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Selection of the cross-section area shape of the ducts used in the shelter ventilation systems – analysis

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Abstract: Ventilation ducts are the basic element of any ventilation system. The paper presents three shapes of ventilation ducts used in industry and discusses them with particular emphasis on the possibility of using them in the construction of shelters. Circle ducts, rectangular ducts, and rectangular ducts with rounded corners. The flow and strength parameters of the indicated ducts were analyzed, and the advantages and disadvantages of individual solutions were presented. Based on the conducted analysis, knowledge gaps were identified.

Keywords: ventilation, internal flows, minor pressure losses, shelters.

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1. Introduction

For many years, shelter construction has been one of the most important topics discussed by scientists dealing with broadly understood construction. Both, legal (Baryłka & Baryłka, 2012; Kwiatkowski, 2012; Szcześniak et al., 2017) and technical (Harmata et al., 2017; Wasilczuk, 2017, 2019) aspects of shelter construction arouse great interest and are the subject of publications and discussion on scientific conferences around the world. Moreover, the problem of building and operating shelters has become particularly important and more and more often discussed due to the growing conflict in Ukraine. Shelters must provide some specific functions, and a few of the most important are (Wasilczuk, 2019):

- protection against the primary and secondary effects of weapons of mass destruction;
- protection against chemical and biological weapons;
- appropriate living conditions.

In order to properly perform the above-mentioned functions, shelters should be equipped with adequate ventilation ensuring air exchange, but also protection against a shock wave. Szcześniak et al. (2010) presented the first Polish design of an automatic explosion-proof valve. The main task of the valve was to protect the shelter's ventilation system against the effects of a shock wave . The valve was characterized by low hydraulic resistance (≤ 300 Pa) and high maximum volume flow rate (to 30 000

m^3/h). Kamionek & Harmata (2020) presented general information related to air purification in permanent protection objects (shelters). They presented possible threats and various ventilation systems (supply system, supply-exhaust system, recirculation system). The article (Kamionek & Harmata 2020)) is one of the most extensive and at the same time widely available studies on ventilation systems in shelters. Harmata et al. (2017) focused on general rules for the use and classification of agents before contamination. In this work, the authors drew attention to the problem of heat dissipation from the shelter and presented general principles and methodology for calculating the amount of heat and moisture from the ground, people, electric lighting, communication devices, IT, and others. Logachev et al. (2015) proposed the use of recirculation ventilation, which allowed to reduce the amount of air blown from the shelter by using a by-pass by 40%. Ovsyannikov et al. (2017) also indicate the possibility of using recirculation to reduce the amount of exchanged air. This solution minimizes the volume of gases that can potentially enter the shelter through leaks.

The authors of mentioned papers focused on the use of a mechanical installation, while Mukhtar et al. (2017, 2018) carried out a numerical simulation of the gravity ventilation system taking into account cables emitting heat. The calculations were carried out for various parameters of the opening of the air intake and exhaust systems, and for a different design of the air supply channel (using a different bend). The results of the numerical calculations coincided with the actual measurements. The experiment allowed them to determine the distribution of the streamline and the flow velocity in the simulated object. In turn, other researchers pointed to the possibility of using a slot leak with a system of baffles (Averkova et al., 2010; Logachev, Khodakov, et al., 2015).

The discussed articles focus on ventilation systems or their components. However, there are no publications on the type of ventilation ducts used in the construction of shelters. For this reason, this article discusses the shapes of ventilation ducts used in industry and their parameters important for the operation of shelters. An additional goal of the publication is also to draw attention to the problem of the appropriate selection of ducts and the need for further research in this area.

2. Shapes of ventilation ducts

In the construction industry, two basic shapes of ventilation duct cross-sections are used. In the case of small diameters of the duct, circular ducts are commonly used, while for larger cross-sections, ducts with a rectangular cross-section are used (Fig. 1). This is due to the fact that a rectangular duct with the same cross-sectional area is lower than a round duct, so the use of rectangular ducts allows designing lower storeys while maintaining the maximum flow velocities specified in the standards. This is noticeable even with small channels. For example, a duct with a circular cross-section and an outer diameter of 320 mm has a cross-sectional area comparable to that of a rectangular duct with outer dimensions of 200x400 mm.

Fig. 1. An example of the use of a rectangular duct in civil construction.

Another type of ventilation duct is a rectangular duct with rounded corners (Fig. 2). These channels are used in industry and are manufactured, among others, by NucAir Technologies Sp. z o.o. However, they are a relatively new solution, and therefore the amount of research into their technical parameters is limited.

Fig. 2. Example of rectangular ducts with rounded corners.

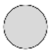
Meeting the same criteria is a key determinant in the selection of ducts for their comparison. In the case of ventilation ducts, the hydraulic diameter should be used:

$$D_h = \frac{4A}{P} \tag{1}$$

where:
A – the duct cross-sectional area, m^2;
P – the wetted perimeter of the cross-section, m.

However, due to the fact that the air velocity in the ventilation ducts should not exceed the specified values; In order not to generate excessive noise, most often round ducts are replaced with rectangular ducts of the same or similar cross-sectional area. Therefore, this study compares the channels with parameters that meet this condition (Table 1). When selecting rectangular ducts with rounded edges, the dimensions of a rectangular duct and two different radii of corner rounding were used. Additionally, Table 1 shows the shape of the duct cross-section. The ducts were selected in this way in terms of utility.

Table 1. Geometric parameters of the analyzed types of ventilation ducts.

Cross-section shape	Shape	The thickness of the wall	Dimensions	Cross-section area	Hydraulic diameter	Moment of inertia I_x
		mm	mm	cm^2	mm	cm^4
Circular		1	ϕ320	794.23	318	1274.78
Rectangular		1	200x400	788.04	264.44	921.40
Rectangular with rounded corners		1	200x400 R100	703.91	275.50	705.49
		1	200x400 R50	767.43	277.08	824.56

3. Flow parameters

During designing ventilation ducts, the key element is the appropriate selection of the volume of air that should be exchanged in a given room, for example for shelters it should be from 8 to 38 m^3/h per person. This condition defines the volumetric flow rate through the duct. Commonly, ducts are selected in such a way that the average velocity of air through the duct is not greater than 5 m/s for spaces where noise should be limited (offices, bedrooms, public spaces) and from 7 to 10 m/s. Based on the required volume flow rate and the maximum value of velocity in the duct, ventilation systems are designed. The amount of air replaced can be calculated on the basis of standards and regulations. In contrast, the air velocity in the ventilation duct is calculated from the continuity equation of fluids as:

$$v_{śr} = \frac{Q}{A} \tag{2}$$

where:
Q – the volume flow rate, m^3/h.

In the case of calculating the ventilation ducts, the compressibility of air is neglected due to the low values of velocity and pressure in the installation. The low-pressure value is maintained even in the case of an overpressure in the facility of 100 Pa, required for the shelters. Ignoring the compressibility for flows below Mach 1/3 is assumed to result in an error of less than 6% (Kamionek & Harmata, 2020).

Losses in ventilation ducts can be divided into minor losses caused by a change in the direction of the resultant momentum in the duct and major head losses caused by friction between the medium and the duct. These losses can be calculated from the following relationships (in the form of pressure drop):

$$\Delta p_{major} = \lambda \frac{L}{D_h} \frac{\rho v_{śr}^2}{2} \tag{3}$$

$$\Delta p_{minor} = \zeta \frac{\rho v_{śr}^2}{2} \tag{4}$$

gdzie:
λ – the major loss coefficients/friction factor;
L – the length of the duct, m;
ρ – the density of the fluid, kg/m^3;
ζ – the minor loss coefficient.

Both the minor and major loss coefficient is determined by the experimental method. In the case of the major loss coefficient, experimental formulas (e.g. Blasius formula or Colebrook-White formula) and the graph originally developed by Nikuradse (the so-called Nikuradse harp) are used. In the case of minor losses, the dependencies described by I. Idelchika (Idelchik, 1987) in 1960 should be used, but simplified tables are commonly used (Hendiger et al., 2013). Analyzing the tables presented in (Hendiger et al., 2013; NucAir Technologies, 2020), it can be noticed that the lowest minor loss coefficient is characteristic for round ducts, then rectangular ducts with rounded corners, and the largest local loss coefficient for rectangular ducts. It should be emphasized here that both publications (Hendiger et al., 2013; NucAir Technologies, 2020) use the average minor loss coefficient, which is independent of the flow velocity.

The analysis of the major loss factor is more complex. However, it can be assumed that circular ducts will be the ducts with the lowest major losses. In the ventilation technique, the Colebrook-White formula is most often used to determine the coefficient of linear losses: :

$$\frac{1}{\sqrt{\lambda}} = -2lg\left(\frac{2,5}{Re\sqrt{\lambda}} + \frac{k}{3,7D_h}\right) \tag{5}$$

where:
Re –Reynolds number;
k – the duct roughness, m;

An analysis of equations (3) and (5) shows that if the rectangular ducts are replaced by a rectangular duct with rounded corners, there will be a reduction of major losses, as long as there is no simultaneous increase in flow velocity associated with a reduction in the cross-sectional area of the duct (Table 1). In a real system, where adequate air exchange must be ensured in a ventilated facility; changing the duct from rectangular to rectangular with rounded corners will result in an increase in average velocity. This will increase the Reynolds number, resulting in increased major losses. The case presented here applies to ducts with small hydraulic diameters, where the introduction of rounding into the duct results in a significant change in cross-sectional area, as in the case shown in Table 1. The problem of major losses in rectangular ducts with rounded corners is also discussed in (Peszynski, 2019; Peszynski et al., 2019).

Fig. 3 shows the contours of velocity in a rectangular and rectangular duct with rounded corners. An analysis of these contours reveals two advantages of rectangular ducts with rounded corners.

1. The maximum velocity in sections with rounded corners is lower than in the case of rectangular ducts. In the case of the studies presented by Peszynski et al. (2019), the difference between the maximum velocity for a rectangular duct and a rectangular duct with rounded corners was 0,04 m/s for the duct 500x800 R100. The problem of velocity distribution in rectangular ducts with rounded edges is discussed in more detail in (Peszyński & Mrozik, 2020; Peszynski & Tesař, 2020).
2. The velocity at the corners of the rectangular ducts is low, which may result in the deposition of dust and other impurities in them. Such places can harbor bacteria and fungi dangerous to human health, which necessitates regular decontamination. A so-called pig is commonly used to clean sewers, which can be made of ice (Quarini, 2002) and is used in each sewer, but more often takes the form of a special device (Chen et al., 2020) and in this case, it is adapted to a specific sewer underneath. in terms of size and shape. In the case of rectangular ducts, the use of a classic pig is difficult due to the corners of the duct and the difficulty of cleaning them thoroughly. The use of rectangular ducts with rounded edges eliminates this problem.

a) b) c)

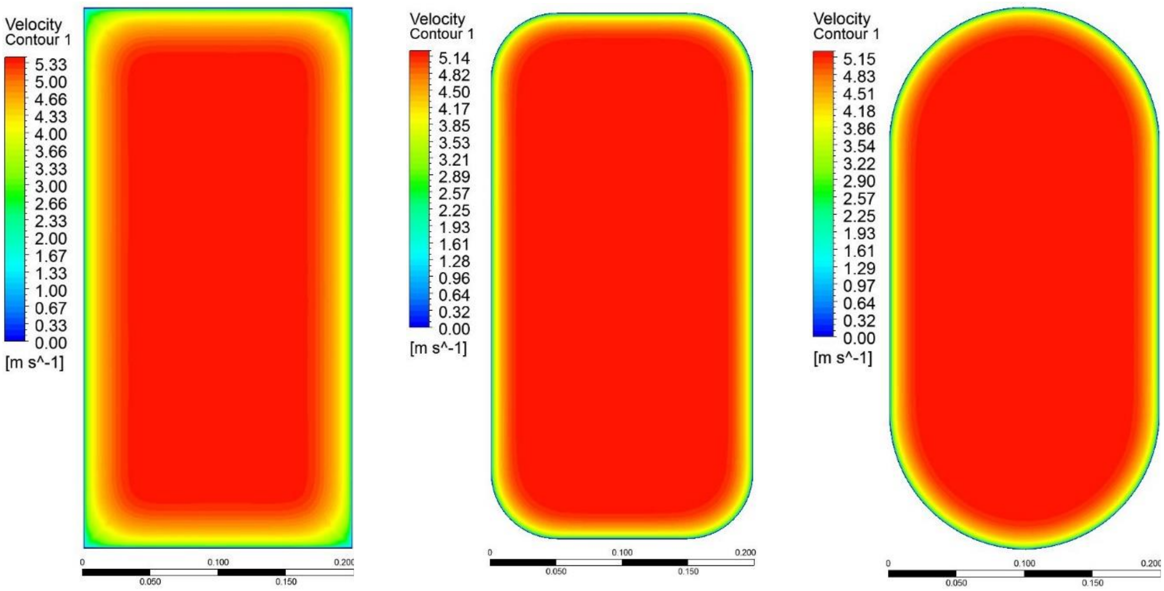


Fig. 3. The velocity contour in a duct with a rectangular section 200x400 (a), rectangular with rounded corners 200x400 R50 (b), and 200x400 R100 (c) for average velocity 5 m/s.

4. Strength parameters

Ventilation ducts are subjected to basically two types of stress: bending stress due to self-weight, and meridional and circumferential stress (according to the membrane theory) due to overpressure in the center of the ducts. It is worth noting that in this respect, round and rectangular ducts with rounded corners show greater strength, which is related to the smaller distance of the wall from the geometric center of the duct. This is especially evident during wall deformation measurements when the channel is subjected to overpressure, where the walls of a rectangular channel deform much more than the walls of a rectangular channel with rounded edges during the leak test. An example of such measurements is shown in Fig. 4. The duct resistance to deformations caused by overpressure is particularly important in ventilation ducts in shelters due to the possibility of an explosion in the duct or an increase in pressure in the duct caused by the shock wave. However, no articles were found that would enable such an analysis to be carried out for the channels in question.

Fig. 4. Ducts during measurements of tightness and deformation of duct walls.

As for the bending stresses, and more precisely the duct susceptibility to deflection, it should be noted that the ventilation ducts, in a simplified manner, can be treated as beams with a homogeneous cross-section. On the other hand, the beam deflection is inversely proportional to the value of the moment of inertia I_x, which is presented in Table 1. Rectangular and rectangular ducts with rounded corners are characterized by a smaller moment of inertia than round ducts and this moment will decrease with increasing the fillet radius. In extreme cases, this may result in the necessity to use a larger number of channel fasteners, to prevent excessive deflection.

5. Summary

Analyzing all the above-mentioned facts, it should be noted that in a shelter installation, the most advantageous, for operational and strength reasons, is the use of round channels. Their shape is characterized by the highest resistance to the load caused by internal pressure, and the pressure losses in these channels are the lowest. However, taking into account the economic issues, the legitimacy of using circular ducts comes down to the construction of new shelters or the adaptation of buildings to shelters by military services. But, Szafrański (2010, 2012) draws attention to the necessity to adapt existing buildings, e.g. residential ones, to serve as shelters by communes, housing communities, or private owners. In this case, the use of round ducts unnecessarily increases the costs, as mentioned at the beginning, thus necessitating the use of rectangular or rectangular ducts with rounded corners. According to the authors of this publication, it is more advantageous, due to the operation of the shelter, to use rectangular ducts with rounded corners, which can generate higher pressure losses (linear losses - in the case of small ducts most often used), but at the same time can provide better strength parameters (further tests are needed) and are easier to clean in case of contamination, caused by both dust deposition and potential radiation contamination. It should be noted that rectangular ducts with rounded corners are not as widely available on the market as rectangular ducts.

Although it is impossible to objectively and clearly indicate the use of which ducts are more economically advantageous, according to the authors, the problems highlighted in this publication are interesting, worth emphasizing, and require further research.

6. Conclusion

The paper presents three shapes of ventilation ducts used in industry: round ducts, rectangular ducts, and rectangular ducts with rounded corners. The flow and strength parameters of the indicated ducts were analyzed, as well as the advantages and disadvantages of individual duct cross-section area shapes. As a summary, the following facts should be highlighted:

(1) Round ducts, although they are characterized by the highest strength and the lowest generated pressure losses, are high in relation to other types of ducts. This precludes their use in the case of storeys of low height. The use of such channels forces the design of higher ceilings, thus increasing the investment cost. In the case of adapting existing structures to the needs of shelters, the use of these channels significantly reduces the height of the room.

(2) Rectangular ducts are characterized by the highest loss coefficients, however, they generate lower pressure losses than rectangular ducts with rounded edges (in the case of small, and at the same time most commonly used cross-sections), which is caused by the increase in the average velocity resulting from the difference in the cross-sectional areas of individual ducts. The velocities at the corners of the channel are low, which can potentially cause sediment to settle there. Channel corners are difficult places to clean thoroughly.

(3) Rectangular ducts with rounded corners generate greater pressure losses than rectangular ducts (in the case of small and most commonly used cross-sections) or round ducts. However, they combine the advantages of round ducts (potentially high explosion strength inside the duct) and rectangular ducts (low height).

The tests to be carried out to fill the gaps includes: studies of the influence of the shape factor on the flow and strength parameters of the duct, comparison of the strength parameters of rectangular and rectangular ducts with rounded corners, optimization of the radius of rounding of a rectangular channel with rounded corners in terms of flow and strength.

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