DIAGNOSTYKA, 2022, Vol. 23, No. 3

e-ISSN 2449-5220
DOI: 10.29354/diag/154859

ANALYSIS OF AIR JETS VELOCITY ATTENUATION AT SPECIAL INITIAL CONDITIONS

Orest VOZNYAK [1], Nadiia SPODYNIUK [2, *], Olena SAVCHENKO [1], Oleksandr DOVBUSH [1], Mariana KASYNETS [1], Oleksandra DATSKO [3]

[1] Lviv Polytechnic National University, Department of Heat and Gas Supply and Ventilation
St. Bandery, 12, 79013, Lviv - 13, Ukraine
[2] National University of Life and Environmental Sciences of Ukraine, Department of Heat and Power Engineering, Heroyiv Oborony Str., 12, 03041, Kyiv, Ukraine
[3] Lviv Polytechnic National University, Department of Civil Safety
St. Bandery, 12, 79013, Lviv - 13, Ukraine
[*] Corresponding author, e-mail: n_spoduniuk@meta.ua

Abstract

The article is devoted to solving the significant problem of efficiency increasing of air distribution in the premise by swirl air jet. The aim of the article is to decrease coefficient of velocity attenuation due to intensification of initial turbulence of different air streams leakage from the air distributor and to obtain of analytical equations for calculation of air distribution in a room to ensure the normative indoor air parameters. Effect of flow twisting results in a reduction of the velocity attenuation coefficient by 2.4 times. The regression analysis testified that the attenuation coefficient of the swirl air jet is more affected by the angle of the twisting plates inclination and less affected by the angle of change of the air flow direction. The attenuation coefficient of all types of rectangular air jets is more influenced by the the ratio of the sides of slit b/l and the angle of change of the air flow direction is also less affected. To minimize the attenuation factor, it is effective to use air distributors at smaller swivel plates inclination angles for swirl air jets and a smaller slit size ratio for all types of rectangular air jets.

Keywords: air distribution, swirl jet, rectangular jet, compact jet, flat jet.

Nomenclature

α – angle of the swivel plate's inclination;
β – angle of the air jet direction change;
b – height of the slit, m;
F_0 – the area of openings, m^2
L – air volume flow rate, m^3/h;
l – length of the slit, m
m – velocity attenuation coefficient;
n – exponent
v – velocity, m/s;
$\overline{v_x}$ – dimension-less current velocity
x – running coordinate, m

Subscripts

0 – initial
c – compact
f – flat
max – maximal
min – minimal
r – rectangular
x – current
s –swirl

1. INTRODUCTION

One of the important tasks of room ventilation is the effective organization of air exchange [1] and in particular air distribution [2]. It should provide the air normalized temperature [3], air velocity [4, 5], concentration of CO_2 [6, 7] and other pollutants [8, 9] in a room, noise level [10], scent, etc. However, the air stream velocity often exceeds the normalized values. The reason is that the effective attenuation of the air jet velocity is not provided. The quantitative characteristics of the air jet velocity attenuation is coefficient m [11]. So, in order to provide normative values of air velocity in the premise working area the air jet velocity attenuation coefficient m should be reduced. Thus, it is desirable so that it would be minimal. For this purpose, it demands of intensive initial turbulence [12 – 14] of air flow and high aerodynamic local resistance of air distributor [15]. If the velocity attenuation coefficient m is high, it indicates insufficient stream turbulence [16, 17]. The velocity attenuation is directly related to air jet long range [18]. When the air jet long range becomes too high it needs to be reduced, because the conditions of comfort are violated [19, 20].

Depending on the purpose of the room, its dimensions and other characteristics, it is advisable to use appropriate air exchange schemes, air distribution devices [21, 22] and air streams [23]. Usually, the air distribution devices are proposed which provide a high intensity of the air velocity attenuation of the inflow stream with the formation of a swirl air jet. Swirl air jets provide intensive air velocity attenuation as they increase air flow turbulence. This is a round shape of air jet, but another suitable one is rectangular shape. A wide category of rectangular air jets is quite common, which include all types: flat, compact and rectangular air jets.

Let us clarify the classification of the air rectangular jets. The reason is particularity of ratio slit sizes, namely length to height. In case of flat air jets tidal slit has a ratio of length to height $l/b \geq 10$, and with a ratio of $1 < l/b < 10$ it is determined to call air jets as rectangular [38]. At the ratio $l/b = 1$ the air jet is axisymmetric (compact), and hole's shape is square or round, obviously.

Papers [24 – 26] investigated rectangular air jets with a ratio of length to height $l/b \geq 60$, 115 and 80, respectively. But according to the proposed classification, such rectangular air jets are flat. Paper [27] investigates a rectangular air jet with a ratio of $l/b = 3$, but at high air speeds, Mach numbers $M = 1.75$, $M = 2$ and $M = 2.5$. Papers [28, 29] present the results of rectangular air jet research in the field of fundamental aerodynamics, not applied ventilation.

If there are swivel plates (Fig.1 a) in the cylindrical hole that can be deviated by a certain angle α, then the swirl air jets are created. The twisting factor determines the special properties and aerodynamic characteristics of swirl air jets. As a result, they have different coefficients of air velocity attenuation and aerodynamic resistance, different acoustic properties, creating aerodynamic noise, depending on the swivel plates angle inclination. Increasing of the aerodynamic resistance of both devices is achieved by reducing the of the inclination angle of the swivel plates for swirl air flows and reducing the ratio of the size of the slit b/l for rectangular ones.

For ventilation of small volume and height it is advisable to design simple and efficient air distributors that would allow to supply a significant amount of the tidal air to the room while ensuring a low air velocity in the premise work area. Air distribution devices with a low coefficient of the velocity attenuation m also are suitable. This is due to the high initial turbulence of the air flow. In this regard, the hypothesis of creating special initial conditions for increasing the intensity of air flow turbulence would be correct. This is crucial for the nature of its spread. One of the simplest ways to intensify the turbulence of the air flow in front of the air vent is to change the conditions of the air jet leakage. This can be achieved by installing a variety of additional local resistances: gates, grilles, rotary blinds, perforation, change of flow direction, jet twisting, etc. This is based on the aerodynamic resistance increasing of the air stream from the air distributor.

Therefore, the air distribution devices must be equipped with appropriate means to ensure the appropriate intensity of air flow turbulence, ie to achieve the required value of the attenuation coefficient of velocity m. It should be noted that the air velocity attenuation factor is directly related to the air jet long-range. An extremely difficult task is to ensure high long-range airflow while reducing its attenuation coefficient at the same time.

As an additional local resistance, the article proposes to use the effect of the flow twisting and changing of air flow direction in the air duct before leaving the nozzle, namely turning at a certain angle (usually 45 and 90 degrees). Such air jets should have the increased turbulence compared to direct air currents. It is necessary to improve mathematical models [30 – 36] of tidal jets in the room in relation to their self-similar properties [37, 38].

Microclimate of premise should be also improved due to energy saving measures of heat source [39], building walls [40, 41], heating system [42 – 44], ventilation system [45] and gas and heat supply systems [46, 47]. It is advisable to use also exhaust air heat and recuperation [48, 49] for energy saving.

Based on the analysis of literature data on velocity attenuation of air streams and given hypothesis, we state:

1. it is expedient to quantitatively investigate the effect of flow twisting on the reduction of the attenuation coefficient of the air jet velocity;
2. it is expedient to quantitatively investigate the effect of changing of the flow direction both for the swirl air jets and rectangular jets of different types to reduce the attenuation coefficient of their velocity;
3. it is necessary to establish calculated graphical and analytical dependencies.

2. GOAL OF THIS PAPER

The aim of the article is to decrease coefficient of velocity attenuation due to intensification of initial turbulence of air stream leakage from the air distributor and to obtain of analytical equations for calculation of air distribution in a room.

To do this it is need:
- to make hypothesis;
- to realize experiment planning and create matrix;
- to carry out experimental investigations;
- to perform the regression analysis;
- to create graphs and chart;
- to obtain analytical equations.

3. MATERIALS AND METHODS

Used theoretical methods of research include the implementation of physical and mathematical modeling of the movement of air flow based on the equations of jet streams. As a result of theoretical studies, calculated dependencies were obtained for determining air flow parameters and geometric parameters of devices with intensive velocity attenuation.

Experimental investigations were carrying out at assumption and simplifications using physical modeling of air flows based on the theory of similarity and modeling scales to transform physical quantities, as well as to visualize their structure in order to verify the stated hypotheses. The planning of multifactorial experiments was accompanied by the construction of a planning matrix for a complete factorial experiment.

The plausibility of scientific hypotheses, propositions, conclusions and recommendations is determined by the use of fundamental laws of jet flows with satisfactory convergence of the results of theoretical and experimental studies, and their processing using the methods of probability theory and mathematical statistics.

4. RESULTS OF RESEARCH OF THE SWIRL, FLAT, RECTANGULAR AND COMPACT AIR JET AT IT LEAKAGE

This work is continuing of air distribution research [11]. The variation of the air volume flow rate L, m^3/h was provided. It was necessary to carry out theoretical and experimental investigations of all types of presented air streams and to determine numerically of tidal air flows characteristics. It is known [11], that round and compact air jets have similar characteristics, though hole's shape for the round air stream is round and for compact air stream is round or square. It would be interesting to compare the round and compact air jets characteristics depending on the running coordinate and size of tidal air distributor.

In this article it is presented a generalization of the graphical and analytical dependencies for determination of characteristics of the swirl, flat, rectangular and compact air streams. Besides that, it is brought them to an universal form. It should be noted that all values are presented in dimension-less form so that to provide universality.

Study of the effect of changing the direction of air flow on the initial turbulence of the air jet, and thus on its attenuation coefficient has been carried out. The following air streams were taken into account: swirl, flat, compact and rectangular.

To study the influence of leakage conditions on the characteristics of the jets, experimental studies were conducted on the installation shown in Fig.1. The investigated inflow jets were additionally being turbulented due to the change of the flow direction by β = 45° and β = 90°, and the air distribution devices were made in the form of nozzles, as shown in Fig. 1.

a)

b)

Fig. 1. Experimental installation: a) – nozzle №1 for a swirl air jet; b) – nozzle №2 for a compact air jet

a)

b)

Fig. 2. Experimental installation: a) – nozzle №3 for a flat air jet; b) – nozzle №4 for a rectangular air jet

Experimental investigations have been carried out at such assumption and simplifications:
- studies were performed under isothermal conditions;
- value of air flow rate was: L = 170 – 670 m^3/h for the swirl air jet and L = 70 – 360 m^3/h for the rest air jets;
- the initial velocity of air was: v_0 = 1 – 4 m/s for the swirl air jet and v_0 = 2 – 10 m/s for all types rectangular air jets;
- the squares of tidal nozzles were: for the swirl air jet F_0 = 0.049 m^2; for the flat air jet F_0 = 0.009 m^2; for the compact air jet F_0 = 0.010 m^2; for the rectangular air jet F_0 = 0.009 m^2.

Testo-405 thermal anemometer was used for measurement of all the air jets velocity. Coordinate system with a grid of points 5×5 cm also has been used.

According to the research results, graphs are constructed (Fig. 3), which characterize the drop of the axial velocity v_x of the swirl air jet during its outflow under isothermal conditions from the nozzle №1 in the absence of (β = 0°) and the presence of change of airflow direction in the air duct by β = 45° and β = 90°. For comparison, Fig. 3 also shows graphs of the axial velocity drop of all types of rectangular air streams, which flow under isothermal conditions from the nozzles №2 - №4.

According to the results of the study of the flow of these jets from the nozzles №1–№4 was determined by the attenuation coefficient m according to formula (1) for swirl and compact air jet, from formula (2) for the flat air stream and from formula (3) for rectangular ones:

$$m_{s,c} = \overline{v}_x \cdot \frac{x}{\sqrt{F_o}} \tag{1}$$

where x – current coordinate, m;
F_0 – square of a supply nozzle, m^2;
$m_{s,c}$ – coefficient of velocity attenuation for the swirl and compact air stream;
$\overline{v}_x$ – dimension-less current velocity which is defined as $\overline{v}_x = v_x / v_o$, that is, the ratio of absolute axial and initial velocities.

$$m_f = \overline{v}_x \cdot \sqrt{\frac{x}{b}} \tag{2}$$

where x – current coordinate, m;
b – height of the flat slit, m; b = 0.03 m;
m_f – coefficient of velocity attenuation for the flat air stream;
$\overline{v}_x$ – relative current velocity of the flat air stream.

$$m_r = \overline{v}_x \cdot \left(\frac{x}{b}\right)^n \tag{3}$$

where x – current coordinate, m;
b – height of the rectangular slit, m; b = 0.06 m;
m_r – coefficient of velocity attenuation for the rectangular air stream;
$\overline{v}_x$ – relative current velocity of the rectangular air stream.

Fig. 3 and Fig. 4 show that for the swirl air jets with increasing swivel plates inclination angle, the velocity attenuation coefficient increases. In particular, for the swirl jets at an swivel plates inclination angle of α = 30°: without direction change (β = 0) m = 0.54, for β = 45° m = 0.50, and for β = 90° m = 0.46 (Fig. 3a); at the inclination angle of the swivel plates α = 60°: without direction change (β = 0) m = 1.52, for β = 45° m = 1.25, and for β = 90° m = 0.98 (Fig. 3b); at the angle inclination of the swivel plates α = 90°: without direction change (β = 0) m = 2.5, for β = 45^0 m = 2.0, and for β = 90° m = 1.5 (Fig. 3c); for a flat air jet without direction change (β = 0) m = 2.5, for β = 45° m = 2.0, and for β = 90° m = 1.5 (Fig. 4a); for rectangular air jet without direction change (β = 0) m = 3.7, for β = 45° m = 3, and for β = 90° m = 2.3 (Fig. 4b); for compact air jet without direction change (β = 0) m = 6.10, for β = 45° m = 5.0, and for β = 90° m = 3.90 (Fig. 4c).

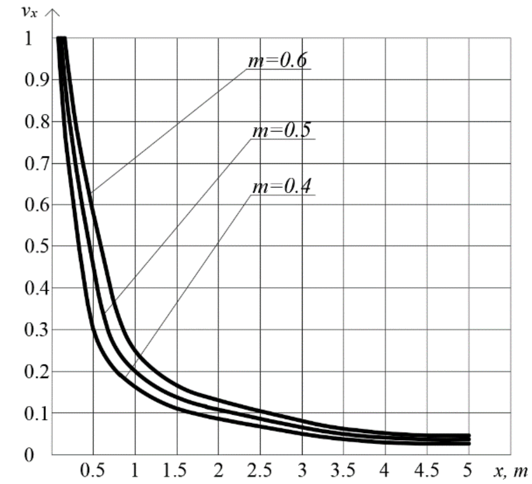
In summary, it should be noted that the velocity attenuation coefficient m decreases for the swirl air jet with changes of direction by β = 45° and β = 90° by 1.08 – 1.17 times at α = 30°, by 1.22 – 1.55 times at α = 60° and by 1.25 – 1.67 times at α = 90° respectively, depending on the angle α of the plates inclination; for a wide class of rectangular air jets the velocity attenuation coefficient m decreases for direction changes by β = 45° and β = 90° by 1.25 – 1.67 times for the flat air jet, by 1.23 – 1.61 times for the rectangular air jet and 1.22 – 1.56 times for the compact air jet, respectively, depending on the size ratio of the slit.

These data indicates the self-similarity properties of the researched air jets.

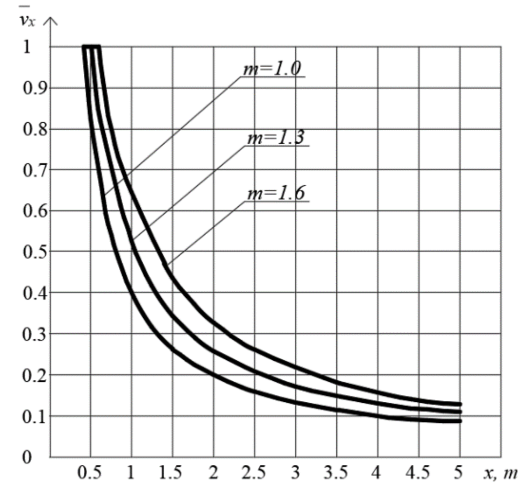
Graphs (Fig. 3 and Fig. 4) show that drop of axial velocity from v_{max} to v_{min} in all studied jets (nozzles No 1 – No 4) is the most intense when changing the flow direction by β = 90°, although at β = 45° it is also significant. This confirms the correctness of the conclusions that the additional turbulence of the air jets results in more intense velocity drop in the air flow.

Based on the obtained results, we state that the output of the air jet from the air distribution devices of all types when turning the air flow at an angle β = 90° creates a sufficient initial intensity of turbulence, which significantly reduces the velocity attenuation coefficient.

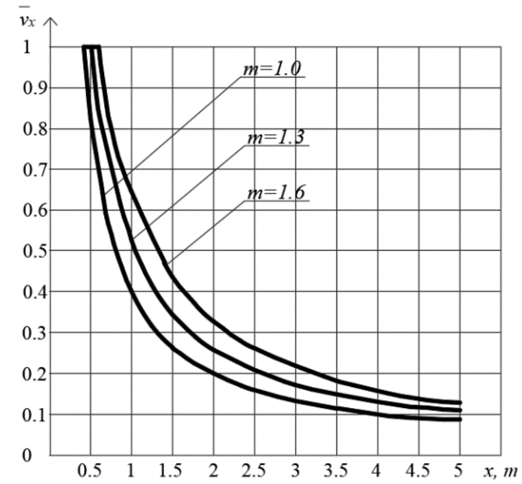
To determine the attenuation coefficient of all considered air jets has been applied planning a complete two-factor experiment, considering 3 levels for determining factors – table 1.



a)

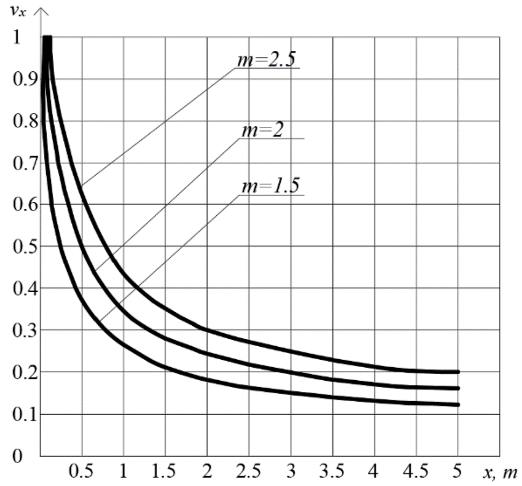


b)

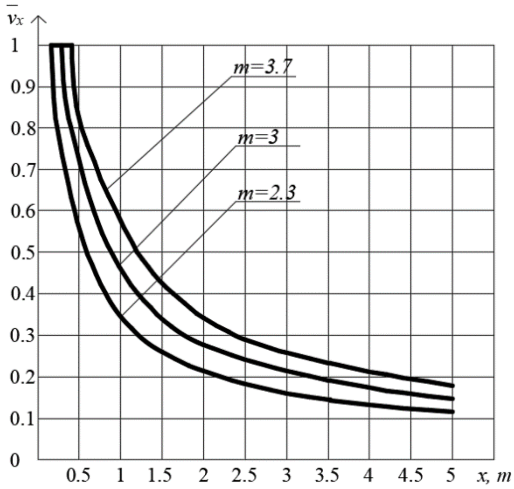


c)

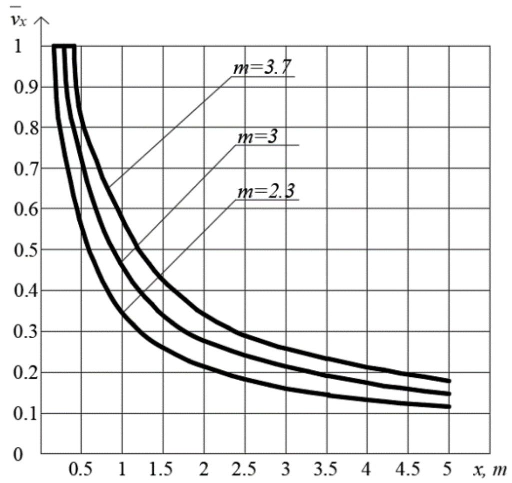
Fig. 3. Dependencies of the swirl air jet axial dimension-less velocities at the different angles β (β = 0°, 45°, 90°) of change of a flow direction and twisting plates inclination α from the current coordinate x:
a) α = 30°; b) α = 60°; c) α = 90°.



a)



b)



c)

Fig. 4. Dependencies of the different air jets axial dimension-less velocities at the different angles β (β = 0°, 45°, 90°) of change of a flow direction from the current coordinate x: a) flat air jet; b) rectangular air jet; c) compact air jet.

For the swirl air jet, the determining factors are:

x_1 = β – angle of change of the air flow direction, β = 0°, 45°, 90°;

x_2 = α – the angle of the swivel plates inclination, α = 30°, 60°, 90°.

For the other considered air jets the determining factors are:

$x_1 = \beta$ – angle of change of the air flow direction, $\beta = 0°, 45°, 90°$;

$x_2 = b/l$ – the ratio of the sides of slit, $b/l = 0.1$ (flat air jet), $b/l = 0.4$ (rectangular air jet), $b/l = 1.0$ (compact air jet).

Table 1

Planning matrix of a complete 2-factor experiment taking into account three levels for determining factors (non linear model)

No	x_0	$x_1 = \beta$	$x_2 = \alpha$	$x_1 x_2$	$y_1 = m$
1	+	-	-	+	0.54
2	+	0	-	0	0.50
3	+	+	-	-	0.46
4	+	-	0	0	1.52
5	+	0	0	0	1.25
6	+	+	0	0	0.98
7	+	-	+	-	2.50
8	+	0	+	0	2.00
9	+	+	+	+	1.50
No	x_0	$x_1 = \beta$	$x_2 = b/l$	$x_1 x_2$	$y_2 = m$
1	+	-	-	+	2.50
2	+	0	-	0	2.00
3	+	+	-	-	1.50
4	+	-	0	0	3.70
5	+	0	0	0	3.00
6	+	+	0	0	2.30
7	+	-	+	-	6.10
8	+	0	+	0	5.00
9	+	+	+	+	3.90

The optimization parameter is the air jet attenuation coefficient *m*. Because of three levels for determining factors are being considered the nonlinear mathematical model has been accepted.

In Table 1, the value of y_1 refers to the swirl air jet, and y_2 - to all types of rectangular ones.

According to the matrix of experiment planning, we obtain the regression equations for the swirl air jet (14) and for all types of rectangular ones (15):

$$y = 1.25 - 0.18x_1 + 0.5x_2 - 0.12x_1x_2 \qquad (14)$$

$$y = 3.33 - 0.49x_1 + 1.0x_2 - 0.11x_1x_2 \qquad (15)$$

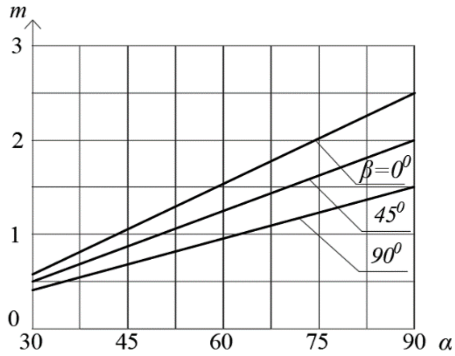
The regression analysis testified that the attenuation coefficient of the swirl air jet is more affected by the angle of the twisting plates inclination and less affected by the angle of change of the air flow direction. The attenuation coefficient of all types of rectangular air jets is more influenced by the the ratio of the sides of slit *b/l* and the angle of change of the air flow direction is also less affected.

On a basis of research results the charts have been created: for the swirl air jet – Fig. 5a and for all types of rectangular air streams – Fig. 5b.

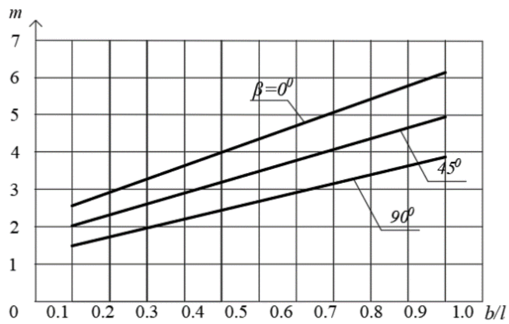
Charts (Fig. 5a and Fig. 5b) are approximated by equations (16) and (17).

$$m = 0.033\alpha + 0.004\beta - 0.0002\alpha\beta - 0.44 \qquad (16)$$

$$m = 2.1 - 0.01\beta - 4.0\frac{b}{l} - 0.015\beta\frac{b}{l} \qquad (17)$$



a)



b)

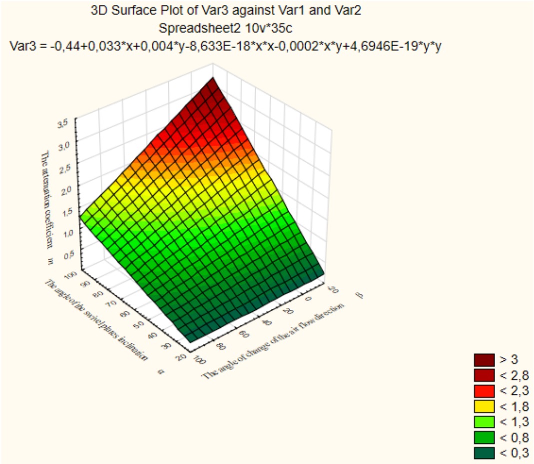
Fig. 5. Charts for determination of the air jets velocity attenuation coefficient:
a) for the swirl air jet; b) for all types of rectangular air streams

It should be noted that the effect of the air flow twisting on the reduction of the air jet velocity attenuation should be evaluated. For this purpose it is necessary to take the ratio of air velocity attenuation coefficients for a cylindrical nozzle with direct air outlet ($m = 6.0$) and a cylindrical nozzle with direct air outlet $\alpha = 90°$ and the swivel plates ($m = 2.5$ – Fig. 1a). The result is 2.4, ie the phenomenon of flow twisting is more effective concerning of the air jet velocity attenuation than the effect of changing of the flow direction for all types of air jets: swirl, flat, rectangular and compact.

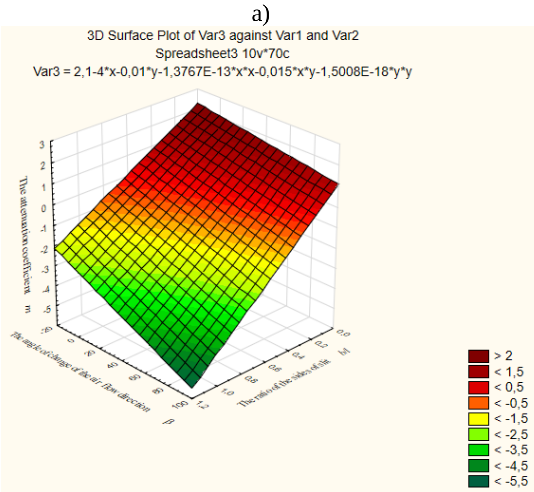
Visualization in 3D format of the velocity attenuation coefficient depending on the α and β angles (Fig. 6a) and the β angle and the ratio of the sides of slit *b/l* (Fig. 6b) is constructed.

The attenuation coefficient of the swirl air jet and all types of rectangular air streams decreases accordingly with decreasing of inclination angle of the twisting plates and with decreasing of the ratio of the sides of slit *b/l*. Increasing the angle of change of the air flow direction in all cases results in decrease of the attenuation coefficient.

Consequently, in terms of air velocity attenuation, it is effective to use the air distributors at smaller inclination angles of the swivel plates for swirl air streams and smaller slit sizes ratio *b/l* for all types of rectangular air flows, where the velocity attenuation coefficient is minimal.



a)



b)

Fig. 6. Visualization in 3D format of the air jets velocity attenuation coefficient:
a) for the swirl air jet; b) for all types of rectangular air streams

The results of the work indicate the possibility of practical application of the investigated air distribution devices for ventilation of small rooms and supply of supply air directly to the work area of the premise.

DISCUSSION

The results of theoretical and experimental investigations of different types of air tidal air jets (swirl, flat, compact and rectangular) are obtained. So does research of its velocity attenuation coefficient and determination of the effect of special initial conditions on turbulence intensity. Since the studies were performed for the swirl, flat, compact and rectangular air jets, the results for other air streams would be interesting. So would be also numerical modelling of all these air tidal jets and exhaust ones.

In future work research on air jets in the field of applied ventilation will be continued and aerodynamic research will be carried out. In particular, the boundaries of the transition zone from compact to rectangular air jets should be established and other special initial conditions should be researched.

CONCLUSIONS

1. Based on the carried out theoretical and experimental research analytical equations for the swirl, flat, compact and rectangular air stream are received, comparison of known analytical dependencies with received experimentally is carried out and the corresponding correction factors are defined.
2. Effect of flow twisting results in a reduction of the velocity attenuation coefficient by 2.4 times, which is much more than the effect of changing the flow direction for all types of air jets: swirl, flat, rectangular and compact.
3. The regression analysis testified that the attenuation coefficient of the swirl air jet is more affected by the angle of the twisting plates inclination and less affected by the angle of change of the air flow direction.
4. The attenuation coefficient of the swirl air jet and all types of rectangular air streams decreases accordingly with decreasing of inclination angle of twisting plates and with decreasing of the ratio of the sides of slit *b/l*. Increasing the angle of change of the air flow direction in all cases results in decrease of the attenuation coefficient.
5. To minimize the attenuation factor, it is effective to use air distributors at smaller swivel plates inclination angles for swirl air jets and a smaller *b/l* slit size ratio for rectangular ones.

Author contributions: *research concept and design, O.V., M.K.; Collection and/or assembly of data, O.V., M.K., O.D.; Data analysis and interpretation, N.S., O.V., O.S., O.D.; Writing the article, N.S. O.S., O.D., M.S.; Critical revision of the article, N.S., O.S., O.D.; Final approval of the article, N.S.*

Declaration of competing interest: *The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.*

REFERENCES

1. Kapalo P, Klymenko H, Zhelykh V, Adamski M. Investigation of Indoor Air Quality in the Selected Ukraine Classroom - Case Study. Lecture Notes in Civil Engineering 2020;47:168–173. https://doi.org/10.1007/978-3-030-27011-7_21.
2. Voznyak O, Yurkevych Yu, Dovbush O, Serediuk Ya. The influence of chairs and passengers on air velocity in bus passenger compartment. Springer, Proceedings of CEE 2019. Advances in Resourse-saving Technologies and Materials in Civil and Environmental Engineering 2019; 47: 518 – 525. https://doi.org/10.1007/978-3-030-27011-7_66.
3. Basok B, Davydenko B, Farenuyk G, Goncharuk S. Computational Modeling of the Temperature Regime in a Room with a Two-Panel Radiator. Journal of Engineering Physics and Thermophysics 2014; 87(6):

1433–1437. https://doi.org/10.1007/s10891-014-1147-5.
4. Kapalo P, Vilcekova S, Meciarova L, Domnita F, Adamski M. Influence of indoor climate on employees in office buildings. A case study Sustainability. 2020;12(14):5569. https://doi.org/10.3390/su12145569.
5. Kapalo P, Voznyak O, Yurkevych Yu, Myroniuk Kh, Sukholova I. Ensuring comfort microclimate in the classrooms under condition of the required air exchange. Eastern European Journal of Enterprise Technologies 2018;5/10(95):6–14. https://doi.org/10.15587/1729-4061.2018.143945.
6. Kapalo P, Domnita F, Bacotiu C, Podolak M. The influence of occupants' body mass of carbon dioxide mass flow rate inside of university class-room – case study. International Journal of Environmental Health Research 2018;28(4):432–447. https://doi.org/10.1080/09603123.2018.1483010.
7. Kapalo P, Meciarova L, Vilcekova S, Burdova E, Domnita F, Bacotiu C, Peterfi K. Investigation of CO_2 production depending on physical activity of students. International Journal of Environmental Health Research 2019;29(1):31-44. https://doi.org/10.1080/09603123.2018.1506570.
8. Lee Y-K, Kim YI. Analysis of indoor air pollutants and guidelines for space and physical activities in multi-purpose activity space of elementary schools. Energies 2022;15(1):220. https://doi.org/10.3390/en15010220.
9. Shapoval S, Shapoval P, Zhelykh V, Pona O, Spodyniuk N, Gulai B, Savchenko O, Myroniuk Kh. Ecological and energy aspects of using the combined solar collectors for low-energy houses. Chemistry & chemical technology 2017; 11(4): 503–508. https://doi.org/10.23939/chcht11.04.503.
10. Voznyak O, Myroniuk K, Sukholova I, Kapalo P. The impact of air flows on the environment. Springer, Proceedings of CEE 2019. Advances in Resourse-saving Technologies and Materials in Civil and Environmental Engineering 2019; 47: 534 – 540. https://doi.org/10.1007/978-3-030-27011-7_68.
11. Voznyak O, Savchenko O, Spodyniuk N, Sukholova I, Kasynets M., Dovbush O. Improving of ventilation efficiency at air distribution by the swirled air jets. Pollack Periodica 2022;17(1):123–127. https://doi.org/10.1556/606.2021.00419.
12. Allmaras SR. Multigrid for the 2-D Compressible Navier-Stokes Equations. 14th Computational Fluid Dynamics Conference. American Insitute of Aeronautics and Astronautics, Norfolk USA 1999. https://doi.org/10.2514/6.1999-3336.
13. Coleman GN, Rumsey CL, Spalart PR. Numerical study of turbulent separation bubbles with varying pressure gradient and Reynolds number. Journal of Fluid Mechanics 2018;847:28–70. https://doi.org/10.1017/jfm.2018.257.
14. Spalart PR, Garbaruk AV. The Predictions of Common Turbulence Models in a Mature Vortex. Flow, Turbulence and Combustion 2019; 102: 667–677. https://doi.org/10.1007/s10494-018-9983-6.
15. Voznyak O, Spodyniuk N, Yurkevych Yu, Sukholova I, Dovbush O. Enhancing efficiency of air distribution by swirled-compact air jets in the mine using the heat utilizators. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2020;5(179):89–94. https://doi.org/10.33271/nvngu/20205/089.
16. Hnativ R, Verbovskiy O. Distribution of local velocities in a circular pipe with accelerating fluid flow. Eastern-European Journal of Enterprise Technologies 2019;2(7-98):58–63. https://doi.org/10.15587/1729-4061.2019.162330.
17. Hulai B, Dovbush O, Piznak B, Kasynets M. Studying Equalization of the Radial Fans Discharge Flow. Lecture Notes in Civil Engineering 2020; 47: 119–126. https://doi.org/10.1007/978-3-030-27011-7_15.
18. Rumsey CL, Spalart PR. Turbulence Model Behavior in Low Reynolds Number Regions of Aerodynamic Flowfields. AIAA Journal 2009; 47(4): 982–993. https://doi.org/10.2514/1.39947.
19. Lis P, Lis A, Janik M. Aspects of the analytical heat consumption monitoring in local buildings' population. Rynek Energii 2012; 102(5): 67–75.
20. Lis A, Spodyniuk N. The quality of the microclimate in educational buildings subjected to thermal modernization. E3S Web of Conferences 2019; 100: 00048. https://doi.org/10.1051/e3sconf/201910000048.
21. Andersson H, Cehlin M, Moshfegh B. Experimental and numerical investigations of a new ventilation supply device based on confluent jets. Building and Environment 2018;137:18–33. https://doi.org/10.1016/j.buildenv.2018.03.038.
22. Khovanskyi S, Pavlenko I, Pitel J, Mizakova J, Ochowiak M, Grechka I. Solving the coupled aerodynamic and thermal problem for modeling the air distribution devices with perforated plates. Energies 2019;12(18):3488. https://doi.org/10.3390/en12183488.
23. Janbakhsh S, Moshfegh B. Experimental investigation of a ventilation system based on wall confluent jets Building and Environment 2014;80:18-31. https://doi.org/10.1016/j.buildenv.2014.05.011.
24. Krothapalli A, Baganoff D, Karamcheti K. Development and structure of a rectangular jet in a multiple jet configuration. AIAA journal 1980; 18(8): 945 - 950. https://doi.org/10.2514/3.50838.
25. Krothapalli A, Baganoff D, Karamcheti K. On the mixing of a rectangular jet. Journal of Fluid Mechanics 1981;107:201-220. https://doi.org/10.1017/S0022112081001730.
26. Krothapalli A, Hsia Y, Baganoff D, Karamcheti K. On the Structure of an Underexpanded Rectangular Jet. Stanford Univ Ca Joint Inst of Aeronautics and Acoustics 1982.
27. Kim JH, Samimy M. Mixing enhancement via nozzle trailing edge modifications in a high-speed rectangular jet. Physics of Fluids 1999; 11(9): 2731-2742. https://doi.org/10.1063/1.870132.
28. Gori F, Petracci I, Angelino M. Influence of the Reynolds number on the instant flow evolution of a turbulent rectangular free jet of air. International Journal of Heat and Fluid Flow 2014; 50: 386-401. https://doi.org/10.1016/j.ijheatfluidflow.2014.10.001.
29. Petracci I, Angelino M, Di Venuta I, Boghi A, Gori F. Experiments and numerical simulations of mass transfer and flow evolution in transient rectangular free jet of air. International Communications in Heat and Mass Transfer 2019;108:104290. https://doi.org/10.1016/j.icheatmasstransfer.2019.104290.
30. Adamski M. MathModelica in modeling of countercurrent heat exchangers. Proceedings - 8th EUROSIM Congress on Modelling and Simulation,

EUROSIM 2013, 2015: 439–442, 7004983. https://doi.org/10.1109/EUROSIM.2013.81.
31. Klymchuk A, Lozhechnikov V, Mykhailenko V, Lozhechnikova N. Improved mathematical model of fluid level dynamics in a drum-type steam generator as a controlled object. Journal of Automation and Information Sciences 2019; 51(5): 65–74. https://doi.org/10.1615/JAutomatInfScien.v51.i5.60.
32. Klymenko H, Labay V, Yaroslav V, Gensetskyi M. Criterial Equation for the Description of Low-Speed Air Distributor Operation. Lecture Notes in Civil Engineering. 2020;47:235–242. https://doi.org/10.1007/978-3-030-27011-7_30.
33. Labay V, Dovbush O, Yaroslav V, Klymenko H. Mathematical modeling of a split-conditioner operation for evaluation of exergy efficiency of the R600A refrigerant application. Mathematical Modeling and Computing 2018; 5(2): 169–177. https://doi.org/10.23939/mmc2018.02.169.
34. Labay V, Savchenko O, Zhelykh V, Kozak K. Mathematical modelling of the heating process in a vortex tube at the gas distribution stations. Mathematical Modeling and Computing 2019; 6(2): 311–319. https://doi.org/10.23939/mmc2019.02.311.
35. Labay V, Yaroslav V, Dovbush O, Tsizda A. Mathematical modeling of an air split-conditioner heat pump operation for investigation its exergetic efficiency. Mathematical Modeling and Computing 2020;7(1):169–178. https://doi.org/10.23939/mmc2020.01.169.
36. Yefimov A, Potanina T. Application of interval analysis for improving reliability of estimation of hardness value spread for nuclear structural materials. Problems of Atomic Science and Technologythis 2020;125(1):206– 210. https://doi.org/10.46813/2020-125-206.
37. Lorin E. From structured data to evolution linear partial differential equations. Journal of Computational Physics 2019;393:162–185. https://doi.org/10.1016/j.jcp.2019.04.049.
38. Lorin E, Ben Haj Ali A, Soulaimani A. Positivity Preserving Finite Element-Finite Volume Solver for The Spalart-Allmaras Turbulence Model. Computer Methods in Applied Mechanics and Engineering 2007; 196(17–20):2097–2116. https://doi.org/10.1016/j.cma.2006.10.009.
39. Myroniuk K, Voznyak O, Yurkevych Yu, Gulay B. Technical and economic efficiency after the boiler room renewal. Springer, Proceedings of CEE 2020, Advances in Resourse-saving Technologies and Materials in Civil and Environmental Engineering 2020; 100: 311 – 318. https://doi.org/10.1007/978-3-030-57340-9_38.
40. Marushchak U, Sanytsky M, Pozniak O, Mazurak O. Peculiarities of nanomodified portland systems structure formation. Chemistry and Chemical Technology 2019;13(4):510–517. https://doi.org/10.23939/chcht13.04.510.
41. Novosad P, Pozniak O, Melnyk V, Braichenko S. Porous Thermal Insulation Materials on Organic and Mineral Fillers. Lecture Notes in Civil Engineering, 2020;47: 354–360. https://doi.org/10.1007/978-3-030-27011-7_45.
42. Pietrucha T. Ability to determine the quality of indoor air in classrooms without sensors. E3S Web of Conferences. 2017;17:00073. https://doi.org/10.1051/e3sconf/20171700073.
43. Redko A, Dzhyoiev R, Davidenko A, Pavlovskaya A, Pavlovskiy S, Redko I, Kulikova N, Redko O. Aerodynamic processes and heat exchange in the furnace of a steam boiler with a secondary emitter. Alexandria Engineering Journal 2019; 58(1): 89-101. https://doi.org/10.1016/j.aej.2018.12.006.
44. Voznyak O, Spodyniuk N, Savchenko O, Sukholova I, Kasynets M. Enhancing of energetic and economic efficiency of coal mines heating by infrared heaters. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu 2021;2(182):104–109. https://doi.org/10.33271/nvngu/2021-2/104.
45. Zhelykh V, Voznyak O, Yurkevych Yu, Sukholova I, Dovbush O. Enhancing of energetic and economic efficiency of air distribution by swirled-compact air jets. Production Engineering Archives 2021; 27(3): 171 – 175. https://doi.org/10.30657/pea.2021.27.22.
46. Savchenko O, Voznyak O, Myroniuk K, Dovbush O. Thermal Renewal of Industrial Buildings Gas Supply System. Lecture Notes in Civil Engineering 2021; 100: 385–392. https://doi.org/10.1007/978-3-030-57340-9_47.
47. Shapoval S, Zhelykh V, Spodyniuk N, Dzeryn O, Gulai B. The effectiveness to use the distribution manifold in the construction of the solar wall for the conditions of circulation. Pollack periodica 2019; 14(2):143–154. https://doi.org/10.1556/606.2019.14.2.13.
48. Adamski M. Longitudinal spiral recuperators in ventilation systems of healthy buildings. HB 2006 - Healthy Buildings: Creating a Healthy Indoor Environment for People. Proceedings 2006; 4: 341–344.
49. Adamski M, Kiszkiel P. Condensation phenomena and frost problems in the air heat recuperators. MATEC Web of Conferences 2014; 18: 01001. https://doi.org/10.1051/matecconf/20141801001.

Received 2022-05-24
Accepted 2022-09-22
Available online 2022-09-23

Orest VOZNYAK
Received his MSc (1983) in Building, PhD (1990), DSc (2018) in Technical Sciences. Currently, he is Professor in the Department of Heat and Gas Supply and Ventilation at Lviv Polytechnic National University, Ukraine.

Nadiia SPODYNIUK
Received her MSc (2007) in Building, PhD (2011). Thesis: Energy efficient Heating provision of the poultry houses. Currently, she is Lecturer in the Department of Heat and Power Engineering at National University of Life and Environmental Sciences of Ukraine.

Olena SAVCHENKO
Received her MSc (1999) in Heat and Gas Supply and Ventilation, PhD (2008). Thesis: Frictional heating of natural gas in the energy separator.
Currently, she is Associate Professor in the Department of Heat and Gas Supply and Ventilation at Lviv Polytechnic National University, Ukraine.

Oleksandr DOVBUSH
Received his MSc (1984) in Building. Currently, he is Lecturer in the Department of Heat and Gas Supply and Ventilation at Lviv Polytechnic National University, Ukraine.

Mariana KASYNETS
Received her MSc (2009) in Building, PhD (2013). Thesis: Improvement of solar panels of periodic action that are combined with a cover of buildings.
urrently, she is Lecturer in the Department of Heat and Gas Supply and Ventilation at Lviv Polytechnic National University, Ukraine.

Oleksandra DATSKO
Received her MSc (1985) in Building, PhD (1994). Thesis: Improving the efficiency of solar heating systems by discrete orientation of solar collectors. Currently, she is Lecturer in the Department of Civil Safety at Lviv Polytechnic National University, Ukraine.