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Methods of Shaping the Metrological Characteristics of Air Gages

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The paper presents the results of investigations on the influence of most important geometrical parameters on the metrological properties of the air gauges. Among others, the diameters of the inlet and measuring nozzles were taken into consideration, as well as the normalized outer diameter of the measuring nozzle. The influence of the ratio of measuring nozzle to inlet nozzle on the metrological properties. In the analysis, the following features were taken into consideration: measuring range of the air gauge, multiplication and the initial slot width corresponding with the beginning of measuring range. As a result of investigation, some recommendations on the air gauge choice dependent on the particular measuring task are presented in the final part of the paper.

Keywords: air gauge, dimensional measurement, metrology, uncertainty, static metrological properties

0 INTRODUCTION

The measurement system analysis is one of the most important issues in the topic of quality management [1]. Air gauges are well known and widely appreciated devices for dimensional measurement [2] with numerous merits including the ability to perform non-contact measurement [3]. After a decade of some declination in air gauge application, they are again delivered by most of the measuring tool producers, and again they became a subject of scientific interest [4].

The importance of the non-contact measurement is indicated in many works, e.g. in [5] and [6]. Some investigations have been performed in order to improve their metrological properties and fully exploit the advantages of air gauging [7], and various models proposed to describe their static metrological properties [8].

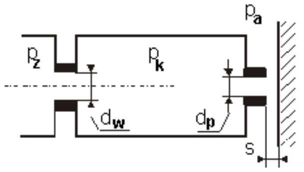

Fig. 1. *Typical back-pressure air gauge*

It has been proved that the air gauges with built-in piezoresistive pressure transducer is the most promising solution [9]. In the present study, this type of the back-pressure air gauges underwent investigations. Fig. 1 presents a model of such air gauge fed with feeding pressure p_z (typically $p_z = 150$ kPa). The pressure p_k in the measuring chamber between inlet and measuring nozzles (d_w and d_p) is dependent on the slot width s: $p_k = f(s)$. A typical graph of this function is presented in Fig. 2 together with the module of multiplication $|K| = f(s)$. Usually, in order to shape the characteristics, diameter d_w could be changed. In most known solutions, the change of the inlet nozzle is obtained by any kind of valve. Sometimes, like in Pneutronik series devices, the inlet nozzle is replaceable [10].

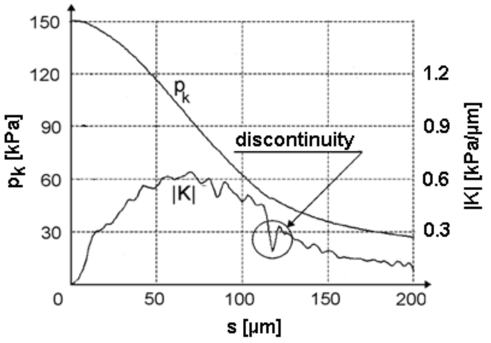

Fig. 2. *Example of the air gauge static characteristics $p_k = f(s)$ and multiplication $|K| = f(s)$*

The investigated parameter of the normalized outer diameter of the measuring

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nozzle [11] is of importance. Fig. 3 depicts the example of a narrow and wide nozzle head surface.

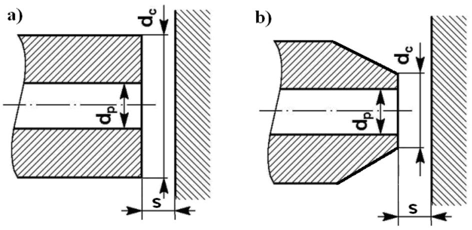

Fig. 3. *Measuring nozzle with wider a) and narrower b) head surface [12]*

The normalized outer diameter of the nozzle is defined as a ratio of the outer nozzle diameter d_c to its orifice diameter d_p: $D_c = d_c/d_p$.

1 AIR FLOW THROUGH THE FLAPPER-NOZZLE AREA

After the air has passed the measuring nozzle, it expands in the area between the flapper surface and the nozzle head. The expansion of the air in the flapper-nozzle area is dependent on the slot width s, as has been described by Breitinger [13] and is illustrated in Fig. 4 for the air gauge with the measuring nozzle of $d_p = 2.0$ mm. When the slot width is small (about 30 to 50 μm) the velocity of the air is small, too, so the laminar flow is possible (Fig. 4a). However, in the area between the nozzle head surface and the workpiece surface the expansion of the air causes disturbances and the flow becomes turbulent. As the slow width grows, the turbulent area moves closer to the nozzle orifice (Fig. 4b). The higher velocity of the air causes a change of the laminar flow into turbulent. In Breitinger's opinion [13], this change first appears in the inlet nozzle, next in the measuring nozzle, and eventually in the slot itself. Each of those turnings affects the pressure p_k in measuring chamber and causes discontinuity of the characteristics like the one shown in Fig. 2. In particular, when the slot is smaller, stream is adjacent to the nozzle head surface (Fig. 4b), but for certain larger slot width (s ~300 μm) it becomes adjacent to the flapper surface (Fig. 4c).

Additionally, in the expanding air different velocity areas appear, where Mach number is smaller, larger or equal to $M = 1$. Fig. 4 shows the localization of those areas dependent on slot width, where 1 – is "dead" area, 2 – striking wave, 3 – area where $M = 1$. The other investigations confirmed the presence of the above described phenomena [14].

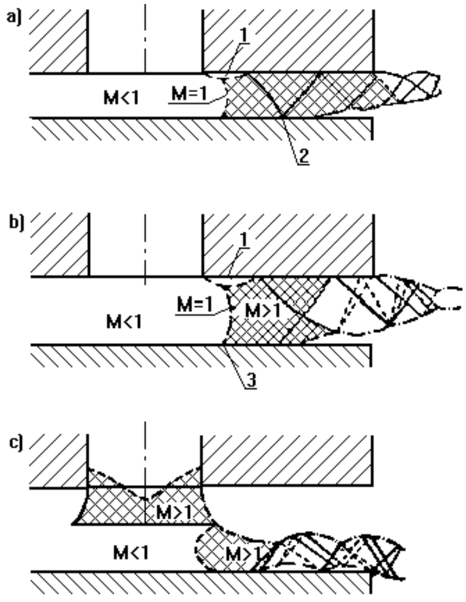

Fig. 4. *Expansion of the air stream in the measuring slot: a) narrow slot, b) medium slot width, c) wide slot [13]*

A typical analysis of the back-pressure air gauge does not consider the influence of the normalized outer diameter on the metrological properties. The static characteristics is usually calculated from the formula [15]:

$$p_k = \frac{p_z}{1 + \left(\dfrac{\alpha_p A_p}{\alpha_w A_w} \right)^2}, \tag{1}$$

where: p_k , p_z are pressure in the measuring chamber, and feeding pressure, respectively, A_p , A_w are the outflow surface for flapper-nozzle area and for inlet nozzle, α_p , α_w are the flow-through coefficients for flapper-nozzle area and for inlet nozzle.

In most literature, the outflow surface A_p is considered to be a cylinder with axis placed in the axis of the nozzle orifice, diameter equal to the nozzle diameter d_p, and the height equal to the slot width s:

$$A_p = \pi d_p s \, . \tag{2}$$

It has been proved, however, that geometrically minimal surface is different from the side cylinder surface [16]. It is a rather conical surface which is shown in Fig. 5 and described by the Eq (3):

$$A_{s,min} = A_p\, k(s_w)\,, \tag{3}$$

where:

$$k(s_w) = \frac{1+k_e}{4}\sqrt{4+\left(\frac{1-k_e}{s_w}\right)^2}\,,$$

$$s_w = \frac{s}{d_p}\,,$$

$$k_e = 0{,}5 + 0{,}5\sqrt{1-8s_w^2}\,,$$

where d_p is nozzle diameter and s is slot width.

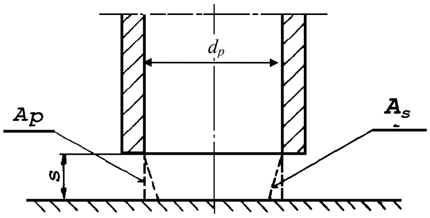

Fig. 5. *Commonly calculated surface A_p and minimal surface A_s [16]*

Consequently, the static characteristics calculated by using cylindrical and conical outlet surfaces are very different, especially in the measuring range of the air gauge. It should be noted, however that Eq. (3) does not refer to the outer diameter d_c. Neither does the formula based on second critical parameters, describing the mass flow rate [17]:

$$m_{t\,\max,p} = \sqrt{\kappa\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}}\sqrt{\frac{1}{R}}A_p\frac{p_k}{\sqrt{\Theta_z}}\,. \tag{4}$$

In both cases, the influence of the normalized outer diameter is included into the flow-through coefficient α_p of flapper-nozzle area.

2 INVESTIGATION APPARATUS

In order to perform investigations on the geometrical features and influence on the air gauge metrological properties, the set of inlet and outlet nozzles of the following dimensions has been prepared:

- d_w: 0.625; 0.720; 0.830 ; 1.020; 1.430 mm
- d_p: 1.010; 1.208; 1.410; 1.609; 1.811; 2.003 mm

The length of the nozzles has been calculated from ratio $l/d = 5$. Inlet nozzles has been made with flat surfaces, while the inner surfaces of the measuring nozzles have been shaped conically with an angle of 60°. A combination of the above listed nozzles provided the air gauges with various metrological properties.

The air gauge fed with pressure $p_z = 150$ kPa (±0.003%) was placed onto the moving table, and a series of values s_i were coupled with corresponding pressure p_{zi}. The reference measurement of the slot width s was performed with inductive sensor GT21 HP (maximal permissible error ±0.15 μm), connected to the measuring column TT500 by Tesa. The back-pressure was measured with a transducer of 0.1 class, type 4043 A5 made by KISTLER AG. The laboratory equipment is shown in Fig. 6.

As a result, a series of the static characteristics $p_k = f(s)$ corresponding with certain geometry of the air gauge were collected. From those characteristics, the parameters of multiplication $|K| = f(s)$, measuring range z_p and its start point s_p were calculated. The non-linearity δ was considered 0.75% and 1%, because of different acceptable levels in different applications.

3 INVESTIGATION RESULTS

3.1 Influence of the Nozzles Diameters

In the analyzed static characteristics discontinuity marked in Fig. 2. appears. It is caused by the complicated phenomena described in section 1. It should be noted, however, that the measuring nozzle $d_p = 1.01$ mm in combination with any of inlet nozzles generated the smallest discontinuities, while the largest appeared in case of $d_p = 2.003$ mm. It could be explained by the higher mass-flow, and hence a higher velocity of the expanded air in the flapper – nozzle area. The air gauges with higher multiplication reveal reduced discontinuity which seems to be attributed to the same explanation: air gauges with higher sensitivity are marked by smaller inlet nozzles, and hence smaller mass-flow.

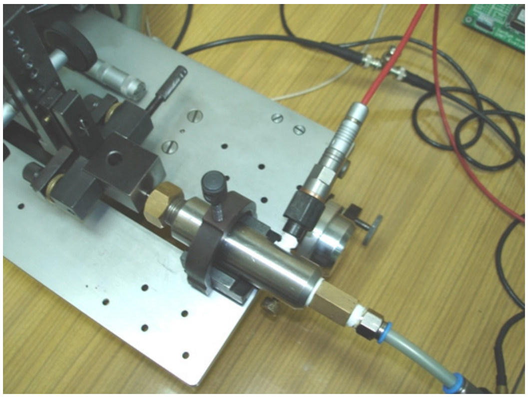

Fig. 6. *The air gauge on the moving table*

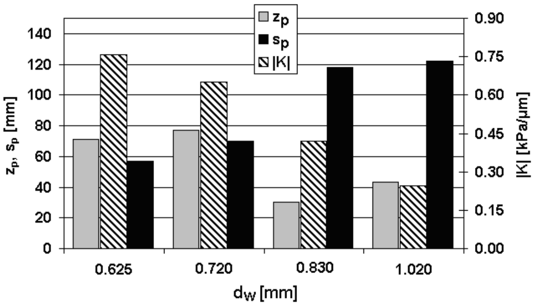

Fig. 7. *Investigation results for $d_p = 1.01$ mm*

The other problem with discontinuity is the following: as the multiplication rises and discontinuity becomes reduced, its localization changes. Larger discontinuity appears at the end of the measuring range (the largest slot width *s*), but in case of higher multiplication discontinuity moves into the measuring range, and in some cases (e.g. $d_w = 0.83$ mm) it appears in the middle of the measuring range z_p. Consequently, the measuring range shortens, as seen in Fig. 7.

For the nozzles $d_w \in < 0.625, 0.83 >$ mm, the measuring range z_p shortens 50% because of the discontinuity. When d_w is increased up to 1.02 mm ($d_p = 1.01$ mm), the multiplication of air gauges becomes 1/3 of what was gained with $d_w = 0.625$ mm. However, the measuring range does not increase so rapidly.

For the air gauges with a measuring nozzle $d_p = 2.003$ mm, the discontinuity is much larger and it appears in the wide range of the multiplications. In that case when the inlet nozzle diameter was increased form 0.72 up to 1.21 mm, the measuring range expanded by just 15%. However, multiplication |*K*| decreased from 0.75 kPa/µm down to 0.45 kPa/µm. When the inlet nozzle was $d_w = 1.43$ mm, one should expect further expansion of the measuring range z_p, but it shortens instead. This shortage calculated with non-linearity $\delta = 0.75\%$ was 8 µm, and with $\delta = 1\%$ was 30 µm. Small discontinuity strongly affects the ability of the air gauge to measure with high accuracy, but when larger non-linearity is acceptable, a larger measuring range could be applied.

To sum up, the discontinuity of static characteristics of air gauge strongly affects its metrological properties. Even though some publications indicate that phenomenon [11], [13] and [14], its influence on the real measuring range had not been examined and described before.

In metrological practice, it is important to know how to choose an appropriate couple of the nozzles for the particular measurement task. Therefore, in the investigations it was assumed to select couples of nozzles with ratios $d_p/d_w = D_{pw} = 1.64$ and 1.94. Such ratios are most common in the air gauges. For $D_{pw} = 1.64$, the measuring range varied from 87 up to 133 µm, and for $D_{pw} = 1.94$ from 40 up to 95 µm.

Fig. 8 presents the values of the measuring ranges z_p and the initial point s_p for the couples of nozzles corresponding with ratio $D_{pw} = 1.64$. The normalized outer diameter was $D_c = 2$, and the data were calculated for non-linearity of $\delta = 0.75\%$ and $\delta = 1.\%$.

The multiplication of those air gauges was similar for $D_{pw} = 1.64$ and $D_{pw} = 1.94$, and it ranged from 0.48 to 0.88 kPa/µm. The initial slot width s_p changed dependent on the nozzles diameters, even for the same value of D_{pw} it was smaller for smaller nozzles' diameters.

In practice, when the purpose is to gain the maximal measuring range saving the relatively high multiplication $|K| \approx 0.6$ to 0.8 kPa/µm, the measuring nozzles of diameter $d_p \approx 1.6$ to 2 mm (with ratio $D_{pw} = 1.64$) should be applied. Such combination allows a balance between high multiplication and the required measuring range. However, the outer diameter should also be taken into consideration.

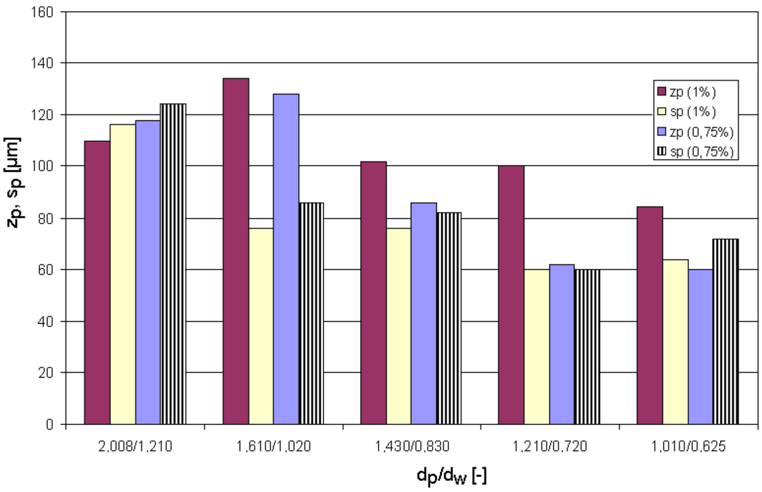

Fig. 8. *The investigation results for the nozzles' couples with* $D_{pw} = 1.64$, $D_c = 2$

3.2 Influence of the Outer Diameter

Most of publications tend to recommend minimization of the outer diameter of measuring nozzles [12] and [13]. In industrial application, measuring heads with different nozzle orifice diameters, but with the same outer diameter are often seen. A thorough investigation strongly indicated that such solutions will always reveal different metrological properties, especially in accurate measurement. It seems absolutely needed to introduce a parameter like normalized outer diameter $D_c = d_c/d_p$.

Fig. 9 presents an example of a series of static characteristics of the air gauge d_w = 0.72 mm; d_p = 1.02 mm and various D_c. It is seen that the graphs $p_k = f(s)$ are different for different D_c.

In case of small multiplication, the discontinuity caused by large D_c appears outside the measuring range and does not affect metrological properties of the gauge.

Decrease of D_c down to value 2 causes displacement of discontinuity into the measuring range. Consequently, the measuring range becomes shorter by 50%. in case of d_w = 0.830 mm. However, for smaller nozzles (smaller mass-flow) this is not the case. A further decrease of D_c down to value 1.5 causes a disappearance of discontinuity, and the measuring range returns to the same values as with D_c = 3. Fig. 10 presents the values of $|K|$ for the air gauge with measuring nozzle d_p = 2.003 mm and different D_c, combined with different inlet nozzles.

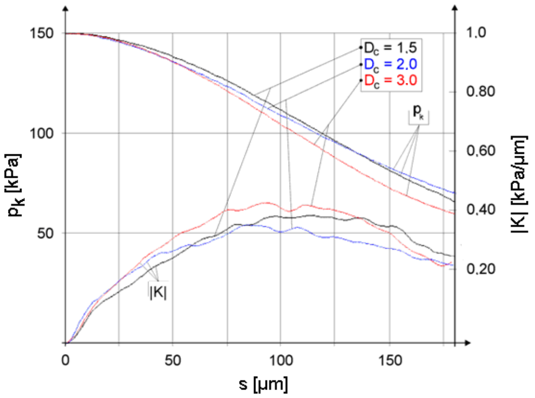

Fig. 9. *Investigation results for* d_p = *1.01 mm*

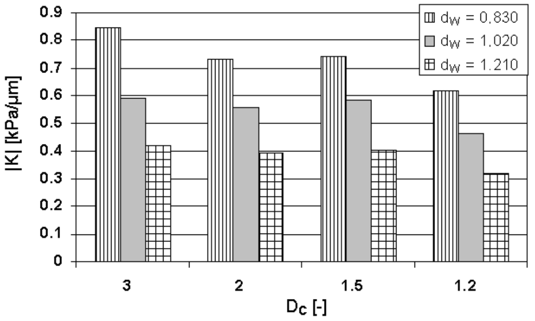

Fig. 10. *Investigation results for* d_p = *2.003 mm*

4 CONCLUSIONS

The analysis has proved that discontinuity of static characteristics of air gauges has a strong impact on their metrological properties. However, a proper choice of the nozzles' geometry could reduce the influence.

The outer diameter of the measuring nozzle is of a large importance. It is recommended to apply either $D_c \leq 1.2$ or ≥ 3.5, but the former could be easily damaged. When the purpose is that the maximal measuring range should be saved with multiplication $|K| \approx 0.6$ to 0.8 kPa/µm, the measuring nozzles should be applied of diameter $d_p \approx 1.6$ to 2.0 mm (with ratio $D_{pw} = 1.64$).

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