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Characteristics of flow in the unit “elbow - supply opening”

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Abstract. The existing literature provides formulas for standard air distribution calculations. However, the calculation coefficients are obtained experimentally for the ideal conditions of connecting air terminal devices. distributors to ducts. In practice, the design of the connection depends on the complexity of the ductwork in the building. This may affect the jet flow conditions and the air circulation in the room. The article considers the flow in the unit “elbow - supply opening” of the ventilation system. The aim of the study is to determine the dependence of the geometric and kinematic characteristics of the jet on the distance between the elbow and the supply opening. The problem is solved numerically in a two-dimensional formulation using the Fluent software package. A combination of the standard k-ε model and standard near-wall functions is used for the solution. As a result, the distribution of velocity and pressure at the outlet of the air terminal device is obtained. The dependences of the variation of the axis slope and axial velocity of the jet, as well as the kinematic coefficient of the supply opening on the distance between the elbow and the supply opening are constructed. The significant influence of the distance between the elbow and the supply opening in the unit on the kinematic characteristics of the jet is shown. The obtained dependencies should be taken into account when calculating air distribution. At distances between the elbow and the supply opening of more than 5 gauges, the characteristics of the jet tend to the characteristics of the jet flowing from the end opening.

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1. *Introduction*

The air quality in the working zone of the room and the energy consumption for the equipment operation determine the efficiency of the ventilation and air conditioning system. The existing methods of calculation of the air distribution in the room determine the main characteristics of the jet flowing from the supply opening, taking into account the influence of geometric characteristics of the grille through the known values of the kinematic (m) and thermal (n) coefficients. However, almost all coefficients m and n from the reference literature were determined experimentally with an ideal connection of the supply air device (AD) – at the end of a straight duct at a distance of at least 3 gauge with an equalizer or 20 gauge without it[1]. In practice, the specific design of the connection of the supply grille to the duct depends on technological necessity and the ductwork's tracing. ADs are often located on the side wall of the duct or at the end but immediately behind the 90° elbow. In this case, the distance from the elbow to the supply AD can be very small, which significantly changes the flow conditions and, therefore, the kinematic characteristics of the supply jet, which, in turn, results in a change in the air distribution in the room.

The parameters of supply jets flowing from different kinds of openings have been investigated for quite a long time. The analytical relationship between the axial velocity, the distance from the supply opening, and the distribution of the longitudinal velocity component in the cross-sections of the jet were obtained in [1, 2]. In [3], hot-wire anemometers and static pressure probes were used to experimentally obtain and generalize data on the distribution of static pressure and velocity, both axial and in the cross-sections of the jet, and in [4], shadowgraph technique was used. Nowadays, jets are constantly investigated using modern and detailed experimental methods. Particle image velocimetry (PIV) was used to determine the axial velocity and turbulence characteristics of the jet as it moved away from the supply opening [5, 6]. The numerical methods for such investigations are widely used. The influence of initial profiles of velocity and turbulence parameters on supply jet characteristics was studied in [7]. The obtained results were proposed to be used in the design of supply ADs. Studies [8, 9] were aimed at controlling the velocity profile of supply jets using screens.

Fewer works consider the parameters of the jet flowing at a non-frontal air supply. Obviously, with such air supply, the profile of the kinematic parameters at the outlet will be significantly irregular and asymmetric. This, in turn, results in differences in the kinematic characteristics of the jet development. The flows from openings of different geometry were studied in [1]. It was shown that the jet profile strongly depended on the velocity profile at the outlet. The length of the initial section changed, as well as the attenuation of the axial velocity. In [10], a flow from a slotted opening located in a duct wall was considered in the presence of a transit flow passing in the channel. This flow significantly distorted the profiles of the kinematic characteristics of the jet at the outlet. The distribution fields of longitudinal and transverse velocity and the static pressure fields, as well as velocity irregularity, were obtained by numerical method, and it was established that the static pressure was not equal to 0. These factors must be taken into account when calculating jet momentum and its kinematic and thermal characteristics. In [11, 12], the results of numerical studies of the flow from the last and middle lateral openings were given, and the relationship between the jet inclination angle and the relative flow velocity of the outflowing air (for the middle opening) and the relative size of the opening (for the last opening) were numerically found. A significant irregularity of velocity and pressure profile in the opening was shown, which apparently led to changes in the kinematic coefficient and the coefficient in the Reichardt exponential formula for the velocity profile in the cross-sections of the jet.

The studies of outflow from real air distribution devices are often conducted numerically [13, 14] and experimentally [15, 16], or both [17, 18], and may refer to very complex problems, such as ventilation in case of a fire in buildings [19] or the implementation of information modeling [20]. Fewer studies consider the influence of different connection options. In [21], numerical and experimental studies of the velocity distribution in the plenum box and at the AD outlet were carried out for the top and side of the plenum box. It was shown that, despite the presence of the plenum, there was a significant irregularity of velocity at the outlet of the AD, and as a consequence, the outflowing jet is deformed. The characteristics of jets flowing out of near-wall ADs were experimentally studied in [22], the velocity profiles and velocity distribution along the length were determined, taking into account the overlap on impermeable surfaces. The influence of the presence of impermeable surfaces on the jet characteristics was shown. Air distribution in a room using ceiling-mounted ADs was considered in [23], and the velocity fields were found experimentally and numerically. Using attaching to vertical surfaces – walls [24] and columns [25] – new ways of ventilation in various rooms were developed [26–28]. Although the parameters of supply jets are studied in the cited works, in most cases, the flow from end openings is considered, and no attention is paid to the change of jet parameters at the non-frontal air supply. For cases of individual ventilation, air distribution through side openings in channels is typically used, for example, in case of the underfloor air distribution system [29]. However, even in such works, the way air inflows into supply openings is often not taken into account.

In [30–32], the characteristics of a jet flowing from the opening, which is located immediately behind the 45° and 90° elbow, were considered. The influence of the distance between the elbow and the supply opening on the distribution of velocity and pressure components was studied at the supply opening cut, on the slope of the outflowing jet, and on the distribution of axial velocity. It was shown that the considered influence was rather significant, and a vortex zone was formed at some distances. The obtained results showed that the close location of elbows at 45° and 90° significantly affected the jet characteristics. In this

[1] European Committee for Standardization (CEN). Ventilation for buildings – Air terminal devices – Aerodynamic testing and rating for mixed flow application. EN 12238:2001. Brussels, 2001. 36 p.

case, a “non-frontal” air supply to AD was realized, which distorted the kinematic characteristics of the jet and resulted in their difference from the characteristics of the jet flowing from the end opening. Such flows remain practically unexplored.

It should be noted that in [31], the default values for turbulent parameters k = 1, ε = 1 were chosen for modeling free boundaries. Further numerical studies have shown that when air flows through the free boundary with very low velocities, the values of the turbulent characteristics are also close to zero, which may affect the calculation results. Therefore, numerical calculations are carried out with minimum values of k and ε equal to 0.

The presence of an elbow or other perturbing element leads to the distortion of flow parameters within the channel. The extent, to which this distortion affects the flow characteristics at the supply opening, depends on the distance l between the perturbing element and the supply opening. The first step to gaining a comprehensive understanding of this process and eliminating the influence of the air distribution system design is to investigate the elbow’s effect on the characteristics of the jet emerging from a free opening. Thus, this article aims to determine how the distance between the elbow and the supply opening influences the geometric and kinematic properties of the jet.

The following tasks are undertaken to achieve set aim:

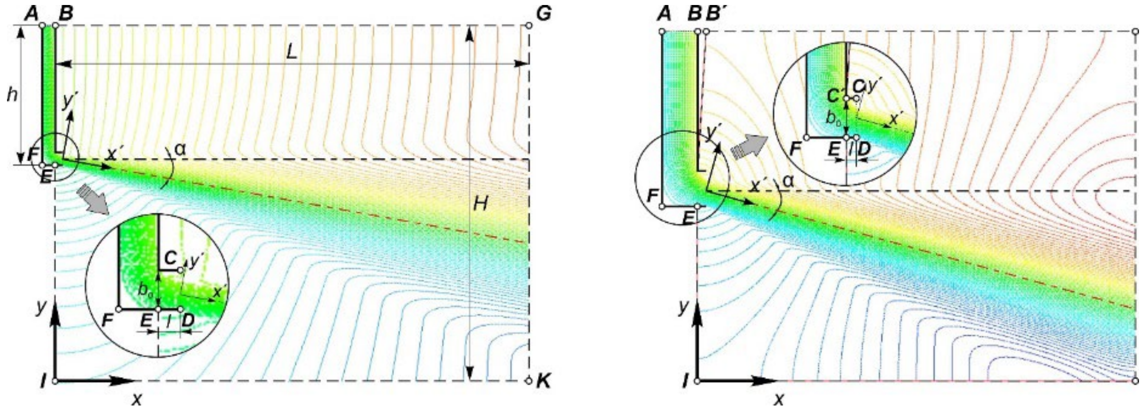
- to develop numerical models of the “elbow - supply opening” unit and conduct a mesh convergence study;
- to determine the pressure distribution and velocity components at the supply opening cross-section;
- to analyze the dependence of the jet parameters on the distance between the supply opening and the elbow.

2. Materials and Methods

The problem has been solved numerically in two-dimensional formulation using the computational fluid dynamics (CFD) software package. The geometry of the investigated area is presented in Fig. 1: b_0 = 0.1 m is the width of the duct; L = 2.7 m is the width of the area; H = 2 m is the height of the area, is the distance from the elbow to the cross-section of the supply opening***,*** which is measured relative to the ***BC'*** wall. The model with following different distances between the supply opening and the elbow were considered: l, m $\left(l/b_0\right)$ = 0.05 (0.5); 0.1 (1.0); 0.15 (1.5); 0.2 (2.0); 0.25 (2.5); 0.3 (3.0); 0.5 (5.0); 0.6 (6.0); 0.7 (7.0); 0.8 (8.0) and 3.5 (35). The velocity at the supply boundary into the channel ***AB*** is given by a uniform profile with v_0 = 3 m/s. At the remote boundaries of the areas ***BG***, ***GK***, ***KI***, and ***IE,*** the pressure inlet boundary condition (BC) is used with set values of overpressure equal to zero and turbulent characteristics k and ε equal to 0. Impermeable boundaries ***AF***, ***FD***, and ***BC'C*** are simulated by means of wall BC, where the conditions of non-flow and non-slip are accepted.

The verification and validation of the problem of a flow in supply opening with elbow unit was carried out in [33]. Different combinations of turbulence models with wall functions were studied. The combinations of standard $k-\varepsilon$ model (SKE) with standard nonequilibrium wall functions (SWF, NEWF) and enhanced wall treatment (EWT); the $k-\varepsilon$ renormalized groups model (RNGKE), standard $k-\omega$ (SKW), $k-\omega$ SST (SSTKW); and the Reynolds stress model (RSM) combined with SWF, NEWF, and EWT was considered. The comparison of experimental and numerical studies with each other has shown that the combination of the SKE and SWF is the most appropriate for the considered problem and will be used further.

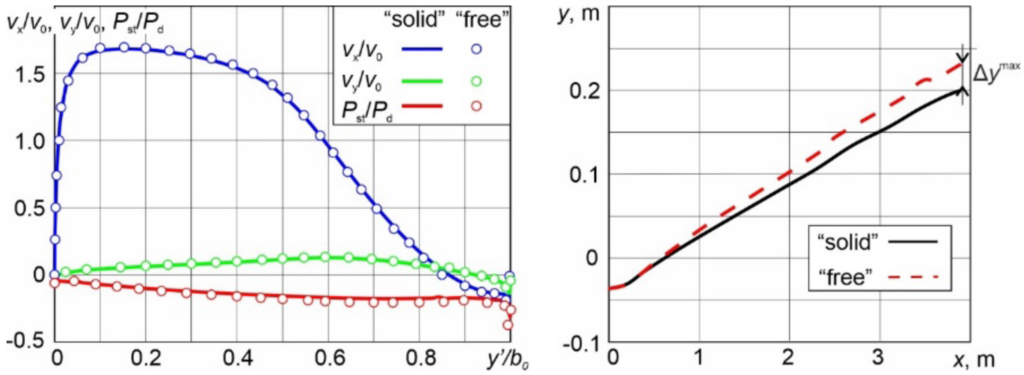
When studying the variant with flow from an opening located at a small distance from the elbow, an additional question arises about the possible influence of the impermeable boundary ***BC'*** (Fig. 1a) on the conditions of airflow to the flowing jet and its further development. Since the problem is solved in a two-dimensional formulation, the flow around the vertical channel (including the ***BC'*** boundary) is impossible, and, accordingly, the flow to the supply will occur differently. To investigate the degree of influence, a test numerical model (free) was created for the distance l/b_0 = 1.5. In this model, a border ***B'C'*** inclined at a small angle was created along the impermeable wall ***BC'***, for which the pressure outlet BC was set, thus simulating the permeable boundary (Fig. 1b), BC on the other boundaries is identical to the original problem (solid).



a) b)

Figure 1. Geometry and streamlines of the investigated flow: a) initial problem (solid); b) problem with permeable boundary *B′C′* (free).

It can be seen that, in the first case, the airflow to the jet from the surrounding space is limited and occurs only through the upper boundary along the impermeable wall. In the second case, air flows into the considered zone perpendicular to all permeable boundaries, which is more physical, but complicates the computer model. However, visually, the streamlines in the main area of jet development differ only slightly. Therefore, the need for such a model can be assessed by the degree of influence on the characteristics under study. For example, it is known from [10] that the jet development is influenced by the flow conditions, namely the distribution of velocity $\left(v_x/v_0,\ v_y/v_0\right)$ and pressure $\left(P_{st}/P_d\right)$ components (Fig. 2a) at the supply opening cut, as well as differences in the shape of the jet axis (Fig. 2b), here v_0 is the mean flow velocity in the channel equal to the velocity at the ***AB*** boundary, v_x, v_y are the longitudinal and transverse velocity components, respectively, $P_d = \rho v_0^2/2$ is the dynamic pressure.



a) b)

Figure 2. Flow characteristics for two problems: a) variation of relative longitudinal, transverse velocity, and static pressure components for straight wall and straight wall with addition of permeable region; b) jet axis for straight wall and straight wall with addition of permeable region.

It can be seen that the distribution of relative velocity and pressure components (Fig. 2a) are different for the considered problems, but the maximum differences are: $\Delta v_x^{\max}$ = 0.9 %, $\Delta v_y^{\max}$ = 1 %, $\Delta P_{st}^{\max}$ = = 3 %. When analyzing the shape of the jet axis, it can be seen that the difference is not significant, and the maximum value is $\Delta y^{\max}$ = 15 % (Fig. 2b).

Thus, the presence of an impermeable boundary, for the case of a small distance from the elbow to the supply opening, leads to some insignificant differences in the jet characteristics during its development. This difference is slightly larger when considering the jet characteristics directly at the outflow. At the same time, it is clear that with increasing distance between the elbow and supply opening, the differences will decrease; therefore, it can be ignored, and the modeling can be carried out according to the solid variant.

When analyzing the velocity profile at a cut of the supply opening, it can be seen that its significant part is occupied by the vortex zone, which is formed when the flow comes off the sharp edge of the elbow and at such a small distance, does not have time to close on the duct wall. This zone leads to peculiarities and deformations of the supply jet development. Therefore, to assess the influence of the distance between the elbow and the supply opening $\left(l/b_0\right)$ on the jet development, the change of parameters at the supply opening cut and along the jet length is investigated when the distance l/b_0 changes from 0.5 to 35.

The profiles of relative longitudinal v_x/v_0 and transverse v_y/v_0 components of velocity and static pressure P_{st}/P_d are investigated at the supply opening cut in comparison with the symmetric profile of the outflow from the end opening without elbow. The presence of a vortex zone at the upper boundary of the region reduces the effective flow cross-section b_{eff}, the upper boundary of which was calculated from the coordinate, where v_{mag} = 0, when going from a negative value to a positive one.

Several quantities will be used to determine the effect of the elbow on the flow. Since the asymmetry of the velocity profile with respect to the channel axis is considered, it is logical to use the flow rates in the upper $\left(L_u\right)$ and lower $\left(L_d\right)$ parts of the channel. The flow rate is the integral of the velocity over the channel width and it represents the area under the velocity profile curve plotted over the channel cross-section. Then, the asymmetry coefficient k_{as} can be defined as the ratio of the difference of flow rates in the upper and lower parts to the total flow rate in this section. The flow rates are determined from the numerical determination of the velocity field:

$$L_u = \sum_{i=N}^{2N-1} v_i \left(\left(y/b\right)_{i+1} - \left(y/b\right)_i \right); \quad L_d = \sum_{i=0}^{N-1} v_i \left(\left(y/b\right)_{i+1} - \left(y/b\right)_i \right).$$

Then, the asymmetry coefficient is

$$k_{as} = \frac{\left(L_u - L_d\right)}{\left(L_u + L_d\right)}. \tag{1}$$

Moreover, in [1], coefficients are used to estimate the irregularity of the velocity profile:

$$\text{Boussinesq} - \beta_0 = \frac{\left(v_0^2\right)_{av}}{v_{0,av}^2}; \tag{2}$$

$$\text{Coriolis} - \alpha_0 = \frac{\left(v_0^3\right)_{av}}{v_{0,av}^3}; \tag{3}$$

$$\text{Velocity fields} - k_0 = \frac{v_{av}}{v_{ax}}, \tag{4}$$

where $v_{av} = \frac{1}{2N} \sum_{i=0}^{2N-1} v_i$ is the average velocity in the section; $\left(v_0^2\right)_{av} = \frac{1}{2N} \sum_{i=0}^{2N-1} v_{0,i}^2$ is the mean square of velocities in the section; $v_{0,av}^2 = \left(\frac{1}{2N} \sum_{i=0}^{2N-1} v_{0,i} \right)^2$ is the square of the mean velocities in the section, $\left(v_0^3\right)_{av} = \frac{1}{2N} \sum_{i=0}^{2N-1} v_{0,i}^3$ is the mean cube of velocities in the section; $v_{0,av}^3 = \left(\frac{1}{2N} \sum_{i=0}^{2N-1} v_{0,i} \right)^3$ is the cube of the mean velocities in the section.

The jet development can be characterized by several values. The variation of these values from that for the jet flowing from a straight channel shows the degree of influence of a nearby elbow. In this work, the inclination angle of the jet axis α is considered; the axial velocity distribution v_{ax}/v_m, the kinematic coefficient m, which is used in the practice of air distribution calculations to describe the jet attenuation. Moreover, the dependences on l/b_0 as the effective width of the supply opening (the width of the opening occupied by the outgoing flow, b_{eff}/b_0), the shape of vortex zones will be defined.

The jet axis is found as the point of maximum value of the velocity modulus. Since the axis is bent at the initial section, for each problem, the main section of the jet is found as a part where the axis is practically straight. The coefficient of variation $CV = \sqrt{(x-\overline{x})^2/(n-1)}$, at this part (where x is the average value of the angle for the sample, and n is the sample size), when determining the average value of the jet angle does not exceed 20 %, and further its angle of inclination α to the geometrical (horizontal) axis passing through the center of the supply opening and counted counterclockwise. The kinematic coefficient m is determined from the results of numerical modeling by the axial velocity distribution:

$$m = \frac{v_{ax}^{mag}}{v_0} \cdot \frac{\sqrt{s}}{\sqrt{b_0}}, \qquad (5)$$

where $s = x \cdot \cos\alpha$ (m) is the distance along the jet axis from the supply opening cut; v_{ax}^{mag} (m/s) is the axial velocity modulus at a distance s.

3. Results and Discussion

The numerical modeling was carried out for models with the distance between the elbow and the supply opening varying in the range l/b_0 = 0.5 ÷ 8.0. The design with the distance l/b_0 = 35 was accepted as a model, in which the influence of the elbow is small. Fig. 3 shows the streamlines for all investigated geometries. Fig. 4a shows the variation of the axis trajectory as a function of distance l/b_0. At distances l/b_0 = 0.5; 1.0; 1.5, it can be seen that the flow cut off from the sharp edge of the elbow is not closed on the channel wall. The resulting area of reduced pressure not only causes circulation of the main flow in the channel but also leads to the ejection of ambient air, drawing it from the outer area inside the supply channel (Fig. 3a–c) and significantly distorts the flow pattern. In addition, it can be seen that for the smallest distances l/b_0 = 0.5 and 1, the inclination angle has a negative value – the jet axis is directed downwards (Fig. 4a). The negative angle of jet inclination is due to the fact that the small size of the elbow does not allow the flow in the channel to fully complete the 90° turn from vertical to horizontal direction. The jet is formed under the influence of the vertical velocity component directed downwards. For distances 1 < l/b_0 ≤ 7, the flow pattern begins to change qualitatively – this elbow length becomes sufficient for the flow to change its direction from vertical to horizontal. At the same time, the impact of the flow against the lower wall of the elbow and insufficient length of the upper wall leads to the opposite effect, and the jet leaves the supply directed upwards (Fig. 3c–i, Fig. 4a). Since the vertical component, in this case, is significantly smaller, the angle of inclination relative to the horizontal is also small (~ 4°, Fig. 4b). It can be seen, that the jet itself visually becomes more symmetrical as l/b_0 increases, and the angle of inclination of the jet axis becomes closer to the horizontal – the geometric axis (Fig. 4a). For l/b_0 > 7, it can be seen that the outlines of the vortex zone cease to change. It is difficult to distinguish such a jet from a jet flowing without the influence of the elbow.

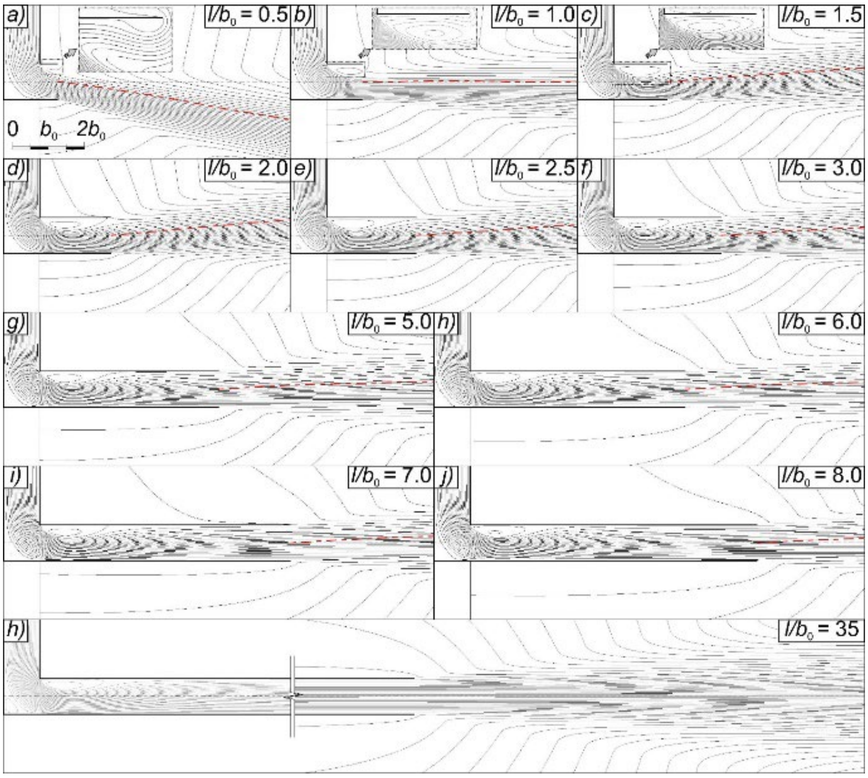


Figure 3. Flow lines for the investigated geometries.

Fig. 4a shows that at l/b_0 = 7, the axis trajectory is not yet horizontal, and the angle of deviation of the axis from the horizontal is small, but greater than 0 (Fig. 4b), and further tends to 0 at l/b_0 = 35. The shape of the axis is almost rectilinear at distances 2 ≤ x/b_0 ≤ 40.

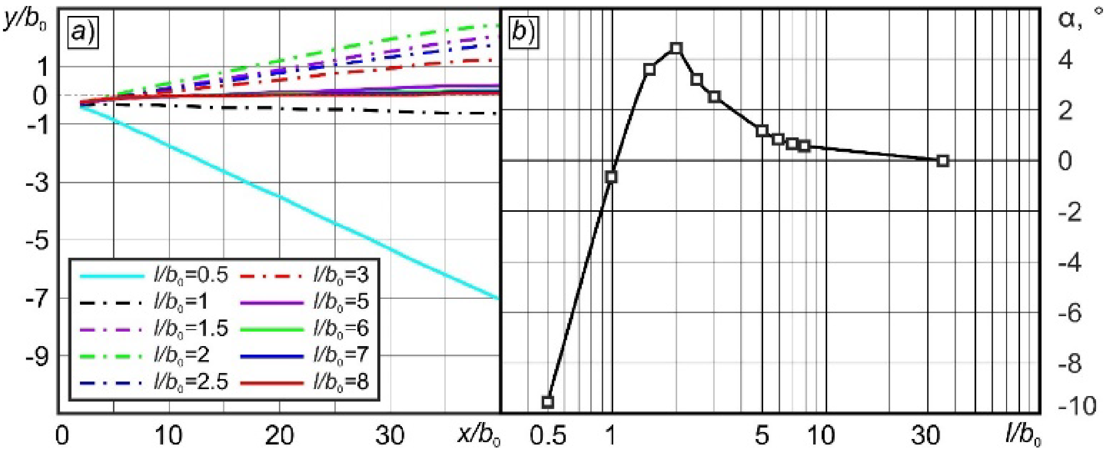


Figure 4. a) flow axis, b) angle of axis deviation from the horizontal.

Fig. 5 shows vortex zones occurring at l/b_0 ≥ 2 at the studied unit (marked as *elbow & supply*). Outlines of vortex zones in a unit are compared with the outlines of the vortex zones occurring in a single elbow (marked as *single elbow*) found analytically using the conformal mapping method and the potential flow theory in [34] (marked as *An. calc.*), experimentally in [35] (marked as *Exp.*), and numerically using CFD methods in [36] (marked as *CFD*). It is possible to confirm the adequacy of the numerical study and further to investigate the influence of closely coupled elbow fittings on the shape of vortex zones (Fig. 5).

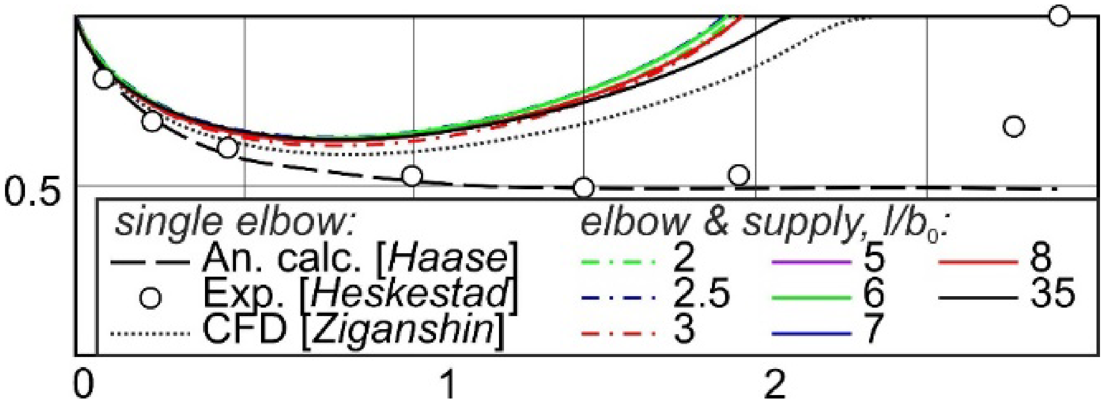


Figure 5. Outlines of vortex zones in an elbow.

It can be seen from Fig. 5, that for l/b_0 ≥ 2, the vortex zones outlines depend weakly and ambiguously on the distance between the elbow and the supply opening, because the elbow is upstream of the supply opening. It can also be noted that the outline of the vortex zone agrees well with other outline studies for a single elbow. Good agreement indicates that there is no upstream influence of the supply opening at distances greater than two gauges.

Next, a more detailed analysis of the effect of the distance from the elbow to the supply opening on velocity (components v_x/v_0, v_y/v_0, and module v_{mag}/v_0) and static pressure $\left(P_{st}/P_d\right)$ at the cut of the supply opening and along the length of the jet is performed.

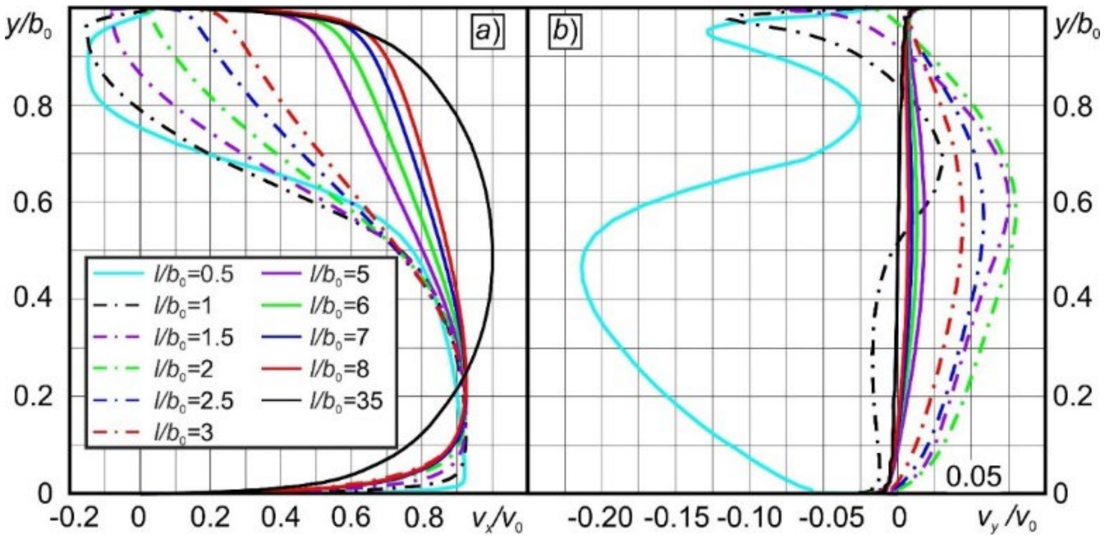


Figure 6. Distribution of components of longitudinal v_x/v_0 (a) and transverse velocity v_y/v_0 (b) of the flow at the supply cut for variation of l / b_0 = 0.5 ÷ 35.

Fig. 6 shows the variation of dimensionless longitudinal v_x/v_0 and transverse v_y/v_0 velocity components in the supply opening cut at different distances from the elbow. It can be seen that for l/b_0 < 8, the longitudinal velocity profiles v_x/v_0 remain irregular, implying that there is an influence of the elbow. For distance l/b_0 = 35, it can be seen that there is no such influence, and the velocity profile is symmetrical about the centerline. The longitudinal components also indicate the presence of a vortex zone – for distances l/b_0 ≤ 1.5, a region with negative values is observed.

The profile of the transverse velocity component in all sections considered is also irregular. However, it is more difficult to judge the size of the vortex zone from these profiles. The profiles at l/b_0 < 1.0, where the region with v_x/v_0 < 0, occupies a large part of the cross-section and practically coincides with the corresponding regions of the longitudinal velocity profiles v_x/v_0, are clearly highlighted. For distances

l/b_0 > 5, the values v_y/v_0 tend to 0, and the jet is equalized. Only a small deviation in the near-wall region, typical for a boundary layer flow, is observed.

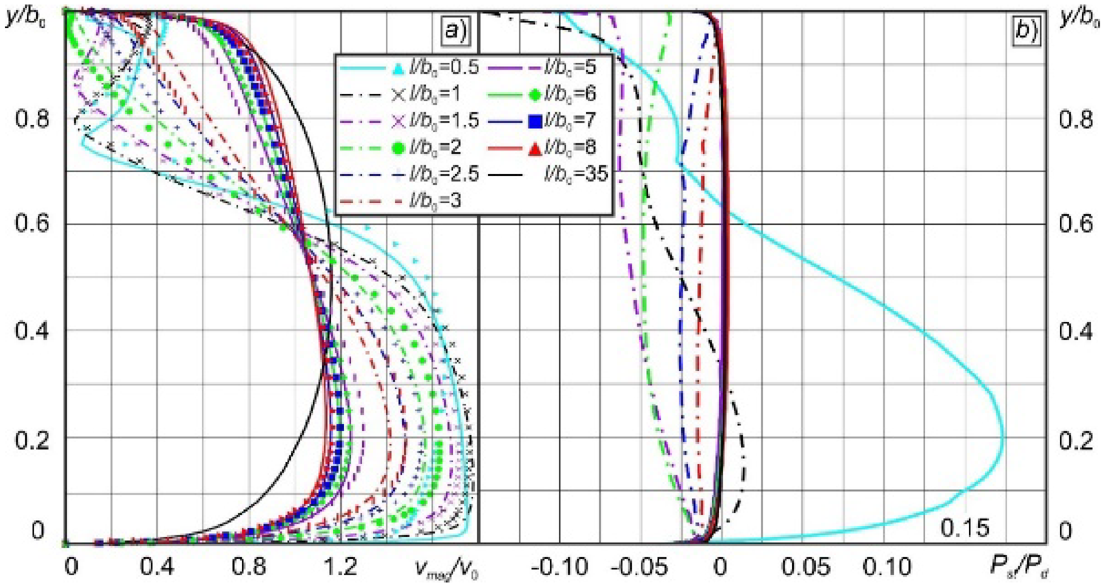


Figure 7. Distribution of relative velocity modulus v_{mag}/v_0 (a) and static pressure P_{st}/P_d (b) at the outflow for distances l/b_0 = 0.5 ÷ 35.

The profiles of the distribution of the relative velocity modulus $\left(v_{mag}/v_0\right)$ (Fig. 7a) show the presence of a vortex zone and demonstrate the influence of the elbow as a perturbing element. This influence can be seen from the analysis of the distribution symmetry of v_{mag}/v_0 relative to the channel axis (y/b_0 = 0.5). In Fig. 7a, the lines show the distribution of v_{mag}/v_0 at the outflow edge for the problems with different distances l/b_0. The icons, in Fig. 7a, show the distribution of v_{mag}/v_0 for one problem with distance l/b_0 = 35, but in the cross-sections of the channel after the elbow. To compare v_{mag}/v_0 in this problem cross-sections are located at the same distances from the outlet l/b_0. When analyzing the flow asymmetry for the cross-section at the outlet (lines in Fig. 7a), a significant asymmetry of the velocity profile is visible for distances l/b_0 ≤ 8. For l/b_0 = 35, the v_{mag}/v_0 profile is symmetric. Comparison of v_{mag}/v_0 distribution in the channel for l/b_0 = 35 (icons in Fig. 7a) shows a similar to v_{mag}/v_0 distribution at the outlet for various l/b_0 (lines in Fig. 7a) character, but slightly differs quantitatively. This comparison indicates that the flow in a long channel (l/b_0 = 35) is similar to a flow at the outlet for corresponding distances l/b_0 and that the influence of the presence of the supply opening is manifested by a decrease in the velocity value by about 4 %. The distribution of the relative static pressure P_{st}/P_d (Fig. 7b), as in [10], shows that, contrary to the usual simplified representation, the static pressure at the outlet is not equal to zero. Static pressure distribution is significantly affected by the flow deformation associated with the presence of the elbow, especially for l/b_0 ≤ 3. When the distance l/b_0 > 6 increases, the static pressure profile becomes symmetric and tends to zero. To quantitatively evaluate the asymmetry of the profile, the asymmetry coefficients k_{as}, Boussinesq β_0, Coriolis α_0, and velocity field k_0 calculated in the supply opening section using formulas (1–4) are used as described earlier (Fig. 8).

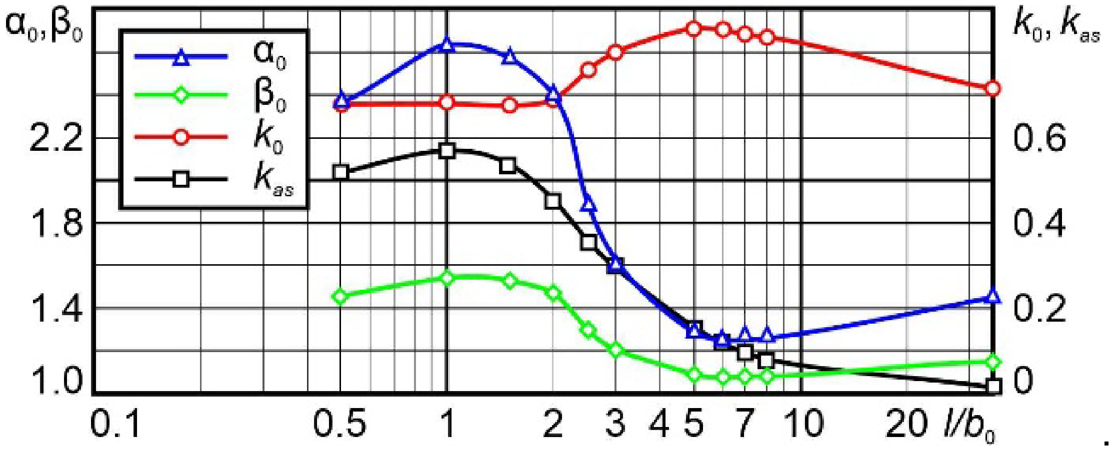


Figure 8. Relationship between the asymmetry coefficients and the distance *l/b₀*.

Here it can be seen that the asymmetry coefficient k_{as} increases with increasing distance l/b_0 from 0.5 to 1, which is due to the increase in flow deformation when the flow is rotated from 0 to 90°. Reaching the maximum of k_{as} ≈ 0.57 at l/b_0 = 1, the asymmetry begins to decrease, and at l/b_0 ≥ 8 it becomes less than 0.08, and at l/b_0 = 35 it is about 0.016, which can apparently be considered an error in numerical modeling. The variation of the Boussinesq coefficients β_0 and Coriolis coefficient α_0 has a similar character, except for the longest distance where the profile becomes more convex. The value of the velocity field coefficient k_0 has an inverse dependence in its formulation. All these coefficients should tend to unity. By the nature of the change of the last three coefficients, it can be seen that although the profile becomes more symmetric, it does not become completely uniform, which can also be seen in Fig. 7a.

The vortex zone formed after the elbow and significant flow irregularity leads to the fact that the jet exit from the supply opening does not occur along the entire cross-section. This jet narrowing leads to a local increase in velocity and errors in the calculations of air distribution devices. Therefore, it is of interest to find the dependence for the effective width of the supply opening on the distance l/b_0. The effective width is determined by the coordinate of the free streamline (outline of vortex zone) crossing the opening cut (Fig. 9).

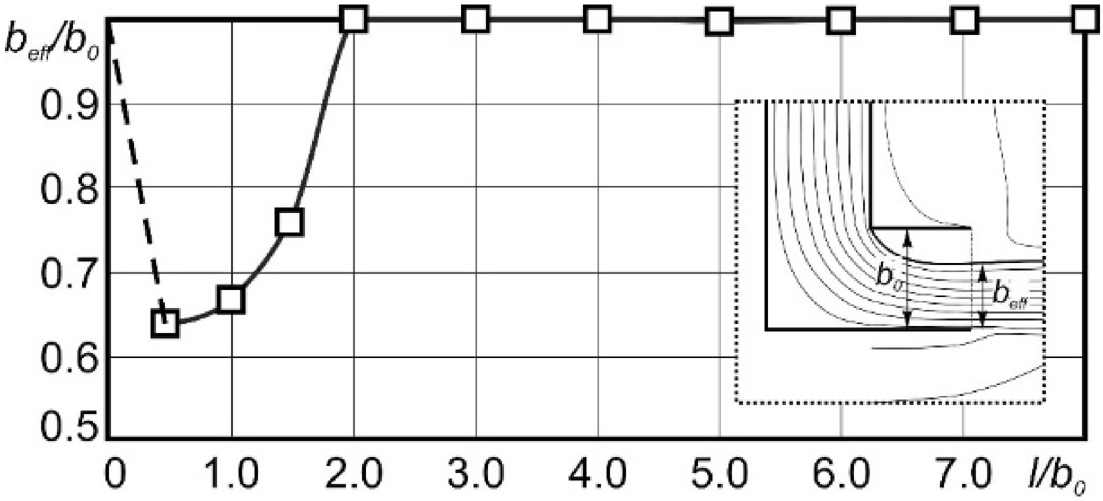


Figure 9. Variation of the effective width of the supply opening (b_{eff}/b_0) for distances l/b_0 = 0.5 ÷ 8.

For l/b_0 = 0.5, a non-minimum value of b_{eff}/b_0 ≈ 0.7 is observed. For small distances to the elbow through the supply opening, the flow in the elbow does not have time to turn completely, and therefore the flow deformation is not maximized. It is clear that at l/b_0 = 0, i.e., when there is no elbow then the case of flow exit through the side end opening is realized. In spite of flow deformation present the effective width b_{eff}/b_0 = 1 [11] (shown by the dashed line). Further, with increasing distance l/b_0, the effective width first decreases, and at l/b_0 = 1 reaches the minimum of b_{eff}/b_0 ≈ 0.6, i.e., the maximum flow deformation and the size of the separation zone exiting through the supply opening are observed. Then, with increasing distance l/b_0, an increasingly smaller part of the vortex zone enters the elbow cross-section of the supply. The effective width begins to increase, and at $l/b_0 \geq 5$ b_{eff}/b_0 it reaches the value of 1, which indicates that the vortex zone ceases to occupy the area of the elbow cross-section of the supply.

The flow deformation introduced by the elbow and affecting the exit conditions will also affect the parameters of the jet flowing out of such an opening. The variation of axial velocity v_{ax}/v_0 along the jet length for cases with different distances l/b_0 is shown in Fig. 10. The variation of axial velocity is plotted using dependence (5) with the kinematic coefficient m = 2.62, which is given in [37] for flat supply openings. The velocity distribution plotted using the relation found analytically in [1] is also given there. The results of CFD and experimental findings of [17] are presented in Fig. 10 (marked with crosses). The mentioned relations are used only for the main section, which tentatively can be taken by the equality v_{ax}/v_0 = 1. It can be seen that at $l/b_0 \geq 2$, the character of the axial velocity change practically coincides with each other and with the data of other authors. This comparison indicates that the elbow does not influence the conditions of flow and jet development. At smaller distances, such influence leads to a difference in the change of axial velocity in the jet. While the character of attenuation remains similar, the velocity values are higher, and the distance l/b_0 is smaller, which is explained by the increase in the maximum velocity at the jet as the deformation increases.

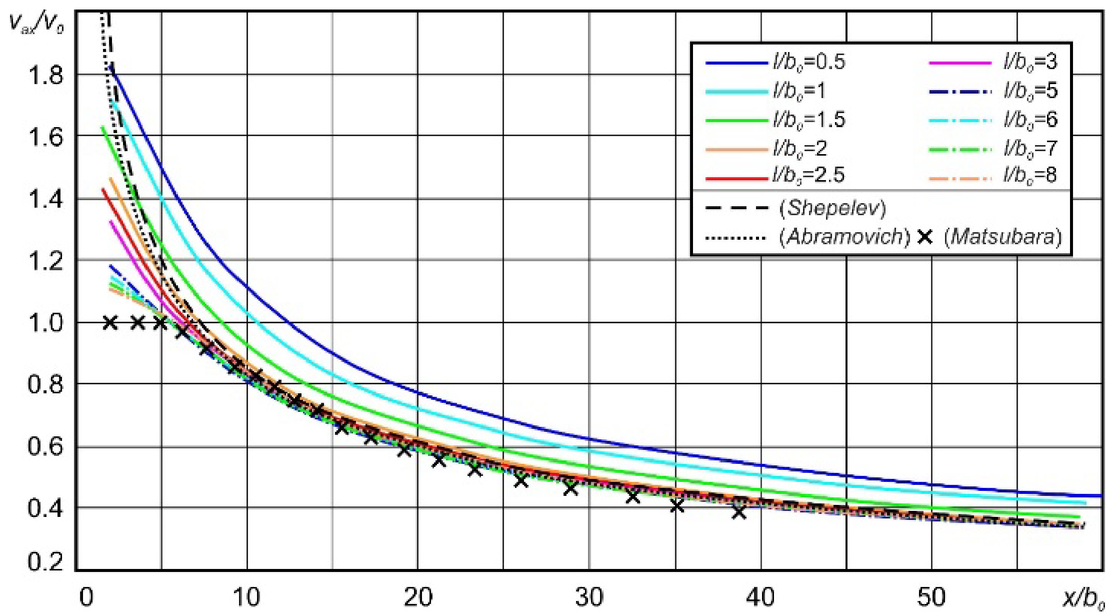


Figure 10. Variation of axial velocity along the jet length for different distances *l/b₀*, and according to [37] (*Shepelev*), [1] (*Abramovich*) and [17] *(Matsubara).*

Taking into account that the character of axial velocity change for small l/b_0 is identical, it is possible to determine the kinematic coefficient m and its dependence on l/b_0 (Fig. 11).

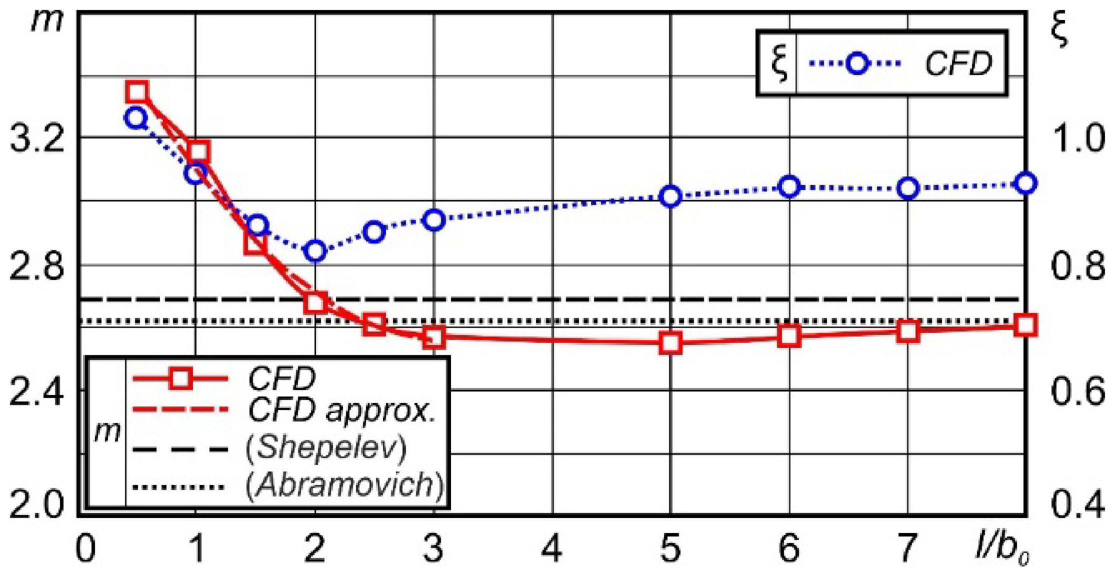


Figure 11. Relationship between m, ξ and *l/b₀*, and the values from [37] (*Shepelev*) and [1] (*Abramovich*).

It can be seen that for l/b_0 > 3 the coefficient m can be considered constant and equal in value to m = 2.56, which is close to the known value m = 2.62 [37]. Accordingly, the influence of the elbow at such distances on the jet development is insignificant. For the range 0.5 ≤ l/b_0 ≤ 3, the dependence of m on l/b_0 is well approximated (R^2 = 0.989) by a polynomial of the second order:

$$m = 0.119 \cdot l/b_0^2 - 0.7418 \cdot l/b_0 + 3.7182.$$

Besides, as stated in [1], the following relationships can be used to determine the change of axial velocity of the jet flowing with irregular initial profile:

$$\frac{v_{ax}^{mag}}{v_0} = \frac{3.8}{\sqrt{2}} \cdot \frac{\xi \cdot \sqrt{\beta_0}}{\sqrt{s/b_0}}, \tag{6}$$

where the Boussinesq coefficient β_0 and an additional coefficient ξ are introduced to account for the irregularity of the profile, which depends on the specific irregularity and the design of the AD and is proposed to be determined empirically. When comparing (6) with (5), it can be seen that the kinematic coefficient in this case will be equal to:

$$m = \frac{3.8}{\sqrt{2}} \cdot \xi \cdot \sqrt{\beta_0}, \text{ and } \xi = \frac{\sqrt{2}}{3.8} \cdot \frac{m}{\sqrt{\beta_0}}.$$

Since, in this case, the opening design is not changed and the irregularity of the profile depends on the distance from the elbow, the relationship between the coefficient ξ and the distance l/b_0 is plotted from the results of the numerical study (Fig. 11). This relationship can also be used to determine the attenuation of the axial velocity of a jet flowing out of a supply opening located after the elbow at the distance l/b_0.

4. Conclusion

1. The presence of the elbow before the supply opening significantly affects the profiles of the longitudinal and transverse velocity and static pressure components at the outlet. At l/b_0 < 5, this influence leads to significant flow deformations and must be taken into account. At l/b_0 > 5, the profiles begin to equalize. However, even at a distance of 8 gauge, the profile remains asymmetrical.
2. At l/b_0 < 5, the flow does not occur over the entire width of the supply opening.

3. At the minimum of the investigated distances l/b_0 = 0.5, the maximum negative angle of jet inclination relative to the geometric axis of the air distributor is observed. In the range of 1 ≤ l/b_0 ≤ 3, the jet inclination angle increases, and further, at a greater distance from the turn, the flow angle is 0.
4. The dependence of the kinematic coefficient m on the distance between the elbow and the supply opening for the range 0.5 ≤ l/b_0 ≤ 8 is plotted.

Thus, the presence of the elbow affects the flow characteristics both at the unit "elbow - supply opening" and at the characteristics of the supply jet. The influence is significant on downstream characteristics – jet and flow parameters at the outlet of the supply opening at the distances l/b_0 < 5. For such units, it is recommended to use the dependences found in this study. At distances l/b_0 > 5, the presence of an elbow before the supply opening can be neglected with accuracy sufficient for design calculations. For the upstream parameters – vortex zone outline, the influence is significant for distances l/b_0 < 2.

As limitations and further prospects for the development of the study, it should be noted that the flows in such units, where several shaped elements are in close proximity to each other, should also be studied from the point of view of aerodynamic resistance, as it is done, for example, in the works on the study of mutual influence of elbows [36, 38, 39]. For such a study, it is possible to use the existing computer models to obtain data on the pressure distribution in the studied units in order to determine the local drag coefficients, the lengths of influence zones, critical distances, and their dependence on the distance between the elbow and the supply opening. It needs experimental validation to obtain the design dependencies [40].

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