Numerical simulation of a z-shaped ventilation elbow and reduction of its resistance

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Abstract. The paper presents the results of a numerical study of the flow in a Z-shaped elbow. Dependencies are found for the local drag coefficient of such a unit, the coupling effect coefficient, the lengths of the influence zones and the outlines of the vortex zones on the distance between the individual components in this unit. The dependence for the LDC, as well as the coupling effect coefficient, agrees quite well with the known experimental data, which indicates the validity of the numerical model. Using the found outlines of the vortex zones, numerical models of energy-efficient profiled Z-shaped elbows were developed and investigated. Graphical dependence of the LDC of such a duct unit on the distance between the single elbows is developed. The resulting dependence shows a decrease in resistance by 70% compared with the standard design. For a whole ventilation system, it will lead to energy savings spent on the drive of the fans, and therefore to reduce operating costs. Using of a large number of such energy-efficient duct elements will allow replacing the fan with a less powerful one, which will lead to reduction in capital costs for construction.

Keywords: Z-shaped elbow, ventilation duct, pressure drop, vortex zones, profiling, resistance reducing.

1 Introduction
A numerical study of the flow in the channel with two consecutive 90° elbows in a Z-shaped configuration is carried out. Such a situation is very common in practice, and it is known that the resistance of such a unit strongly depends on the distance between the single elbows and can be either less or more than the resistance of two separately located elbows [1]. This situation is due to the features of the interaction of the vortex zones arising in the first elbow in downstream direction with the vortex zones of the second elbow, which lead to different deformations of the main flow and pressure losses in the Z-elbow as a unit. In general, the question of the interaction of sequentially located disturbing elements, which are, for example, joint elements in the duct and pipe channels, has not been studied very well due to the huge variety of disturbing elements as well as their mutual combination. For this reason, in the practice of designing and conducting aerodynamic and hydraulic calculations, such interaction is not taken into account at all, although, especially in ventilation and air conditioning systems, disturbing elements in the duct networks are usually located very close to each other and significantly affect each other. Studies of the mutual influence of disturbing elements and finding dependencies to determine the resistance of units containing several duct components are very relevant, and will reduce errors in determining the ductwork resistance and, accordingly, the required fan pressure. In addition, having studied in detail the flow characteristics in such units, they, for example single duct elements, can be optimized and investigated to reduce their resistance.

From the point of view of available information and research, the unit in the form of a Z-shaped elbow is one of the few that is the subject of some studies, which allows it to be used as a test, to configure the numerical solution scheme. The well-known handbook [1] provides data on the...
dependence of Z-shaped elbow resistance on the distance between the single elbows in the range from 0.4b to 10b (b is the channel width). In [2], the flow in a Z-shaped unit of circular cross section, consisting of two five-gore elbows with a rounding radius of 1.5 channel diameters, was experimentally and numerically studied. Experimentally we used a five-hole directional velocity probe and numerically determined velocity fields in the cross sections of the channel. It is shown that even after a non-“sharp” elbow, significant deformations of the velocity field arise. The flow recovery after the unit is obtained at a distance of more than 9 diameters. A good matching was also found between the results obtained numerically and experimentally using the RANS RSM model (difference of about 15%), while a seemingly more detailed LES model in this case shows worse results. Unfortunately, there is no resistance data in this work. In [3], with the 2-dimensional Particle Image Velocimetry (PIV) method the detail velocity fields were examined with calculation of turbulent characteristics for a Z-shaped bend similar to that described above - also rounded with a radius of 1.5 channel diameters, but only for zero distance between individual bends. It is noted that the velocity and components of turbulence kinetic energy throughout the first along the current elbow are similar to a single elbow, but by the end of the first elbow they become higher than that of a single one. A series of studies of the resistance of Z-shaped elbows of different structure - three-gore, five-gore, die stamped, pleated, mitered with vanes, and mitered without vanes [4] was also experimentally conducted for a range of distances between individual bends from 0 to 10 diameters, with increment of 0.3m. The results of comparing the obtained LDC values with doubled values for single elbows of the same design are presented. It is shown that the unit resistance can be either greater or less than doubled single elbow LDC value, depending on the distance between the elbows, and for the maximum distance studied, the resistance difference is still observed. In addition, authors conclude that for rounded bends this difference is not large. But this difference is the greater the less smooth the turn of the bend. For rectangular channels, one can note the work [5], where two configurations of doubled bends: Z- and U-shaped, are studied experimentally and numerically, for different ratios of the cross section dimensions of the channel from 1: 5 to 5: 1, also rounded along the radius from 1 to 3 hydraulic diameters of the channel. Moreover, such a wide range of changes in the configuration of the unit was studied numerically, and the change in velocity and pressure drop was experimentally determined for one configuration, which was then used to validate the results obtained numerically. Based on the results of comparing the experimental velocity distribution in the channel cross sections and calculations using the RSM turbulence model, good matching is obtained and further research is carried out using this model. The numerical distribution of the velocity along the axis of the channel with a Z-shaped bend shows that its value, after the unit returns to its original value at distances of more than 80-120 diameters, depends on the ratio of the cross section dimensions, which can also serve as an indirect indicator for the lengths of the zones where the duct elements influence each other. On the other hand, apparently here it is necessary to distinguish between zones of influence according the velocity fields and by the pressure drop. There is also no data on the effect on the resistance of the distance between the single elbows.

For the Z-shaped “sharp” configuration, there are also several studies, both numerical and experimental. For example, in [6], such a unit was numerically modeled in a two-dimensional setting with a distance between elbows equal to 3 channel widths. The presence of a number of vortex zones was found, both when flow separates from the sharp edges and in the corners of the bends, as well as the difficulty of validating the results obtained, since there is no data on their outlines and the decision on the correctness of using the k-ω model is made by visual assessment of the outlines and size of the vortex zones. In a series of works [7–9], also experimentally and numerically for a Z-shaped elbow with a distance between individual elbow of 3 channel widths, the separation zones were also studied in more detail, their main dimensions were given, but only for Re numbers 300 ÷ 2000, that is, for the laminar flow regime, while the channels of ventilation systems are characterized by a developed turbulent regime.

There are also few works devoted to improving the design of ventilation ductworks [10] and their elements. In [11], a decrease in resistance by 9.8% was achieved by selecting the most optimal
circumference of the inner and outer fillets of rectangular bends connected in a Z-shaped elbow, but unfortunately, the dependence on the distance between the bends was not investigated. For Z-shaped connected channels, one can note the work [12], where the influence of the installation of guide vanes inside the elbows is numerically studied, which leads to a decrease of its resistance. The study uses the “standard” $k-\varepsilon$, because it leads to adequate results, and the more detailed Reynolds Stress Model did not lead to a convergent solution. Based on the research results, the LDC values for Z-, U- and P-shaped elbows were obtained for the distances between elbows 1, 3, 5 and $\infty$ without installing guide vanes and when installing one and two vanes. For the Z-shaped configuration, a reduction of LDC by a value of 50 to 60\% is shown. In [13], optimization algorithms are used to fit the Z-shaped connecting channels in the form of Bézier curves with minimal resistance. More sophisticated techniques for optimizing the form of HVAC channel systems elements are used in the so-called topology optimization [14–16]. It should be noted that methods for improving duct elements with installation of guide vanes, as well as designs obtained by topological optimization, significantly complicate the manufacturing technology, and therefore, increase the cost of manufacturing such elements, which is not profitable for building ventilation systems. The options discussed above in which the inner edge of the tap is rounded off also lead to a significant decrease in the unit resistance, but at the same time it also leads to an increase in the dimensions of the part and the impossibility of placing such ducts in limited technical spaces. Thus, the method of aerodynamic improvement of the duct element design without complicating the technology of its manufacture, and also not leading to an increase in its size, is relevant. One of such methods is profiling the wall of the element or installing a special profiling insert inside it, the outlines of which repeat the outline of free streamline that bound the vortex zone that occurs in the “sharp” design of that fitting. Using this method [17], studies were carried out and the designs of single duct fittings were improved: elbow [18, 19], asymmetric tee [20], sudden expansion [21], round exhaust hoods [22, 23], side exhaust orifices [24, 25], as well as a unit in the form of a U-shaped elbow [26]. It is shown that in this way it is possible to achieve a reduction of resistance of a single fitting and if a unit consisting of several components by a value of 20 to 70\%.

2 Methods

The study is carried out numerically using the Ansys Fluent CFD software. Figure 1 shows the geometry of the channel with a Z-shaped elbow - “sharp” (a) and profiled according to the outline of the vortex zone (b). The channel width was $b = 0.1$ m, the channel length to the first branch was 4 m (40 $b$), the distance between the elbows $l_c = 0.04$ m (0.4 $b$); 0.1 m (1 $b$); 0.2 m (2 $b$); 0.5 m (5 $b$), 1.5 m (15 $b$), 3.5 m (35 $b$), the length of the channel after the second elbow was 5 m (50 $b$). The lengths of the channels before and after the unit consisting of two elbows are taken sufficient long to eliminate influence of a disturbing element in the form of a z-shaped elbow to the flow. At the $AB$ boundary, the boundary condition (BC) “velocity inlet” was specify with a uniform velocity profile $v = 10$ m/s; the outlet from the channel (ED boundary) - BC “pressure outlet” with an excess pressure set equal to zero, on the walls of the channel - BC “wall”.

An important stage of numerical study is verification and validation. The validation and verification stages here were combined by conducting a grid convergence study for different combinations of turbulence and near-wall models for one Z-shaped elbow geometry ($l_c = 0.04$ m) and further comparing the results with the known resistance values of such a fitting element [1].
Figure 1. Computational domain and characteristic stream lines for the Z-shaped elbow with $l_c = 5b$.

Grid convergence study was carried out by sequential refining of computational mesh – first four stages of refining throughout whole computational domain, and then for better resolution of the boundary layer – 7 stages of refining the flow region along solid boundaries. For example, for a task with $l_c = 3.5m$, the initial computational mesh had the following parameters: minimum cell size 25 mm, total number of cells in the computational domain 2000 pcs. After all stages of refining, the size of the minimum cells was $2.44 \times 10^{-5}$ mm, and total number of cells reached $7.38 \times 10^6$ pcs.

As a result of such a study, which is described in more detail in [27], a combination of the turbulence model “standard” k-ε with “enhanced wall treatments” is selected based on the validation results, which is then used to carry out numerical modeling for all the studied Z-shaped elbow designs.

3 Results and discussion for the “sharp” Z-elbows

3.1 Vortex zones outlines

The outline of the vortex zone is taken to be the extreme streamline that delimits the vortex zone and the main flow in the channel. Figure 1 shows the flow characteristic of a large distance between elbows, when all 4 separate vortex zones are formed – 1VZ and 2VZ in the corner and separated from the sharp edge of the first elbow, 3VZ and 4VZ, respectively, in the corner and separated from the sharp edge of the second elbow. For Z-shaped elbow with $l_c = 2$ and less merging of 2VZ and 3VZ observed (figure 2).
Figure 2. Flow in a Z-shaped elbow with $l_c = 2b$.

The outlines of the vortex zones for all studied distances $l_c$ are presented in figure 3. In this case, the outlines of 1VZ and 2VZ (Figure 3a, 3b) as expected have weak dependence on the distance between the elbows, except for distances $l_c$ less than 2b, where 2VZ and 3VZ are already merging, and also influence to the 1VZ.

In Figure 3b and 3d, in addition to the outlines of 2VZ and 4VZ, respectively, for comparison, the outlines of vortex zone obtained for single elbow experimentally [28], analytically [29] and numerically [19] are shown. It can be noted that with a general correspondence of the 2VZ to the vortex zone in a single elbow, there is still some difference. For 4VZ, a significant dependence of the outline on the distance $l_c/b$ is noticeable, and, accordingly, the difference from the single elbow. Moreover, it can be seen that for the smallest distance $l_c = 0.4b$, the separation zone has the smallest dimensions, since in this case a flow different from other variants occurs - a flow with a slight shift relative to the axis of the channel. Further, with an increase of distance between the single elbows ($l_c/b = 1$ and 2), the 4VZ increases significantly, which is apparently a consequence of the effect of the large vortex zone formed by merging 2VZ and 3VZ.

Figure 3. Vortex zones outlines: a) 1VZ; b) 2VZ; c) 3VZ; d) 4VZ for Z-shaped elbow with $l_c/b = 0.4 \div 35$ and 2VZ and 4VZ for a single elbow.

With a further increase in $l_c/b$ from 5 to 35, the 4VZ first one decreases and then increases slightly, gradually approaching the size of the single elbow VZ.

3.2 Resistance

Based on the results of the total pressure field numerical calculation, the LDC value was determined by the method described in detail in [19, 23] and a graphical dependence of the Z-shaped elbow LDC on the distance between the elbows $l_c/b$ was obtained (Figure 4). It also shows the change of LDC for the same unit according to [1], and the doubled value of the LDC for single elbow according to [1] and [19].

As can be seen from Figure 4, the character of the LDC dependences for the whole unit on the distance $l_c/b$ found numerically and given in [1] is in good, although the quantitative numerical values are approximately 20–25% higher, which can be considered as acceptable error in the numerical calculation and experimental data. In addition, it can be seen that the value of the LDC of the unit has a minimum (approximately 5.8 times less than doubled value of single elbow LDC) at the smallest distance $l_c = 0.4b$. With an increase of distance between elbows, the LDC value increases and reaches
its maximum (about 2 times higher than the doubled value of single elbow LDC) at a distance \( l_c = 2b \) and then begins to decrease gradually approaching the doubled value of single elbow LDC.

**Figure 4.** Dependence of LDC (\( \zeta \)) and coupling effect coefficient \( \psi \) on \( l_c/b \) for the Z-shaped elbow and the doubled value of LDC for a single elbow (2\( \zeta_{\text{single}} \)).

It should be noted that even for distances \( l_c = 35b \), the unit LDC remains slightly higher (~ 16 %) of the single elbow doubled value, which may be due to the error in calculating the friction pressure losses in such long sections of the channel between the branches, and as the limit distance of the mutual influence of the elbows apparently, one can take \( l_c = 15b \). Exceeding this distance there is no significant change in the LDC value for a Z-shaped elbow. The same figure also shows the dependence of the coupling effect coefficient \( \psi \), which is defined as the ratio of the local drag coefficient of the whole unit (\( \zeta_Z \)) to the sum of the LDC of the individual elements included in this unit (2\( \zeta_{\text{single}} \)): \( \psi = \zeta_Z / 2\zeta_{\text{single}} \). It can be seen that in accordance with the aforecited LDC unit changing, the coupling effect coefficient takes on values both less and more than 1, and then tends to 1 with an increase of the distance between the elbows.

### 3.3 Length of influence zones

To take into account the influence of the Z-shaped elbow on other fitting elements of the ventilation ductwork, it is necessary to know the lengths of influence zones extending up and downstream from the unit. Earlier [30], such zones were defined as a part of channel near the duct element, respectively upstream \( (l_{IZ,\text{up}}) \) and downstream \( (l_{IZ,\text{down}}) \) along the flow on which a non-linear change of pressure drop occurs, which is a consequence of the flow deformation occurring in that fitting element. Figure 5 shows the dependencies for \( l_{IZ,\text{up}} \) and \( l_{IZ,\text{down}} \) for the Z-shaped elbow and for a single elbow.

**Figure 5.** Dependence of \( l_{IZ,\text{up}} \) and \( l_{IZ,\text{down}} \) on \( l_c/b \) for the Z-shaped elbow and for the single elbow.

It can be seen that the length of the influence zone of a whole unit does not depend on the distance \( l_c/b \) and, just as for a single elbow, this value is very small – 0.5b. The character of the dependence of the length of the influence zone after the Z-shaped elbow is similar to the change in LDC — it is minimal for the smallest of the studied values \( l_c/b = 0.4 \), and with its increase it also increases and for \( l_c/b = 1 \) —
it slightly exceeds the length $l_{IZ,down}$ for a single elbow, after which it begins to decrease and already at $l_C/b = 5$ it becomes slightly less than the $l_{IZ,down}$ value for a single elbow, after which it again begins to rise gradually approaching the value for a single elbow. This suggests a similar mechanism of flow deformation in the Z-shaped elbow and single elbow.

4 Results and discussion for the “profiled” Z-shaped elbows

4.1 Resistance

Using the previously obtained vortex zones (VZ) outlines for all studied Z-shaped elbows geometries, numerical models of profiled elbows were developed. In accordance with an earlier study of single elbow profiling variants, the profiling by the VZ in the corners of the elbows (1VZ and 3VZ - Figure 1) does not lead to a significant effect with a LDC decrease [31]. Therefore, a further numerical simulation of the Z-shaped elbow is carried out with profiling by 2VZ and 4VZ for $l_C/b \geq 5$, when they are separate. For distances $l_C/b < 5$, when the merging of 2VZ and 3VZ occurs, profiling is carried out according to the outline of VZ resulting from their merging and by the 4VZ outline. The dependence of the profiled Z-shaped elbow LDC ($\zeta_{Z,prof}$) on $l_C/b$ is shown in Figure 6, as well as the value of the double LDC of profiled single elbow ($2\zeta_{single,prof}$), the mutual influence coefficient $\psi$ of the elbows of which consists the unit are also shown there. It can be seen that, similarly to the LDC dependence for a non-profiled “sharp” unit, the LDC of a profiled unit at $l_C/b = 0.4$ has the smallest values (about 5.9 times less than the doubled value of the profiled single elbow LDC), which increases sharply with increasing distance and takes maximum value at $l_C/b = 2$ (approximately 3 times higher than a doubled profiled single elbow LDC). Further, with an increase of the distance, the LDC begins to decrease gradually, tending to the double value of the profiled single elbow LDC, and at distances $l_C/b \geq 15$ it already does not change significantly.

Figure 6. Dependence for LDC ($\zeta_{Z,prof}$, $2\zeta_{single,prof}$), coupling effect coefficient $\psi$ and efficiency of profiling $\Delta \zeta$ of profiled Z-shaped elbow on $l_C/b$.

Figure 5 also shows the change in profiling efficiency $\Delta \zeta = 100\% \cdot (\zeta_Z - \zeta_{Z,prof})/ \zeta_Z$. It can be seen that, with the exception of the distance range $0.4 < l_C/b < 5$ where $\Delta \zeta$ varies from 60% to 80%, for the rest of the distance range, the profiling efficiency is approximately constant at about 70%.

4.2 Length of influence zones

Similarly to the non-profiled “sharp” design of Z-shaped elbows for the profiled one, the dependences of the influence zones lengths up and downstream on the distance $l_C/b$ were determined (Figure 7). In addition, Figure 7 shows the change in the lengths of the influence zones for a single elbow.
Figure 7. Dependence of $l_IZ_{up}$ and $l_IZ_{down}$ on $l_C/b$ for the profiled Z-shaped elbow and for the profiled single elbow.

It can be seen that, as for a “sharp” design of the unit, the length of the influence zone upstream has a small value $l_{IZ_{up}} = 0.5b$ and is constant, which also corresponds to $l_{IZ_{up}}$ for a single elbow, but slightly higher. The nature of the change in the length of the influence zone after the Z-shaped elbow $l_{IZ_{down}}$ is completely similar to the change in $l_{IZ_{down}}$ for the “sharp” unit design (Figure 5) – the minimum value at the smallest value of $l_C/b$, then increases with growing distance between the elbows, becoming slightly larger, and then decreasing, becoming somewhat smaller than $l_{IZ_{down}}$ for a single profiled elbow. With a further increase of the distance $l_C/b$, the length of the influence zone again increases further, tending to $l_{IZ_{down}}$ of a single profiled elbow. It should also be noted that the $l_{IZ_{down}}$ value for the profiled Z-shaped elbow is in the same order as for the non-profiled (“sharp”), which confirms the conclusion made for other fitting elements [9, 19] – profiling does not affect the flow deformation due to disturbance introduced by the duct element, but only eliminates the vortex formation and reduces its pressure losses.

5 Conclusions
A detailed numerical simulation of the flow in the Z-shaped elbow was carried out and the outlines of the vortex zones and the local drag coefficients (LDC) values depending on the distance between the separate elbows included in the unit of Z-shaped elbow were found. In this case, the dependence of the LDC matches quite well with previously known experimental results, which confirms the validity of the numerical model. In addition, graphical dependences were obtained for the up and downstream influence zones lengths for the Z-shaped elbow. Further, using the data on the outlines of the vortex zones, we simulated the flow in the profiled Z-shaped elbow, and a decrease in resistance was obtained for the entire investigated range of distances between the elbows by about 70%. The results can be used in the design of air ductworks of ventilation and air conditioning systems with low resistance.

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