NUMERICAL SIMULATION OF AIR CURRENTS AT THE INLET TO SLOT LEAKS OF VENTILATION SHELTERS

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A mathematical model, computational algorithm, and computer program for calculating the vortical air flows in the slot leak of ventilation leaks equipped with thin baffle plates arranged randomly in space are developed on the basis of the method of discrete vortices. The laws governing the variation in the characteristics of detached flows at the inlet to the slot leak of the baffle plate are discovered. The computed values are compared to experimental data and calculations performed by means of other methods.

Keywords: method of discrete vortices, ventilation shelter, leak, baffle plate

INTRODUCTION

Entry of air through a leak is among the factors that tend to increase the power capacity of ventilation shelters. The greater the area of the leak, the greater must be the power of the ventilator motor responsible for creating the required rarefaction inside the shelter and, correspondingly, the speed of air through the leak, thus hindering entrainment of dust into the surrounding space. Because of technological reasons, it is not always possible to achieve a completely airtight shelter. For example, leaks are needed to allow for passage of a conveyor belt. The question arises, how can the volume of air that enters through a leak be reduced without reducing the area of the leak. One way of achieving this is by increasing the hydraulic resistance of the leak by equipping it with thin baffle plates. Detachment of flow from the sharp corners of the baffle plates promotes the appearance of vortical regions, where the energy of the intake flow is lost. Moreover, the detached airstream reduces the area of the effective intake through the leak. Thus, aerodynamic shielding of a leak by means of thin baffle plates makes it possible to reduce harmful inflow of air through the use of the effect of airstream separation. It is therefore of scientific and practical interest to investigate detached air currents in the most widely employed types of slot leaks of ventilation shelters [1, 2] equipped with baffle plates.

Calculations of a detached current with the use of the Zhukovskii method at the inlet to a slot leak provided with baffle plates (Fig. 1) mounted in the wall of the casing were performed in [1]. The laws governing the variation of the compression coefficient across the slot with different ratios of the length of the baffle plate to the width of the slot were also determined in this study. It was suggested that the flow is potential and that the velocity is constant on the free flow line. The flow boundary has a simplified form (cf. Fig. 1*a*) and, correspondingly, the geometry of the shelter is not taken into account. Significant difficulties arises when attempting to solve the problem for several types of shelters. It is not possible to calculate the flow between the free current line and the baffle plate within the framework of this model.

Separation of flow from the edges of a round tube with flanges (Fig. 2) was studied in [4] on the basis of the method of discrete annular vortices. The influence of the baffle plate and the inflow airstream outflowing from the sides of the baffle plate on the Coriolis coefficient at the inlet opening of

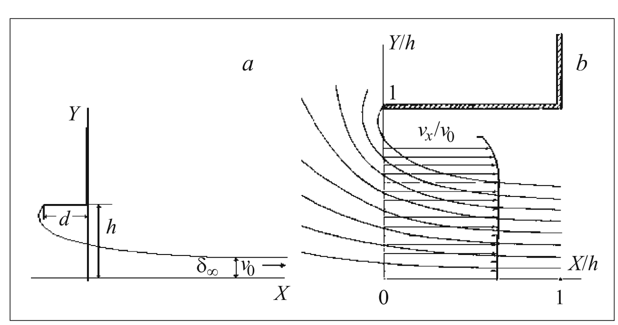

Fig. 1. Calculation of potential flow at inlet to a slot leak. *a*) boundaries of flow region; *b*) profile of horizontal component of velocity and current line.

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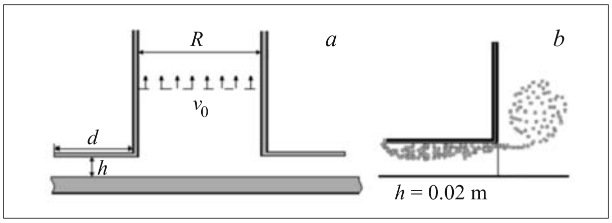

Fig. 2. Calculation of vortex flow at the inlet to a slot leak: *a*) boundary of flow region; *b*) results of calculation.

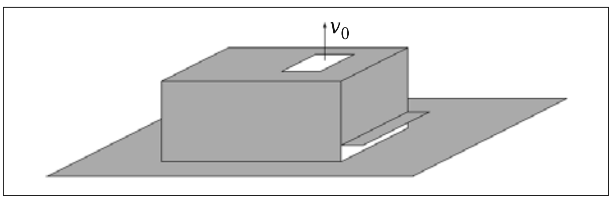

Fig. 3. Ventilation shelter with slot leak equipped with a shelter.

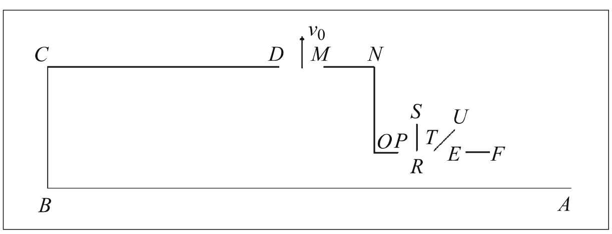

Fig. 4. Statement of problem.

a slot leak was estimated. In this shelter the boundary of the flow region was significantly simplified and an axisymmetric formulation of the problem was used, something that is not acceptable for physical flows in ventilation shelters.

The objective of the present study is to develop a mathematical model, computational algorithm, and computer program for calculating the vortical nonstationary airstreams inside a ventilation shelter and at the inlet to a slot leak equipped with thin baffle plates arranged randomly in space.

CONSTRUCTION OF MATHEMATICAL MODEL AND COMPUTATIONAL ALGORITHM

Statement of problem. Physical statement of problem: Find the field of velocities within the shelter and in the slot leak (Fig. 3) at the inlet to which thin baffle plates are mounted. There may be not just a single baffle plate, as shown in Fig. 3, but a collection of plates forming a labyrinth for the passage of air. Since the length of the leak is more than 10 times greater than its width, we will consider a planar problem (Fig. 4).

In order to solve the problem we will use the method of discrete vortices. The mathematical statement of the problem consists in a solution of a Laplace equation for the potential function φ at every computational moment of time,

$$\Delta\varphi = 0$$

for given values of the boundary normal component of the velocity $\left.\frac{\partial\varphi}{\partial n}\right|_S = v_n(x) - U_n$, where x is a point of the boundary S. The function U_n expresses the influence of free vortices converging into a flow with sharp edges at every computational moment of time along the direction of the external normal $\vec{n}$.

Derivation of basic computational relations. Suppose that the boundary of the region consists of z lines which serve to discretize a set of attached vortices and control (computational) points. Vortices must be present at the bends and end-points of the lines. In the middle, between two attached vortices, are found the control points. Then if there are N attached vortices, there will be $N - z$ control points.

Let us consider the initial moment of time $t = +0$, when the intake opening is functioning. At this moment of time, only attached vortices are present in the region. The influence of all these vortices at the control point x^p in the direction of the normal is determined from the expression

$$v_n(x^p) = \sum_{k=1}^{N} G(x^p, \xi^k)\Gamma(\xi^k), \tag{1}$$

where

$$G(x^p, \xi^k) = \frac{(x_1 - \xi_1)n_2 - (x_2 - \xi_2)n_1}{2\pi[(x_1 - \xi_1)^2 + (x_2 - \xi_2)^2]};$$

(x_1, x_2) are the coordinates of the point x^p; (ξ_1, ξ_2), the coordinates of an attached vortex with circulation $\Gamma(\xi^k)$ situated at the point ξ^k; $\{n_1, n_2\}$, coordinates of the unit normal vector $\vec{n}$ to the boundary of the region; and $v_n(x^p)$, velocity at the point x^p along the direction $\vec{n}$, which is assumed to be known in the statement of the problem.

By varying p from 1 to $N - z$ in (1), we obtain a system of $N - z$ equations with N unknown circulations $\Gamma(\xi^k)$, where $k = \overline{1, N}$. We complement the present system with z equations, each of which is a discrete analog of the Thompson condition, i.e., invariance of circulation along a liquid path that encompasses a profile and wake (sum of the circulations of attached vortices situated on a given line and of free vortices that converge with this line equal to zero). We then obtain a closed system of linear algebraic equations

$$\begin{cases} \sum\limits_{k=1}^{N} G(x^p, \xi^k)\Gamma(\xi^k) = v_n(x^p); \quad p = \overline{1, N - z}, \\ \sum\limits_{k=1+n_{c-1}}^{n_c} \Gamma(\xi^k) = 0, \quad c = \overline{1, z}, \end{cases}$$

where $\sum\limits_{c=1}^{z} n_c = N$; $n_0 = 0$; and n_c is the number of attached vortices on the c-th line.

After the unknown circulations have been determined, the velocity at any point of the region in any given direction is determined from (1), where a particular point is substituted for x^p.

At the moment of time $t = 1 \cdot \Delta t$ there occurs a separation of L free vortices from L sharp edges of the boundary. Strictly speaking, the vortices lying on these edges are already free vortices, since according to the previously proved Chaplygin – Zhukovskii – Kutt hypothesis [5], an attached vortical layer in a profle from which a sheet of vortices converges will vanish. A convergence of the free vortices occurs along the direction of flow velocity. The new position of the free vortices is calculated from their former position from the formulas

$$x' = x + v_x \Delta t, \quad y' = y + v_y \Delta t, \tag{2}$$

where v_x and v_y are components of the velocity calculated from (1) with $\vec{n} = \{0, 1\}$ and $\vec{n} = \{1, 0\}$, respectively, the coordinates (x, y) being substituted for (x_1, y_2). The circulation of the free vortices does not vary over the course of time. Taking into account the converged free vortices, the system of equations for determining the unkown circulations of the attached vortices assumes the following form:

$$\begin{cases} \sum_{k=1}^{N} G(x^p, \xi^k)\Gamma(\xi^k) \\ + \sum_{l=1}^{L} G(x^p, \varsigma^l)\gamma(\varsigma^l) = v_n(x^p); \quad p = \overline{1, N-z}, \\ \sum_{k=1+n_{c-1}}^{n_c} \Gamma(\xi^k) + \sum_{l=1+L_{c-1}}^{L_c} \gamma(\varsigma^l) = 0, \quad c = \overline{1, z}, \end{cases} \tag{3}$$

where ζ^l is the point where a free vortex that had converged with the l-th sharp edge is situated and L_c, the number of points of convergence of the vortex sheet with the line c; $\sum_{c=1}^{z} L_c = L; \; L_0 = 0.$

Still more L free vortices converge at the next moment of time, with the previous vortices acquiring a new position of their own, as determined from (2), where the constituent velocities are determined in light of the presence of free vortices in the flow:

$$v_n(x) = \sum_{k=1}^{N} G(x, \xi^k)\Gamma(\xi^k) + \sum_{l=1}^{L} G(x, \varsigma^l)\gamma(\varsigma^l).$$

At time $t = 2 \cdot \Delta t$ the system (3) is transformed into the form

$$\begin{cases} \sum_{k=1}^{N} G(x^p, \xi^k)\Gamma(\xi^k) + \sum_{\tau=1}^{2}\sum_{l=1}^{L} G(x^p, \varsigma^{l\tau})\gamma(\varsigma^{l\tau}) \\ = v_n(x^p), \quad p = \overline{1, N-z}, \\ \sum_{k=1+n_{c-1}}^{n_c} \Gamma(\xi^k) + \sum_{\tau=1}^{2}\sum_{l=1+L_{c-1}}^{L_{\tilde{n}}} \gamma(\varsigma^{l\tau}) = 0, \quad c = \overline{1, z}, \end{cases}$$

where $\zeta^{l\tau}$ is the point where the free vortex that had converged with the l-th sharp edge at moment of time τ is situated and $\gamma(\zeta^{l\tau})$ is its circulation.

At an arbitrary moment of time $t = m \cdot \Delta t$ the system of equations for determining the unknown circulations of attached vortices has the form

$$\begin{cases} \sum_{k=1}^{N} G(x^p, \xi^k)\Gamma(\xi^k) + \sum_{\tau=1}^{m}\sum_{l=1}^{L} G(x^p, \varsigma^{l\tau})\gamma(\varsigma^{l\tau}) \\ = v_n(x^p), \quad p = \overline{1, N-z}, \\ \sum_{k=1+n_{c-1}}^{n_c} \Gamma(\xi^k) + \sum_{\tau=1}^{m}\sum_{l=1+L_{c-1}}^{L_c} \gamma(\varsigma^{l\tau}) = 0, \quad c = \overline{1, z}, \end{cases}$$

and the velocity at any given point is determined from the expression

$$v_n(x) = \sum_{k=1}^{N} G(x, \xi^k)\Gamma(\xi^k) + \sum_{\tau=1}^{m}\sum_{l=1}^{L} G(x, \varsigma^{l\tau})\gamma(\varsigma^{l\tau}).$$

If a free vortex approaches an impenetrable boundary at a distance less than λ (the distance between adjacent attached vortices and the control point), it moves away from the boundary along the normal to a distance λ. But if a free vortex approaches an admission opening at the same distance, the vortex is eliminated from further discussion.

In the case of an approach to a vortex a distance $x < \lambda$, the magnitude of the velocity which is induced by this vortex is determined from the formula

$$v(x) = xv / \lambda,$$

where v is the velocity induced by a vortex situated at a distance λ.

RESULTS OF CALCULATION AND DISCUSSION

The computer program that was developed using the above computation relations makes it possible to determine the velocity field, construct current lines, and track the variations in the vortex structure of the air currents over time. As an example, the vortex flow within a shelter and at the inlet to a leak were calculated assuming the following parameters (cf. Fig. 4): $CB = 0.35$ m; $CD = 0.93167$ m; $DM = 0.13333$ m; $MN = 0.29$ m; $v_0 = 1$ m/sec. These dimensions correspond to the dimensions of a laboratory sample of a ventilation shelter

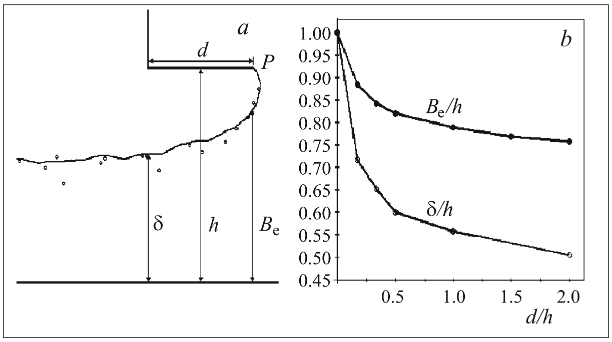

Fig. 5. Characteristics of vortex flow at the inlet to a slot leak provided with a baffle plate: *a*) detached current line; *b*) dimensionless width of indraft at inlet to leak B_e/h and at inlet to shelter δ/h expressed as a function of the dimensionless length of the baffle plate.

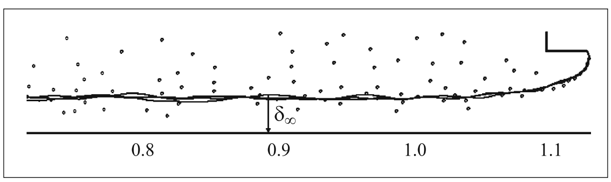

Fig. 6. Current line of separated flow at different moments of time.

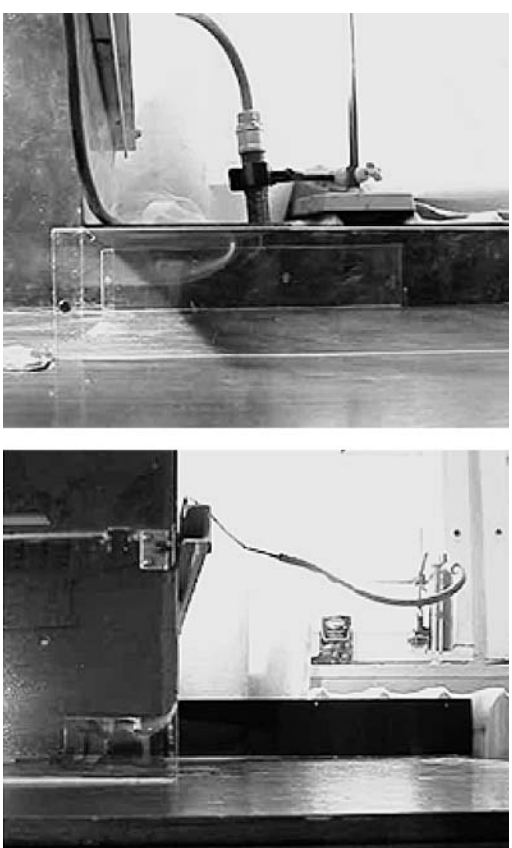

Fig. 7. Separated air currents at the inlet to a slot leak with and without a baffle plate.

that has been studied experimentally with the difference that the area of the rectangularly shaped indraft section (cf. Fig. 3) is distended by the width of the shelter.

The vortex flow was calculated for different lengths of a baffle plate mounted at the inlet to the leak. With an increase in the length of the baffle plate, the section that is functioning as an intake becomes stabilized quite rapidly (Fig. 5) and even with a length of the baffle plate of one-half the gauge ($d \approx 0.5h$) it becomes practically invariant with any further growth in the length of the baffle plate.

A calculation of the separated flow was performed with $\Delta t = 0.0025$ sec, and separation of free vortices (depicted by means of small circles in Fig. 5*a*) was realized at the point *C*. The quantization step $\lambda = 0.005$. Note that with a length of the baffle plate greater than two gauges, the dimensionless effective intake at the inlet to the leak remains invariant and equal to 0.76. For a slot admission opening freely situated in space, this quantity as found by the Zhukovskii method is equal to 0.78 [6]. By means of a realization of the Zhukovskii method for the geometry of the region depicted in Fig 1 it was possible to calculate the value of $B_e/h = 0.81$ for a baffle plate of length 1 gauge. If the length of the baffle plate is allowed to grow without limit, this quantity attains a value of 0.775. At a significant distance from the inlet to the shelter, the dimensionless value of the thickness of the airstream δ_∞/h varies in the range 0.5 – 0.58 and is independent of the length of the baffle plate (Fig. 6). In calculations performed using the Zhukovskii method, this quantity is found to be equal to 0.5.

The resulting computational pattern of the separated flow at the inlet to the leak and that observed in a full-scale experiment carried out by Asst. Prof. Yu. G. Ovsyannikov are in satisfactory agreement.

The current lines constructed using the newly developed computer program within the shelter (Figs. 8, 9) and those observed in the full-scale experiment (Fig. 10) possess complex structures. A phenomenon in which the central vortex shifts towards to the right-hand wall of the shelter as the length of the baffle plate is increased was observed in the experiment. The numerical experiment did not “capture” this phenomenon, though the vortex formation did change its position over the course of time (Fig. 9); velocity pulsations were observed.

According to the full-scale experiment, the line of separation of the airstream disintegrates in roughly 1 – 2 gauges upon entering the shelter (cf. Fig. 7). As the length of the baffle plate is increased, the line of separation begins to oscillate in the numerical experiment as well (Fig. 11), though in the full-scale experiment the line of separation disintegrates and the indraft flow completely fills the admission opening between the baffle plate and the floor (cf. Fig. 10).

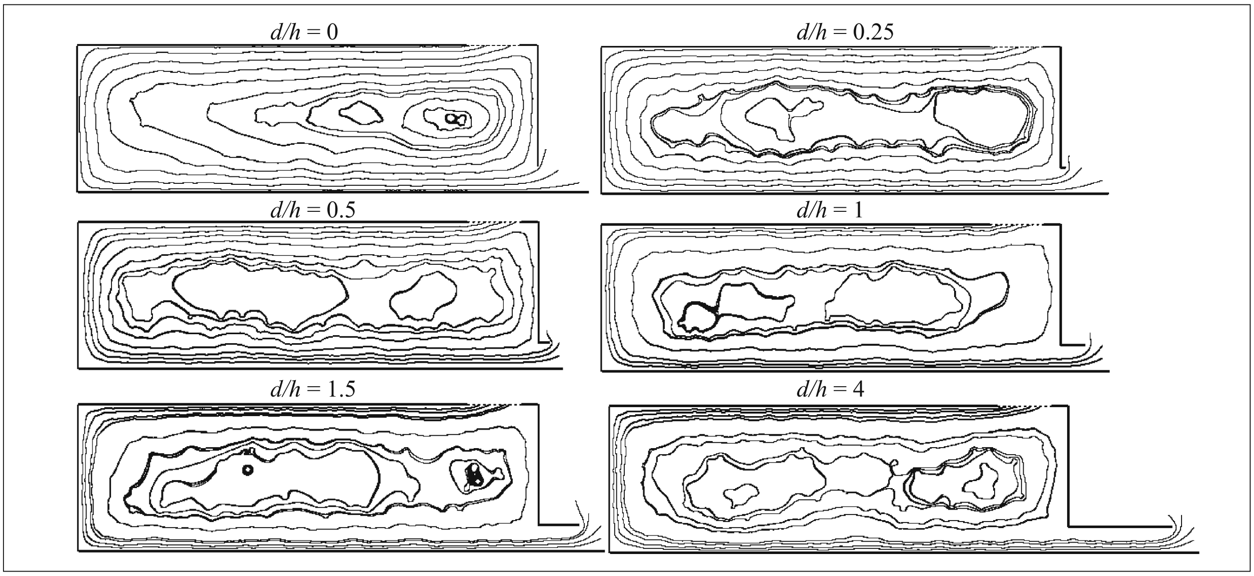

Fig. 8. Current lines in ventilation shelter in the case of baffle plates of different lengths.

The kinetic energy (Coriolis) coefficient α, which expresses the irregularity of the velocity field, is calculated using the formula

$$\alpha = \frac{\int\limits_S v_x^3 \, dS}{\left(v_{x_{\text{av}}}\right)^3 S} \approx n^2 \frac{\sum\limits_{i=1}^{n} v_i^3}{\left(\sum\limits_{i=1}^{n} v_i\right)^3},$$

where $v_{x_{\text{av}}} = \frac{\int_S v_x \, dS}{S}$ is the mean horizontal component of the velocity; v_x, horizontal component of the velocity; S, study section; v_i, horizontal component of the velocity at apex of i-th segment; and n, number of segments into which the given section is partitioned.

The Coriolis coefficient was calculated in a section at the inlet to the ventilation shelter of the slot leak. The number of sections in the partition $n = 11$, and the horizontal components of the velocity were calculated at points at distances of 0.005, 0.01, ..., 0.055. Since the current is nonstationary, velocity fluctuations are observed at these points and, correspondingly, fluctuations in the Coriolis coefficient in this section as well. Therefore, its value was averaged over time. Following saturation of the entire region of the ventilation shelter with free vortices (the number of which varied in the range 550 – 700), five moments of time were selected arbitrarily and the value of α determined for each moment, after which their arithmetic mean was found.

The Coriolis coefficient grows substantially with an increase in the length of the baffle plate (Fig. 12) to one gauge. The value of the Coriolis coefficient is directly related to the coefficient of local resistance. For example, upon a sudden expansion the values of these two parameters may be considered equal. It should be note that in a full-scale experiment the magnitude of the rarefaction in the shelter becomes maximal with a baffle plate of length one-half the gauge.

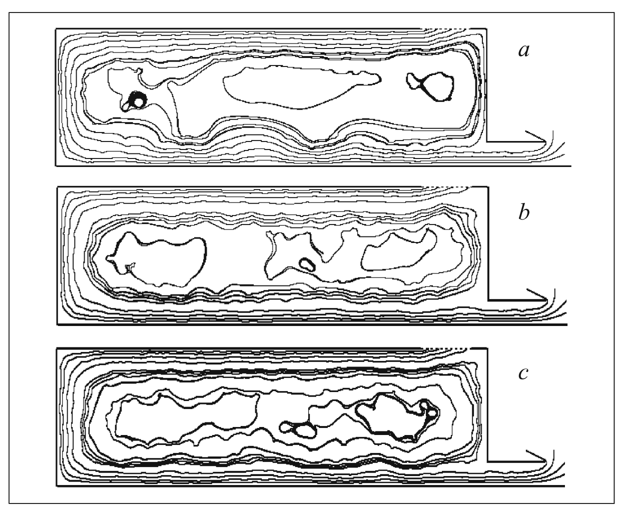

Fig. 9. Current lines with $d/h = 1.5$ at different moment of time.

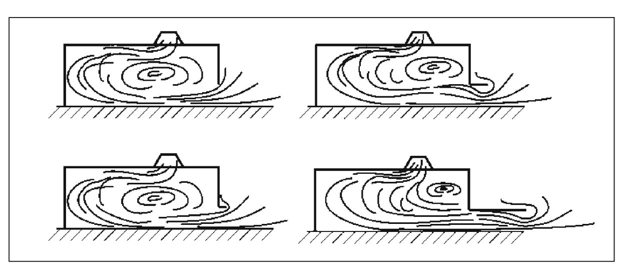

Fig. 10. Experimentally observed flow patterns.

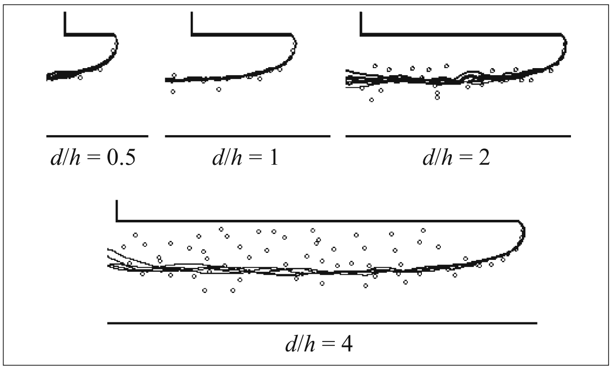

Fig. 11. Separated line of flow at different moments of time with baffle plates of different lengths.

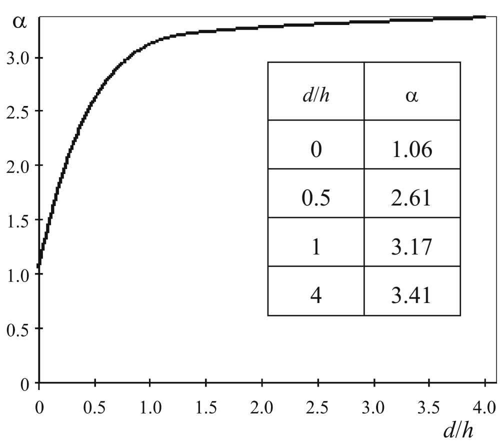

Fig. 12. Variation of Coriolis coefficient α at entry to ventilation shelter with increasing length of baffle plate.

If the leaks are equipped with an arrangement of baffle plates (Fig. 13), the vortex structure of the flow becomes greatly complicated. Losses of energy as the resulting local resistance are overcome promotes an increase in rarefaction in the ventilation shelter, which makes it possible to reduce the volume of ventilation and decrease the power requirements of ventilation systems.

CONCLUSION

A mathematical model, computational algorithm, and computer program for calculating vortex irregularities in nonstationary flows in an ventilation shelter with slot leaks equipped with thin baffle plates was developed on the basis

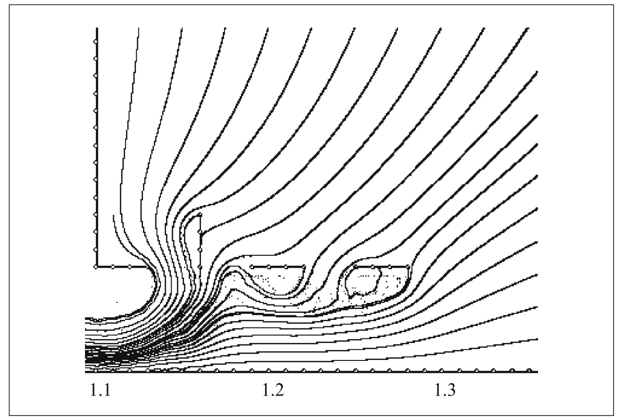

Fig. 13. Vortex pattern of flow at entry to slot leak of ventilation shelter equipped with thin baffle plates.

of the method of discrete vortices. The characteristics of the detached flow were shown to depend on the length of a baffle plate mounted at a right angle to the entry to the slot leak. It is shown that the structure of the flow is affected by the location and presence of thin baffle plates that significantly increase turbulization of the flow and the hydraulic resistance of the inlet to the slot leak and, as a consequence, reduce entrainment of air and power consumption in the operation of ventilation shelters.

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