because of the reciprocating connection between the pneumatic sensitivity and the application range of the pneumatic comparator, the greater the pneumatic sensitivity is, the smaller the application range. This means that the tolerance field that can be controlled in given conditions is smaller. In another word, we can say that for a given pneumatic comparator, we can influence its accuracy and tolerance field width by altering the supply pressure. Having in mind Figure 5, and what has been said about signal instability, we have to check if we are in the area in which the pressure jump is possible. After that, one has to consider the vacuum position and strength in the flapper-nozzle area, as explained before.

Axial pressure distributions for the minimum and maximum supply pressure, p_o = 2 bar and p_o = 4 bar, for all orifice diameters D = 0.5 mm - 4.0 mm are presented in Figure 8. For p_o = 2 bar, there are no linear parts of the curves that serve for pneumatic sensitivity determination for orifice diameters D = 1.4 mm and D = 4 mm. For supply pressure of 4 bar and orifice diameters of 1.4 mm and 4 mm, the slope of the $p(\delta)$ is somewhat greater, but even this is not enough in order for the pneumatic comparator to work properly. Orifices with diameters of 1.4 mm and 4 mm are not in use in pneumatic metrology. Once again is confirmed that the higher supply pressure implies a greater slope of the $p(\delta)$ curve, for a single orifice diameter in a convergent-divergent nozzle in a measuring branch of the comparator.

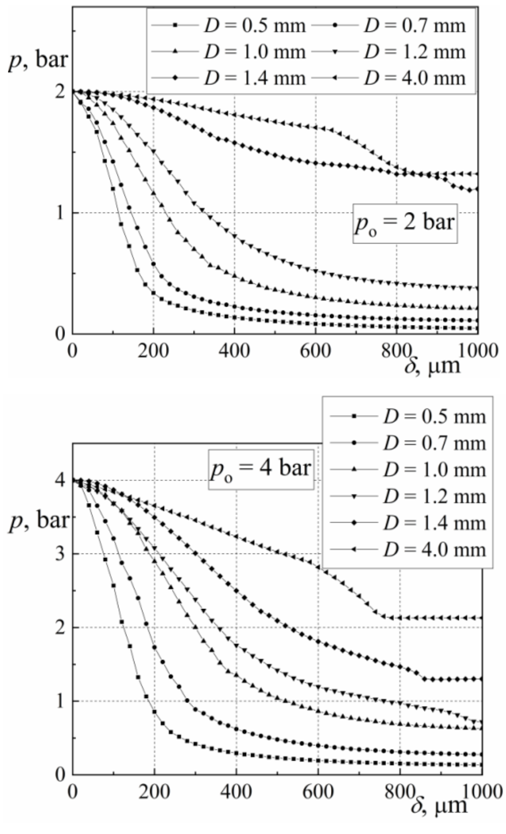

Figure 8. Influence of the orifice diameter *D* on the axial pressure distribution for p_o=2 bar (up) and p_o=4 bar (down).

Figure 8 shows the value of pressure p for the axial distance δ = 1000 μm, for all supply pressures p_o and all values of the orifice diameter D in the measuring branch. As expected, the highest pressures p are achieved for the highest supply pressure p_o and the greatest nozzle diameter D in the measuring branch of the differential pneumatic comparator. The influence of the supply pressure is more pronounced for greater values of the orifice diameter D. The pressure curves are approximately linear. For a single supply pressure, an increase of the orifice diameter D leads to an increase in the pressure on the flapper. This increase of pressure p is more pronounced for higher values of supply pressure. For greater values of diameter D, the influence of the supply pressure p_o is also greater.

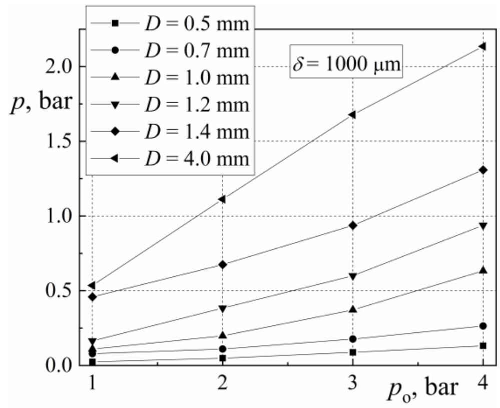

Figure 9. Distribution of pressure on the workpiece surface for different supply pressures p_o and orifice diameters *D.*

Looking at the distribution of pressure on the flapper in relation to the d/D ratio (Figure 10), it is obvious why the most common ratio for measuring nozzle diameter and ori–fice is 1.64 and 1.94 [22]. For these conditions, the pres–sure on the flapper i.e. the controlled workpiece surface is minimal, independent of the supply pressure value.

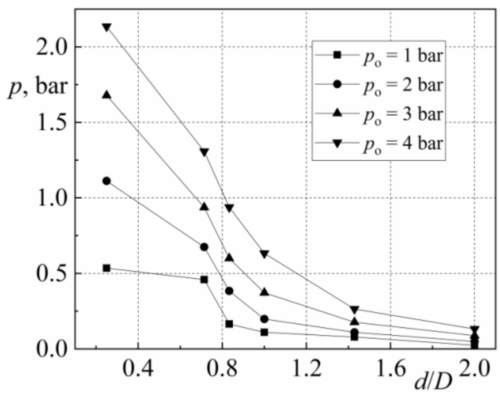

Figure 10. Dependence of the pressure on the workpiece surface on the *d/D*ratio for different values of supply pressures p_o.

Figure 11 gives the flow rate values depending on the axial distance δ between the outlet nozzle surface and the flat surface, for all supply pressures p_o and orifice diameters D = 0.7 mm and D = 1.2 mm. It is clear and expected that for higher supply pressure, under all other same conditions, a higher airflow is achieved. It can be seen from the diagrams that for certain values of the axial coordinate, a constant flow is established, which is a consequence of nozzle choking. Choking of the nozzle is first achieved for the lowest supply pressure. As the supply pressure increases, so does the axial distance for which a constant flow is achieved. For a single supply pressure, a higher flow rate is achieved with the increase of the orifice diameter D in the measuring branch. If we know that the role of the orifice in the convergent-divergent nozzle N_2 is to dampen the airflow through the comparator, this kind of behavior is expected. Hence, air flow in the pneumatic comparator is directly proportional to the supply pressure and the diameter of the orifice D.

Earlier we discussed the vacuum position and strength in the flapper-nozzle area and the accuracy and application range of the comparator. All those parameters depend upon the supply pressure. Since higher supply pressure leads to higher energy consumption, this is not favorable from the energy efficiency standpoint. However, if there is waste air under pressure in the production line, then this becomes a smaller issue.

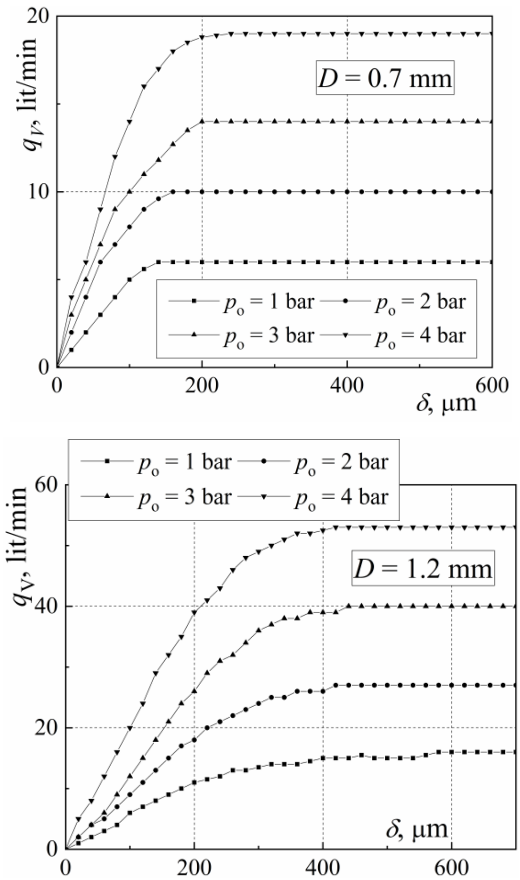

Figure 11. Influence of the orifice diameter on the volumetric flow rate through comparator for different supply pressures.

4. CONCLUSION

This paper deals with the influence of various factors i.e. parameters on the proper functioning of the back pressure air gauge. The subject of the analysis was supply pressure p_o, diameter D of the orifice in the convergent-divergent nozzle N_2 in the measuring branch of the comparator, as well as the axial distance δ bet–ween the flapper and the measuring nozzle outlet cross-section. We were looking for optimized conditions for the control of a workpiece with a certain tolerance field. This was done through analysis of the distribution of pressure on the workpiece in the axial and radial directions as well the analysis of the airflow through the back pressure air gauge.

The smallest vacuum is achieved for the greatest slot width and smallest supply pressure considered. For supply pressures of 1 bar and 2 bar, the vacuum is mo–ving away from the measuring nozzle axis. For two higher supply pressure considered in this work, with the increase in slot width, the vacuum gets bigger. In order to increase the pneumatic sensitivity of a predetermined pneumatic comparator, one has to increase the supply pressure. The influence of the supply pressure rise on the accuracy of the comparator is more pronounced for smaller values of the orifice diameter D. the greater the pneumatic sensitivity is, the smaller the application range, i.e. the tolerance field width that can be cont–rolled with a given comparator. For a single supply pressure, an increase of the orifice diameter D leads to an increase in the pressure on the flapper surface. In order to decrease the needed volumetric flow rate, it is necessary to lower the supply pressure.

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NOMENCLATURE

D	diameter of orifice in nozzle N_2
d	measuring nozzle diameter
r	radial coordinate
p	pressure
p_o	supply pressure
q_V	volumetric flow rate

Greek symbols

δ	axial coordinate

О НЕКИМ ВАЖНИМ ВЕЛИЧИНАМА КОЈЕ УТИЧУ НА ПРАВИЛАН РАД ДИФЕРЕНЦИЈАЛНОГ ПНЕУМАТСКОГ КОМПАРАТОРА

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Пнеуматска метрологија је ефикасан и практичан начин контроле тачности израде машинских делова у великосеријској производњи. То је бесконтактна мерна техника заснована на линеарној зависности притиска на површи машинског дела од његовог растојања од излазног пресека мерне млазнице. Правилно функционисање диференцијалног пнеу– матског компаратора зависи од неколико геомет– ријских параметара као и од услова струјања унутар уређаја. Главнипроблеми ове технике контроле су запрљање главе мерне млазнице и промене у тач– ности компаратора. У овом раду се испитује утицај притиска напајања, пречника конвергентно-дивер– гентне млазнице у мерној грани и аксијалног расто– јања у области машински део – мерна млазница на перформансе мерног уређаја. На неки начин поку– шавамо да оптимизујемо перформансе датог пнеу– матског компаратора у односу на поље толеранције за које је намењен. Величина, јачина и положај вакуума у зони измђу мерне млазнице и контроли– саног машинског дела зависе од притиска напајања и аксијалног растојања између попречног пресека излаза мерне млазнице и површине радног пред– мета. За одређену комбинацију ова два параметра можемо утицати на наведене параметре вакуума. Пнеуматска осетљивост компаратора може се повећати повећањем притиска напајања. Што је већа тачност пнеуматског компаратора, мањи је опсег примене, односно, мања је ширина толеранцијског поља које можемо да контролишемо датим уређајем.