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Peculiarities of separated flows in ventilation elbows and their nodes studied numerically

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Abstract. This study examines vortex zones (VZs) that form in single ventilation elbows and their U-shaped and Z-shaped nodes. Reducing local drag in these elements is important for reducing energy consumption in ventilation systems, which can account for up to 80 % of the total network drag. A mathematical model based on the discrete vortex method (DVM) was developed to calculate the VZ boundary in a steady state. The model places attached vortices along the flow boundary and free vortices detached from sharp edges, iteratively determining their circulation and position. Convergence is achieved with a sampling step of $h = 0.00125$ m (3522 boundary elements), yielding an average vertical velocity in the control section that differs by only 0.18 % from the solution with $h = 0.0025$ m, and a difference in the VZ width of 0.47 %. For a single 90° elbow, with an increase in the relative channel width from $b_2/b_1 = 0.5$ to 2.0, the maximum VZ width increases from approximately $0.27 b_1$ to $1.20 b_1$. The DVM results are in good agreement with the experimental outlines of VZs at a distance of up to two calibers from the sharp edge. Two-dimensional calculations of the Reynolds-averaged Navier-Stokes equations were performed in the Ansys Fluent computational fluid dynamics (CFD) software package using the standard $k-\varepsilon$ model with extended wall modeling. The determined local drag coefficients (LDCs) for a single elbow differ by less than 1 % from the previous numerical data and have the same change trend as the experimental results, with a difference of about 20 %. For U-shaped and Z-shaped nodes with distances between individual elbows equal to $d_2/b_1 = 2$ and 4, the DVM shows the merging of VZs at a shorter distance, while the CFD method shows separate VZs, demonstrating the influence of the downstream ventilation elbow. The developed approach using DVM and CFD allows for the precise determination of VZ outlines in nodes consisting of ventilation elbows and opens up prospects for the design of shaped energy-efficient ventilation system components.

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1. Introduction

Mechanical ventilation and air conditioning systems together with pollutant capture or localization systems are used in both civil and industrial buildings to ensure the necessary microclimate parameters for sanitary, hygienic, or technological requirements [1, 2]. According to statistics, the operation of heating, ventilation, and air conditioning systems accounts for approximately 40–60 % [3] of the total electricity consumption of buildings. Overcoming the aerodynamic drag of ventilation networks, imposed by duct fitting elements ("local resistances"), accounts for up to 70–80 % of their total resistance [4]. The main consumers of electrical energy are draft equipment (fans, smoke exhausters, pumps), the power of which is directly proportional to the flow rate of medium passing through them and the network resistance (pressure losses in the elements of the networks). Therefore, one of the areas for energy conservation in ventilation and air conditioning systems is the reduction of energy losses in the ductwork elements, which will reduce the carbon footprint of electricity generation and is an important task of environmental engineering [5–7], especially in conditions of increasing loads on systems under changing climatic parameters [8].

The scientific works for reducing pressure losses by overcoming local resistances by shaping the element walls or by installing variously curved guide vanes are being well developed. Various types of fitting elements have been studied. For elbows and bends, a resistance reduction of 25–31 % was obtained [9, 10]. The reduction in local resistance coefficients for tees was found to be from 6 to 99 % for the forward flow direction and from 2 to 98 % for a side branch, depending on the ratio of the transverse dimensions and the flow rates of air flowing through the branches [11–14]. For a tee connecting kitchen exhaust hoods to a flue, a design and installation location in the main shaft of a cycloidal guide vane was developed. This design reduces the resistance to flow in the forward direction by up to 44–197 % and increases the resistance to flow in the opposite direction by up to 4–171 % [15]. When installing a guide vane in a side branch, the flow is separated, separation processes are reduced, and resistance decreases from 8 to 74 % [16]. By selecting the appropriate position and curvature shape of the guide vane installed in the forward direction, the flow resistance can be reduced by up to 44 % [17]. The improved designs of air and check dampers, including optimized shutter position and profiling of the pressure bars [18, 19] result in a decrease in resistance in the open state by up to 87 %, which is especially important for "normally open" fire dampers. Optimization of the curved shape of the fairing of the supply ventilation diffuser is used to increase the quality index of the air distribution device [20], which also includes the aerodynamic resistance. Flows in static pressure chambers [21] and in other fitting elements in case of constrictions [22] and expansions are also the subject of research and design optimization. In these cases, a significant reduction in aerodynamic resistance is also achieved.

The considered studies used both numerical and natural experiments, and a wide range of methods for finding the outlines for shaping: biomimicry and machine learning [9]; biomimicry of branched plant structure [12]; methods based on the principle of field synergy and viscous dissipation; methods using the principle of field synergy and entropy increase [10, 20]; the method of shape optimization by gradient descent [11]; the use of guide vanes to reduce fluid deformation and convert mechanical energy into internal energy and turbulent energy dissipation [13, 14, 17, 18]; methods based on the calculus of variations [15]; a combined method of optimization of geometric parameters and the installation of deflectors, using the principle of energy dissipation and vortex force [16]; an improved method of topology optimization for the design of low-drag elements and methods of machine learning and numerical modeling [19]; a method of structural-parametric optimization of static pressure chambers [21]. The shape of the Boltzmann curve was obtained and applied for a shaped element in the form of a confuser [22]. For an elbow, a development of the method of topological shape optimization using the Forchheimer model was proposed [23]. In this case, solved were the problems of reducing the resistance of elements of not only air ducts of ventilation, air conditioning and smoke removal systems but also of water pipes, pipelines of heating systems [24, 25], in a heat exchanger [26] cooling and water supply [9, 16, 19], and distribution static pressure chambers [21].

Studies of flow characteristics in engineering systems are also developing in the direction of identifying peculiarities in a specific operating condition. For example, the work [27] summarizes the obtained data on the influence of various parameters on local resistance losses, including atmospheric pressure, inlet velocity, humidity, oxygen concentration, pipe diameter, wall roughness, velocity ratio, and area ratio between branches and the main duct. In addition, when considering methods for improving the energy efficiency of duct networks, an important issue is the effective balancing of all branches, which can be taken into account by, for example, the criterion of minimum life cycle cost (LCC) of the system [28]. The paper provides a detailed review of the existing methods for designing duct networks and demonstrates the advantages of the developed balancing technique based on minimum LCC. In this case, one should perform an accurate calculation of the aerodynamic resistance of all shaped elements, including their mutual influence on each other. The work [29] considers the problems associated with balancing airflow distribution in duct networks, taking into account the undeveloped turbulent flow regime and the complex dependence of the resistance of fitting elements on their velocity. The methods developed based on

machine learning and computational fluid dynamics (CFD) make it possible to regulate such complex systems with an accuracy of up to 5 %. Special stabilizers are also being developed to perform balancing and automatic regulation of airflows [30], and issues of regulating the exhaust air flow for natural ventilation systems of multi-story buildings are considered. When studying fitting elements in a three-dimensional formulation, it becomes important to find a method for determining the vortex zone (VZ) outlines [31, 32].

The approach being developed by the authors (a scientific school) is devoted to the study of VZ outlines and shaping based on them [4, 33]. CFD and the discrete vortex method (DVM) were used for the study. The DVM was used to determine the VZ outlines at the inlet of the exhaust ducts. It is of interest to consider the application of the DVM to the study of other fitting elements of mechanical ventilation systems, in particular, to consider the possibility of its application to describing the VZ when the flow turns in a duct fitting element in the form of an elbow and nodes composed of consecutively arranged elbows. A similar study is conducted using the CFD method to compare the results with each other and with the existing data from other authors.

The goal of this work is to develop a discrete mathematical model, a computational algorithm, and a computer program for calculating the VZ boundary for flows inside air ducts – in elbows and their nodes using the DVM in a steady-state formulation. To achieve this goal, it is necessary to solve the following problems: to construct numerical CFD and DVM models; to configure and validate the models, to compare the calculation results with each other and with the calculated and experimental data known from literature.

2. Methods

During numerical modeling of elbows for channels with a depth (dimension in the direction normal to the plane of view) significantly (more than 7–10 times) exceeding the channel width, they can be considered as two-dimensional, which is confirmed by the known experimental data on the resistance of elbows [34]. The numerical modeling of the VZ outlines in channels with elbows confirmed the three-dimensional shape of the separation zone [35–36]. However, the existing deviation from the VZ outlines obtained in the two-dimensional formulation does not lead to a significant increase in efficiency, when they are subsequently used for profiling shaped elements (an increase in efficiency is about 17 %). Moreover, from a technological standpoint, manufacturing an insert with a three-dimensional shape or profiling the channel wall along such a surface poses a highly challenging task, and therefore, it is not justifiable for practical application. Manufacturing of a shaped element profiled along the outlines (a two-dimensional curve) merely involves bending the plane of the channel wall and can be accomplished without any changes to the manufacturing technology for standard shaped elements on the existing production lines equipped with sheet-metal plasma cutting machines. For this reason, determining the two-dimensional VZ outlines is relevant.

When constructing a numerical DVM model, the non-stationary nature of the vortex formation process allows for the use of a non-stationary formulation. However, to determine the VZ outlines for the purpose of using them for profiling, it would be necessary to further average them over time, which is time-consuming and results in the same shape of the separation zone as when using a more rapidly converging solution in a stationary formulation.

2.1. Construction of a Discrete Mathematical Model

A discrete mathematical model (Fig. 1b) of flow separation from a sharp edge A during a turn had been constructed as follows. The boundary of the region had been constructed symmetrically with respect to the Ox axis, that had ensured the absence of air flow across the Ox axis, since each attached or free vortex located in the upper half-plane (Fig. 1b) corresponded to a vortex in the lower half-plane, symmetrical with respect to the Ox axis. The circulations of these vortices had been set equal in magnitude but opposite in sign: $\Gamma(\xi^k) = -\Gamma(\xi^{k+N})$, where $k = \overline{1, N}$, N was the number of vortices in the upper half-plane.

$2N$ attached vortices had been uniformly distributed along the flow boundary. The distance between them had been set equal to the discretization step h . Flow separation occurred at point A and point A' , symmetrical with respect to the axis, at which a free vortex layer of $2N_A$ vortices had been formed.

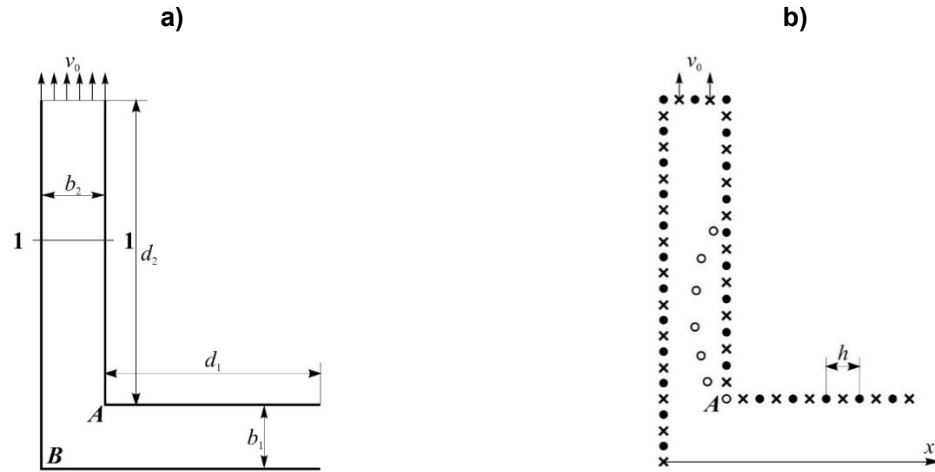


Figure 1. Formulation of the problem: a) flow boundary; b) discrete model.

The influence of all vortices on a point $x(x_1, x_2)$ along the direction $n = \{n_1, n_2\}$ had been determined by the sum:

$$v_n(x) = \sum_{q=1}^N \left(G(x, \xi^q) - G(x, \xi^{q+N}) \right) \Gamma(\xi^q) + \gamma_A \sum_{k=1}^{N_A} \left(G(x, \zeta_A^k) - G(x, \zeta_A^{k+N_A}) \right), \quad (1)$$

where $G(x, \xi) = \frac{1}{2\pi} \cdot \frac{(x_1 - \xi_1)n_2 - (x_2 - \xi_2)n_1}{(x_1 - \xi_1)^2 + (x_2 - \xi_2)^2}$ was the velocity at a point $x(x_1, x_2)$ along the direction

$n = \{n_1, n_2\}$, caused by the action of a vortex of single circulation located at a point $\xi(\xi_1, \xi_2)$; γ_A was the circulation of free vortices at a point A ; ξ^q was the location point of the q -th attached vortex; ζ_A^k , ζ_A^k , was the location point of free vortices that have come off the sharp edge A ; N_A was their amount. If the distance from the point x to the point ξ had exceeded $h/2$, then $G(x, \xi) = 2((x_1 - \xi_1)n_2 - (x_2 - \xi_2)n_1) / (\pi h^2)$. In case of their coincidence $G(x, \xi) = 0$.

The free vortex locations had been determined iteratively. At the first iteration, the coordinates of the control point $x^p(x_1^p, x_2^p)$ had been substituted instead of $x(x_1, x_2)$ in formula (1). Varying p from 1 to N had yielded a system of N linear algebraic equations with N unknown vortex circulations. After solving this system, a streamline was constructed from point A , along which free vortices were uniformly distributed with a step of h . When the streamline had approached the domain boundary at a distance smaller than the discretization step, its construction was stopped. At this point, the first iteration had been completed. The second iteration also consisted of solving the system of equations, taking into account the new location of the free vortices. Iterations had been performed until the difference in the absolute value of the free vortex circulations at the subsequent and previous iterations was greater than the accuracy of 10^{-8} .

2.2. Construction of a Numerical CFD Model

The Ansys Fluent (Release 18.2) computational software was used for the problem solution. The geometries of the computational domains for all three problems: a single elbow, and nodes consisting of two consecutive elbows in U-shaped and Z-shaped form, are shown in Fig. 2.

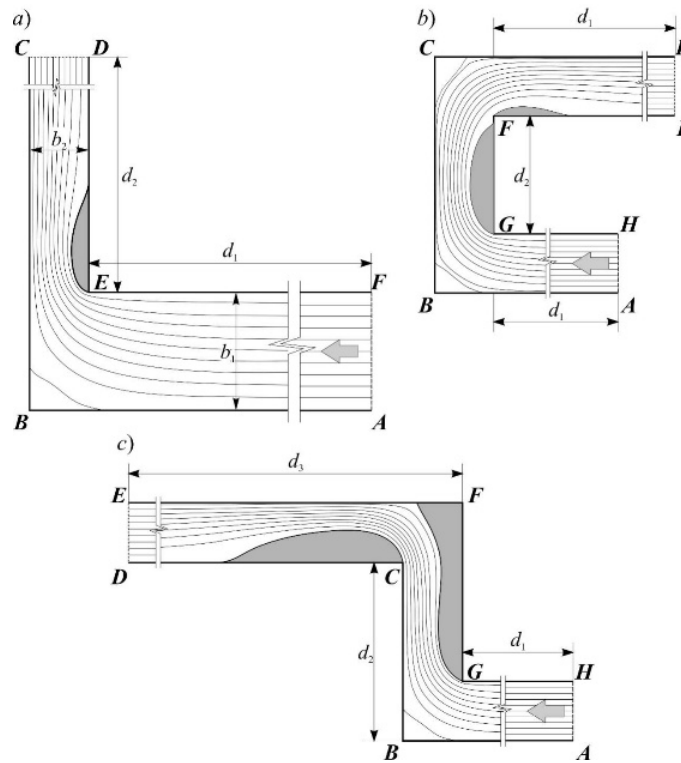


Figure 2. The geometry of the computational domains:
a) single elbow at 90°, b) U-shaped elbow, c) Z-shaped elbow.

At the boundaries FA (single elbow) and HA (Z- and U-shaped elbows), the boundary condition (BC) of constant and uniform velocity $v_0 = 10$ m/s ($Re \sim 5.9 \cdot 10^4$) had been set; at the boundaries CD (single elbow) and DE (Z- and U-shaped elbows), the condition of constant excess pressure equal to zero (release to atmosphere) had been set. The remaining boundaries had been set as impermeable walls with a no-slip condition. The channel widths had been set as follows: $b_1 = 0.1$ m, $b_2 = 0.05$ ($0.5 b_1$); 0.1 ($1.0 b_1$); 0.15 ($1.5 b_1$); 0.2 ($2.0 b_1$). The channel length before the elbow d_1 had been chosen equal to $40 b_1$ to be sufficient to equalize the flow after the inlet. Similarly, for a single elbow, the length after it had been chosen $d_2 = 40 b_2$. Previously, numerous comparative studies have shown (e.g., [37]) that such a length is sufficient to ensure a fully developed profile after the inlet BC in the form of a uniform profile, as well as to equalize the flow after shaped elements, for the correct determination of the local resistance coefficient. For nodes in the form of Z- and U-shaped elbows, the flow had been modeled and studied for the following distances between two consecutive elbows: $d_2 = 2 b_2$ and $4 b_2$. The length of the outlet channel after the nodes $d_3 = 40 b_1$ had been also chosen to be sufficiently large to equalize the flow parameters in the channel cross-section.

Since flows in shaped elements can be quite complex, many researchers note the lack of universal models for all ventilation elements and the need to validate numerical models for the elements being studied specifically [38]. In the cited work, the limited scope of application of $k - \varepsilon$ models in the study of flows in three-dimensional bends is noted, and the acceptable accuracy is observed for $Re < \sim 1 \cdot 10^5$. In this study, the use of the “standard” $k - \varepsilon$ model with “enhanced wall treatments” (two-layer concept with automatic switching (crosslinking) based on the dimensionless distance value y^+) for two-dimensional nodes from elbows is based on detailed preliminary studies and model validation [37, 39] and, in addition, fits into the previously specified range ($Re \sim 5.9 \cdot 10^4$) [38]. As previously, here the first-order upwind discretization was used for validation, and convergence was assessed by achieving absolute residuals for all equations of less than $1 \cdot 10^{-10}$ and maintaining the control parameter constant over more than 100 iterations. The control parameter chosen was the mass-averaged total pressure at the channel outlet, which characterizes the overall resistance and its constancy. During the verification process, a “grid dependence” study had been conducted for each problem by sequentially refining the computational grid. At the first stage, refinement had been performed over the entire computational domain, until a dimensionless number y^+ reached ~ 30 , and further the layers along all solid boundaries decreased until y^+ reached ~ 1 [40]. The grid

solution had been accepted as final if the difference in the local drag coefficient (LDC) values between the last and penultimate grids had not exceeded 1 %. The parameters of the initial and final grids for several problems are given in Table 1.

Table 1. Computational grid parameters.

Problem	Initial grid parameters			Final grid parameters		
	Number of cells, thousand pcs.	Max. cell size, mm	Max. cell size, mm	Number of cells, thousand pcs.	Max. cell size, mm	Max. cell size, mm
Single elbow ($b_2/b_1 = 1.5$)	~8	12.5	12.5	~3029	1.56	$4.9 \cdot 10^{-2}$
U-shaped elbow ($b_2/b_1 = 2.0$)	~5.2	12.5	12.5	~2413	1.56	$4.9 \cdot 10^{-2}$
Z- shaped elbow ($b_2/b_1 = 2.0$)	~5.4	12.5	12.5	~2472	1.56	$4.9 \cdot 10^{-2}$

The LDC values had been determined using the methods described in previous works [33, 39]. The VZ outlines had been determined by the outermost current line separating the main flow from the circulation flow inside the VZ.

3. Results and Discussion

3.1. DVM Study

Figs. 3–6 present the calculation results for $b_1 = 0.1$ m; $b_2 = 0.1$ m; $v_0 = 1$ m/s; $d_1 = 0.4$ m; $d_2 = 0.8$ m.

Figs. 4 and 5 show the relationship between the maximum width of the separation (vortex) zone δ (Fig. 3) and average velocity in the section 1–1 (Fig. 1a) on the discretization step h . Analysis of these graphs show that the step $h = 0.00125$ m is sufficient. For the discretization steps of $h = 0.0125$ m; $h = 0.0025$ m, $h = 0.00125$ m, $h = 0.000625$ m, the separation lines having the free vortices are practically overlapped. The value of the average vertical component of velocity in section 1–1 is equal to $v_{av}/v_0 = 0.99678$ and differs by 0.18 % from the value obtained with the step $h = 0.0025$ m. The δ value in a similar comparison differs by 0.47 %.

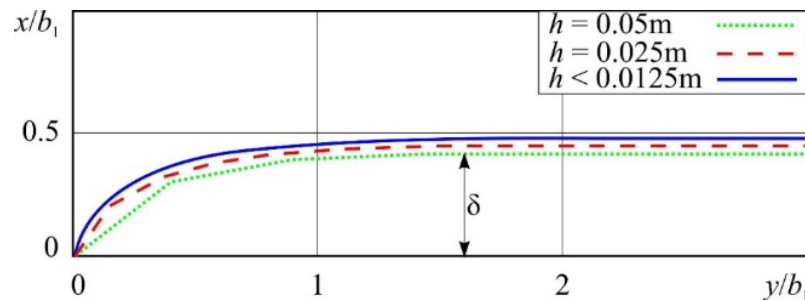


Figure 3. Separation streamlines.

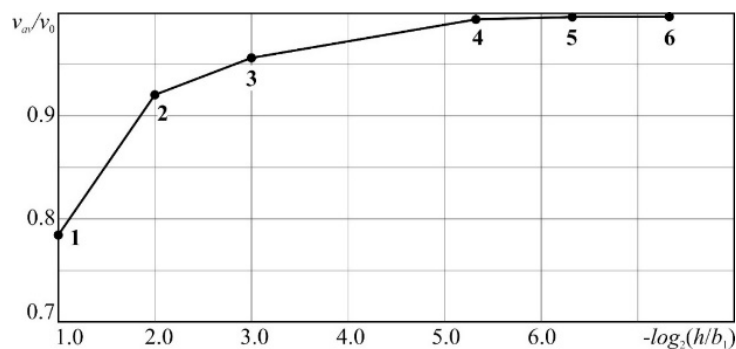


Figure 4. Change in average velocity in section 1-1 of the duct: 1 – $h = 0.05$ m, 90 boundary elements (BE); 2 – $h = 0.025$ m, 178 BE; 3 – $h = 0.0125$ m, 354 BE; 4 – $h = 0.0025$ m, 1762 BE; 5 – $h = 0.00125$ m, 3522 BE; 6 – $h = 0.000625$ m, 7042 BE.

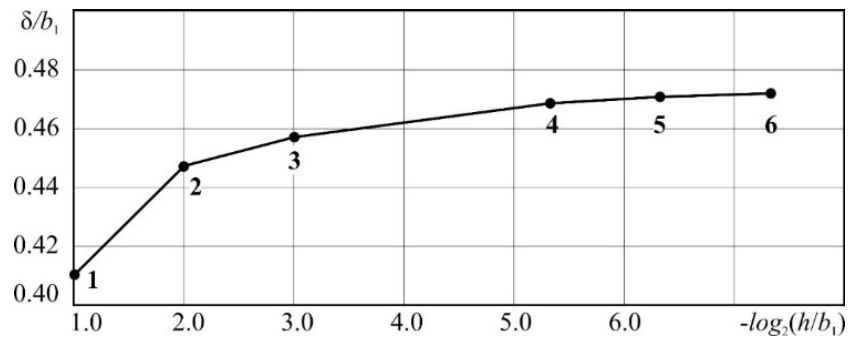


Figure 5. Change in the VZ width.

Fig. 6 shows the VZ outline formed from the sharp edge A (Fig. 1a). The experimental data are taken from [41], which, although they were obtained long ago, have not lost their relevance, since there are no newer ones. Moreover, these data confirm their validity, since many newly obtained independent results from various analytical and numerical methods agree with each other and with the cited experimental data. Calculation using the conformal mapping method (CMM) had been performed using the Zhukovsky–Roshko flow model [42] and using smoothed particle hydrodynamics (SPH) method [43]. Note that the results obtained using the DVM₈ method (the separation streamline had been calculated up to a cross-section distance of $d_2 = 8b_1$ from the sharp edge A) and the CMM and SPH method are almost overlapped. Up to two calibers (caliber is b_1), the DVM calculations agree with the experiment. The VZ outline calculated using CFD methods [39] is significantly smaller. It should be noted that [42] suggests that the VZ outline constructed using CFD more closely matches the physical representation, while the ideal incompressible fluid flow model does not adequately describe the process. However, the previous visualization of similar flows [4] shows that a clear VZ outline is visible only at the initial stage. Further, the VZ boundary becomes blurred due to the high turbulence of the flow, and the point of flow attachment to the solid boundary is not visible.

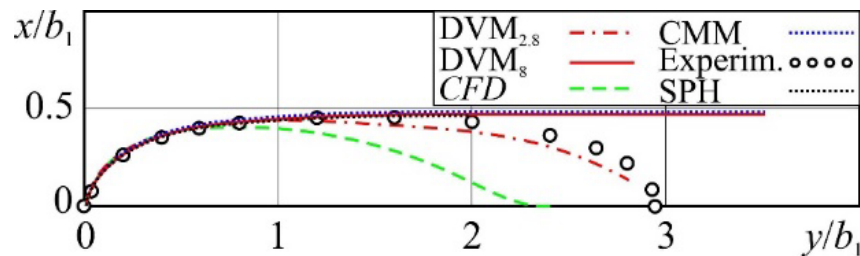


Figure 4. Separation line (VZ outline) constructed using different methods for $b_2 = b_1$.

Fig. 7 shows streamlines for the case when the separation streamline (free vortices) is constructed before the exhaust section (DVM₈) for different channel width ratios. Also shown here (Fig. 7a) is a dotted line of possible profiling during a turn, obtained by parallel horizontal shift of the VZ boundary by δ . The maximum VZ width increases as the width b_2 increases relative to b_1 .

Note that when limiting the calculation length of the separation streamline (free vortices) to a section of $2.8b_2/b_1$ from the sharp edge A , a flow pattern more similar to the experimental one is obtained (Figs. 6 and 8). In this case, shaping does not require increasing the dimensions of the fitting element, and a shaping insert can be inserted along the determined VZ boundaries. Note that the plots of δ versus channel width ratio in Figs. 7b and 8b coincide qualitatively and quantitatively, so, the maximum VZ width almost does not depend on the calculation length.

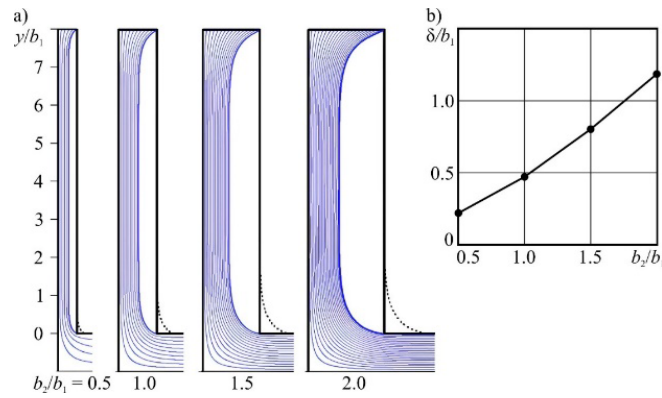


Figure 5. Streamlines for different width ratios $b_2/b_1 = 0.5; 1; 1.5; 2.0$ (a) and the relationship between the maximum VZ width and the channel width ratio (b).

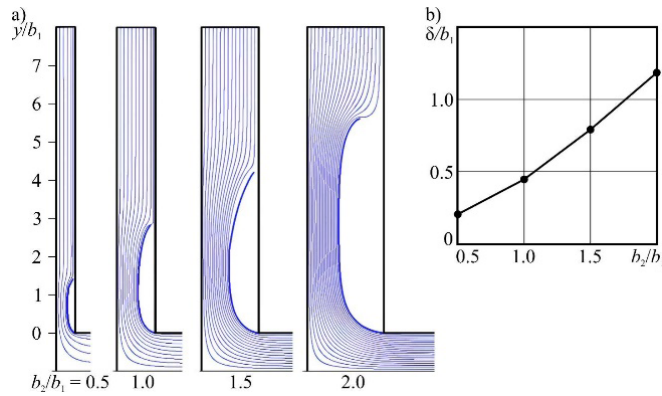


Figure 6. DVM calculation of streamlines for various distances to the section of separation streamline up to $2.8 b_2/b_1$ ($b_2/b_1 = 0.5; 1; 1.5; 2.0$) (a) and the relationship between the maximum VZ width and the channel width ratio (b).

During a turn, VZ arises as a result of flow separation not only from the sharp edge but also from the smooth surface near angle B (Fig. 1a). To simulate such separation, the discrete model shown in Fig. 8 should be used without placing vortices symmetrical with respect to the x -axis. Here, at some point S , where the attached vortex is located, a free vortex appears at a distance h from S . A free vortex sheet is constructed along the streamline, starting from this free vortex. The final arrangement of the free vortices is determined iteratively. Accordingly, the resulting free vortex sheet determines the VZ outline.

The calculation ratios in this case have the following form:

The influence of all vortices on the point $x(x_1, x_2)$ along the direction $n = \{n_1, n_2\}$ is determined by the sum:

$$v_n(x) = \sum_{q=1}^N G(x, \xi^q) \Gamma(\xi^q) + \gamma_A \sum_{k=1}^{N_A} G(x, \zeta_A^k) + \gamma_S \sum_{k=1}^{N_S} G(x, \zeta_S^k), \quad (2)$$

where ζ_S^k is the location of free vortices descending from point S , N_S is their number (fig.9). The location of point S had been determined by a computational experiment. The point S had been moved horizontally from angle B until the shape of the resulting VZ ceased to change significantly. Point S had been located at a distance h from the attached vortex. The experiments had shown that this point could not be placed within the vortex itself, since, due to errors and the discrete nature of the model, the free streamline could extend beyond the flow boundary into the outer region. The circulation γ_S is equal to the circulation of the vortex located on the boundary, above which point S is located.

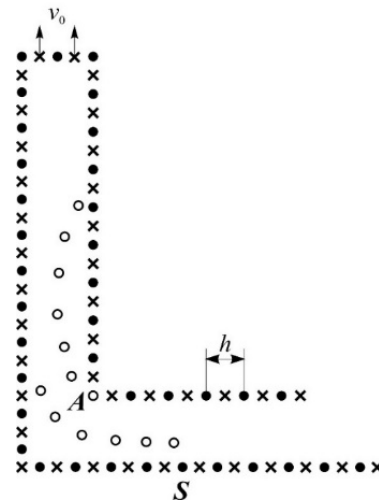


Figure 7. The discrete elbow model without using symmetric vortices.

The flow pattern for the considered case is shown in Fig. 10. The figure also shows VZ boundaries in the bend constructed using CFD methods [44]. It can be seen that the vortex flow region constructed using DVM significantly exceeds its outline. Note that the VZ outline determined from sharp edge A is almost identical to the case of the absence of VZ forming from point S .

VZ outline for multiple elbows can be determined using DVM. For example, Figs. 11 and 12 show the VZ outlines for a Z-shaped and U-shaped elbows. These figures show that VZs can merge at a small distance between bends.

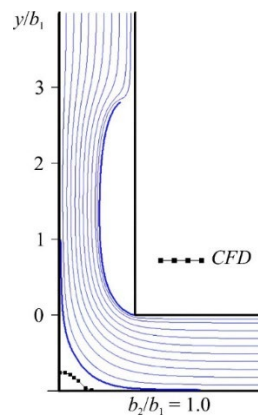


Figure 8. An elbow with two vortex zones.

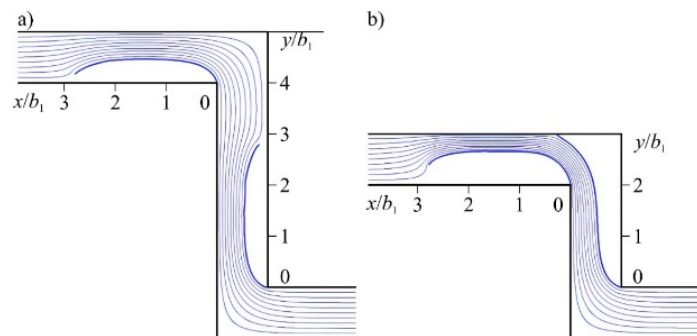


Figure 9. A node with a Z-shaped elbow with the following length of channel between single elbows: a) $d_2 = 4b_1$; b) $d_2 = 2b_1$.

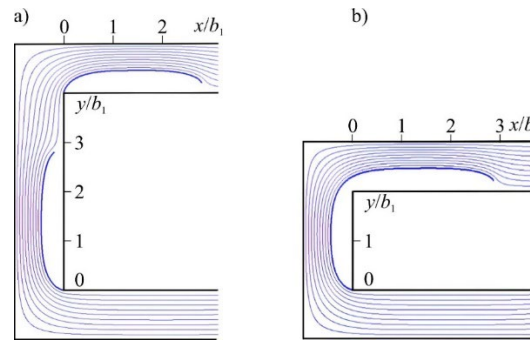


Figure 10. A node with a U-shaped elbow with the following length of channel between single elbows: a) $d_2 = 4b_1$; b) $d_2 = 2b_1$.

3.2. CFD Calculations

CFD methods make it possible to construct not only velocity field and streamlines but also the fields of other hydrodynamic parameters – pressure, turbulence, etc. The calculated pressure fields enable determining the LDC values. For the considered nodes and their dimensions, the LDC values are known from the previous experimental [34] and numerical [33, 39] studies. The available data made it possible to validate the results obtained in this numerical experiment. Fig. 13 shows (“CFD”) the relationship between LDC values (calculated by CFD) as a function of the relative channel width in the elbow b_2/b_1 after a turn.

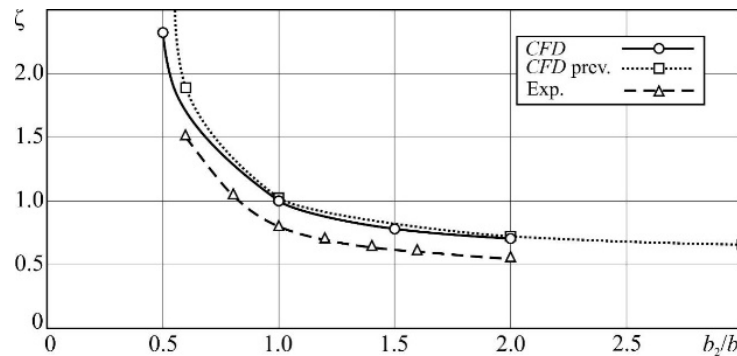


Figure 11. LDC values ζ as a function of the relative channel width in the elbow b_2/b_1 after a turn for a current “CFD”, previous “CFD prev.” numerical and experimental “Exp.” studies.

The Fig. 13 also shows the relationship between ζ and b_2/b_1 obtained experimentally (“Exp.”) [34] and numerically by the authors in the previous work (“CFD prev.”) [39]. In this study, a similar dependence was determined for partially different values of b_2/b_1 . It can be seen that the results are in good coincidence with each other, the LCD values obtained in this work have the same trend and differ from the previously obtained data by no more than 1 %. The difference from the experimental data is about 20 % (as before). Given that when comparing the results of studies conducted by different methods, quite large deviations (over 40 %) are often observed, many researchers [45, 46] consider a deviation level of 15 % to be a good approximation. Therefore, in our case, the level of agreement with the experimental data [34] is not good but satisfactory, and it demonstrates the validity of the model used.

Fig. 14 shows VZ outlines obtained by numerical calculation using CFD, compared with data obtained using discrete vertices method DVM_{2.8}.

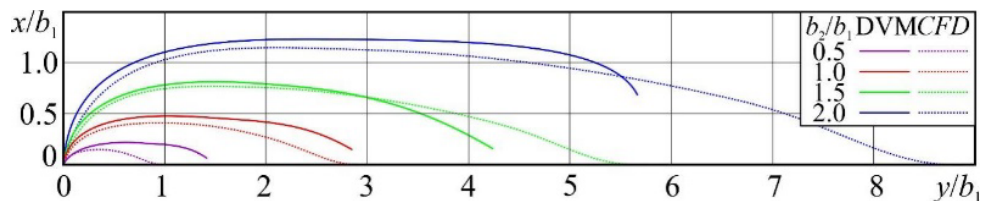


Figure 12. VZ outlines.

It can be seen that for $b_2/b_1 \geq 1.0$, VZ outlines, constructed using two methods, are relatively equal and have the same type of dependence on b_2/b_1 up to the maximum width coordinate. Further, the nature

of the VZ width (δ) dependence changes. VZ width δ , calculated by CFD method, shows a more smooth and gradual change than that calculated by DVM.

Figs. 15 and 16 show VZ outlines in Z- and U- shaped elbows. VZs, constructed by DVM and VZ for a single elbow, are also shown here for comparison.

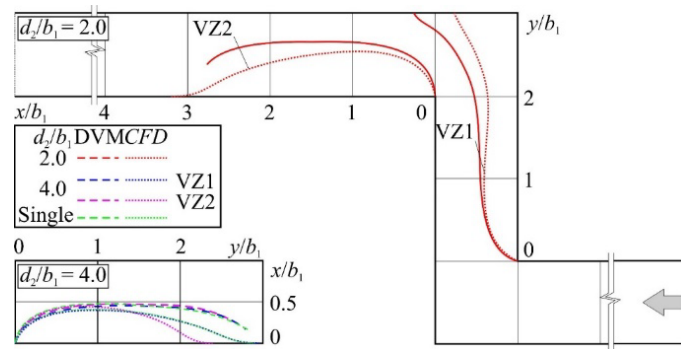


Figure 13. VZ outlines in a Z-shaped elbow.

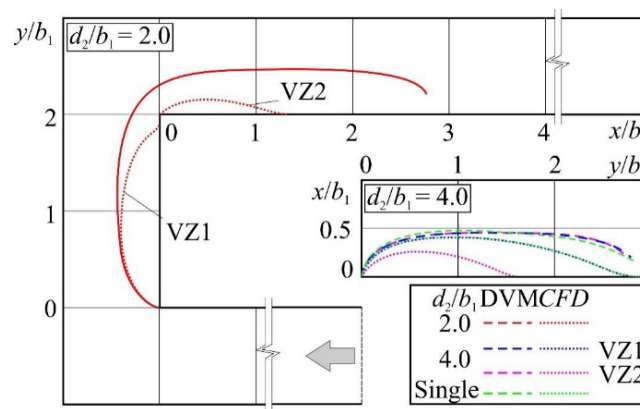


Figure 14. VZ outlines in a U-shaped elbow.

At the nodes, as previously in the single elbow, similarity in outlines is observed up to the point of maximum width, after which a divergence begins. Furthermore, for the short variant ($d_2/b_1 = 2$) of the U-shaped elbow node, a significant difference in the VZ character is observed. DVM calculation shows that VZ1, breaking away from the sharp edge of the first elbow, does not have time to close onto the channel wall and merges with the second VZ2 into a single VZ. At the same time, the VZ outlines found by the CFD method are separate. Analyzing the behavior of the VZ outlines as the distance increases to $d_2/b_1 = 4$, it can be noted that in the DVM calculation, the VZ1 and VZ2 outlines and for the single elbow practically merge, indicating the absence of mutual influence between the elbows at this distance. In the CFD calculations, the VZ1 outlines and for the single elbow merge, while the VZ2 outline differs significantly. This indicates no upstream influence but a significant downstream influence from one elbow to the other.

4. Conclusions

For the first time, a mathematical flow model has been developed using the DVM for air duct elements in the form of elbows, nodes, and their combinations. The VZ outlines for duct elbows calculated using DVM demonstrate sufficient accuracy and allows one to obtain the VZ outlines of much faster than, for example, using CFD methods. Convergence of the developed mathematical model with increasing number of attached vortices was established. The calculated and experimental VZ outlines agree satisfactorily. There are some differences for small distance nodes. The developed mathematical model and software make it possible to study VZ outlines in duct elbow-shaped elements, taking into account VZ merging and flow separation from a smooth surface. The relationship between maximum VZ width and the duct channel width ratio were obtained. CFD methods were used to construct the VZ outlines and their dependence on the distance between single elbows in a node, as well as their convergence with the DVM results in the first part of the VZ outlines.

Future research could include DVM modeling to establish the relationship between the VZ size in an elbow and the elbow angle; VZ outlines construction for a sudden flow expansion, in tees and other fitting components; calculation of LDC as a function of VZ dimensions. It is important to further explore methods

for studying VZ outlines, including experimental ones, in order to determine VZ outlines along its entire length and to find models that most adequately describe them. It is of interest to determine the LDC of shaped fitting components based on the determined outlines and to compare the obtained values for the corresponding shaped components based on VZ modeling results obtained using other methods.

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