

Simplified Analysis of Turbulence Intensity in Curvilinear Wall Jets

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A simplified approach for estimation of turbulence intensity of turbulent submerged wall jets on cylindrical surfaces with different curvature is shown. It is a continuation of researches, performed by professor of Kyiv National University of Construction and Architecture Andrei Tkachuk. By using the geometric and kinematic analysis of turbulent macrostructure, it is proposed to found not only averaged flow characteristics but also turbulent pulsations. Analysis of visual researches of submerged jets in different works allows assuming such kind of flow as touching large round vortices (puffs), which roll by free flow boundary. In this work, geometric and kinematic analysis of this macrostructure chart in concave submerged wall jets is performed, and turbulence intensity is found. Results of the same analysis for submerged convex wall jets allow obtaining common dependencies for different curvature. The results are accepted by comparison with known experimental data.

Keywords: wall jet, turbulence intensity, jet boundary layer, large eddies, puffs.

1. INTRODUCTION

This work is based on the lecture "Geometric Analysis of Turbulence Parameters in Wall Jets Dependent on the Wall Curvature" at 17-th International Conference of Geometry and Graphics ICGG-2016, held by International Society of Geometry and Graphics (ISGG). The lecture has been strongly revised including remarks and question answers during the discussion on the Conference. The authors have a permit from ISGG for publication of this work after revisions outside the Society.

Energy efficient ventilation and air conditioning is possible only if air exchange organization (the design of air distribution and outlet) is efficient. Most of the flows in rooms are turbulent. It means that air velocity changes randomly (pulsates) in time.

If human body dissipates metabolic heat without stress for heat regulation system, the microclimate conditions are comfort. There are five microclimate factors: air temperature [1, 2], air humidity [1, 2], average temperature of all surfaces (radiant temperature) [1, 2], air velocity [1, 2], and turbulence intensity (relation between velocity pulsations and average velocity) of flows [2]. The turbulence intensity measuring and predicting is necessary, but it is a difficult task. Similar task may be also solved in aviation, ecology, urban aerodynamics etc.

Usually, the turbulence intensity for air exchange organization can be found by complex experimental researches in special laboratories or by computational fluid dynamic.

Computational fluid dynamic (CFD) software [3] is expensive. It requires powerful hardware. The arrangement of CFD simulation for optimization of air exchange organization is the same as physical experiments. We cannot obtain the optimal conditions from CFD equations directly.

Only one CFD model is universal, very precise and does not have any experimental constants or fictitious values. It is Direct Numerical Simulation (DNS) of Navier-Stokes Equations [4]. The main problem is very huge memory and time consumption because of very large computational mesh. Time and memory saving models [3, 5-9] are based on smaller mesh, replacing the lost data by fictitious values (e.g. turbulence viscosity), additional equations, and experimental coefficients. All of them are redundant and may be avoided if mathematics will provide more effective tools for average solution of unstable equations. Also, there are no proofs of universality of these experimental coefficients, so special tasks require experimental validation [8].

Unlike this, A. Tkachuk, the Professor of Kyiv National University of Construction and Architecture, has propose a theory of turbulent flows [10]. The main assumption is minimal influence of viscosity on developed turbulent flows. The flows can be accepted as ideal liquid flows with singularities – small vortices – that act as foreign bodies. Small-scale turbulent boundary layers at rupture of tangential velocity component can be accepted as films of round touching vortices as it shown on the figure 1 [10]. Kinematic analysis of this scheme gives the most of known experimental and semi-empirical equations for averaged flows in pipes, near to walls etc.

Continuation of this approach for turbulent subsonic submerged (inside the same air, liquid or gas) jet flows (hereinafter referred to as jets) may describe such flows without experimental constants and fictitious values.

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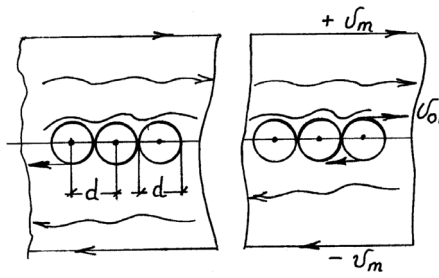


Figure 1: Scheme of tangential velocity rupture between velocity minus V_m [m/s] and plus V_m [m/s] (relative to the vortices axes) shown as a vortex sheet rotated with peripheral velocity V_0 [m/s]

2. MAIN CONCEPTS

Unlike near to wall flows, jets or mixing layers between flows contain large eddies so-called puffs. They stay visible by dyeing the flow [11, 12] at relatively small Reynolds number – up to 10^4 [12]. Different sources provide different data about Reynolds number influence on jet parameters. B. Gräff, H. Recknagel, E. Sprenger et al; P. Frings and J. Pfeifer [12] recommend the following equation of axial velocity u_m [m/s], related to initial velocity u_0 [m/s], for main part of a free axis-symmetrical jet from a nozzle of diameter D_0 [m] and area A_0 [m²] at distance x [m] from it:

$$u_m / u_0 = (1 / m') (D_0 / x), \quad (1)$$

where m' is coefficient of mixing of jet and ambient air (liquid, gas). For small initial turbulence $m' = 0.1 \dots 0.2$; for great one – $m' = 0.2 \dots 0.5$.

Independently, M. Grititlin [13] has obtained the equation, analogous to (1):

$$u_m / u_0 = m A_0^{1/2} / x, \quad (2)$$

where $m = 2 / (\pi^{1/2} m')$ is a coefficient of axial velocity change. Let us accept data of [13] for near to constant temperature and typical local resistance coefficient of nozzle $\xi = 1.1$. Using the equations (1, 2), it is possible to obtain typical values in ventilation $m' = 0.17$ or $m = 6,8$ as at small initial turbulence. The “great” initial turbulence [13] can be obtained by special turbulators at the nozzles, used in special air diffusers. However, for simple nozzle the value at small turbulence is applicable for ventilation in a wide range of Reynolds number.

On other side, if high-ordered large-scale vorticity does not visualize, its absence is not proved. Maybe, medium-scale vorticity inside the large-scale vortices is visualized. Thus, for ventilation tasks it is possible to enlarge the scope of dependencies, obtained using the visualizations at low Reynolds number, to cover a wide range of Reynolds number.

By A. Tkachuk’s theory, a jet can be presented as a large-scale vortex sheet. The averaged shape of the puffs is near to round. All jets inject the ambient air (fluid, gas) in the direction, normal to the jet direction.

Let us consider a concave wall jet near to a concave cylindrical wall (figure 2). It consists of two layers: thin wall boundary layer between the wall w and the division line d , and also, thick jet boundary layer between the line d and the boundary line b .

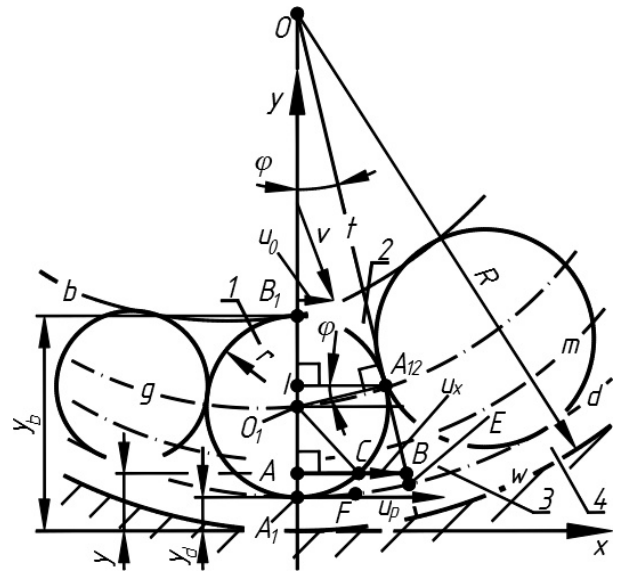


Figure 2: Scheme of concave wall jet: 1 – puff; 2 – external part of interpuff layer; 3 – internal part of interpuff layer

The puff centre locus is the line g . The locus of maximum velocity in sections is the line m .

Any concave wall jet always runs in an accompanying flow with velocity u_b [m/s]. The last caused by the injection flow with velocity v [m/s], to next flow sections. Usually, it is considered as a part of the wall boundary layer. Nevertheless, in this work we will describe only the pure jet boundary layer with the puffs.

Let us choose a puff 1 with radius r [m] and use a Euclidean coordinate system x, y . Its y -axis goes away from the wall w and contains the puff 1 and the wall w centres. The x -axis is a tangent to the wall w in the jet direction. It is possible to neglect jet expansion during passage of the puff 1 through the y -axis. This allows replacing time averaging by averaging along a line at fixed y [m] inside a quasi-period (or half-period) of the macrostructure with the puff.

In external part of the interpuff layer 2 there is only injection to the flow. Therefore, the x -velocity is equal to u_b [m/s]. In internal part 3 we only can interpolate x -velocity u_x [m/s] by a polynomial that is dependent on y only.

3. GEOMETRIC ANALYSIS OF THE SIMPLIFIED MACROSTRUCTURE CHART

At first, the quasi-period with the puff 1 may be defined. Let us define a line t as a tangent to the puff 1 from the wall w centre O downstream relatively to the axis y . The tangent point is A_{12} . The point A_1 is the nearest point on the puff 1 to the wall w (on the line d) in the section along the axis y . Its ordinate is y_d [m]. The most distant point in the same section (on the line b) is B_1 with ordinate y_b [m]. The centre of the puff 1 has the ordinate [m]

$$y_c = (y_b + y_d) / 2. \quad (3)$$

The puff radius [m]

$$r = (y_b - y_d) / 2. \quad (4)$$

Angle ϕ between the tangent t and the axis y can be found from the right triangle $\Delta OA_{12}O_1$ with the right

angle $OA_{12}O_1$, known opposite leg $|A_{12}O_1| = r$ [m], and hypotenuse $|OO_1| = R - y_c$ [m]. Using the equations (3, 4):

$$\sin(\varphi) = (y_b - y_d) / (2R - y_b - y_d). \quad (5)$$

A line designation between vertical lines (absolute value) in this work means length of the corresponding line. Tangent of the angle:

$$\tan(\varphi) = \frac{1}{2} \left(\frac{R - y_d}{y_b - y_d} \left(\frac{R - y_d}{y_b - y_d} - 1 \right) \right)^{-1/2}. \quad (6)$$

At some fixed y [m] there is a line AB , parallel to the x -axis. The point A is on the y -axis, the point B is on the line t . Velocity averaging may be performed by this line. Let us call C the intersection of the line AB and the puff 1 boundary. For the averaging we need to know length [m] of both parts of the line: AC and BC . Length [m] of the line AB using the equations (4, 6):

$$\begin{aligned} |AB| &= (R - y) \tan(\varphi) = \\ &= \frac{1}{2} (R - y) \left/ \left(\frac{R - y_d}{y_b - y_d} \left(\frac{R - y_d}{y_b - y_d} - 1 \right) \right)^{1/2} \right. \end{aligned} \quad (7)$$

Length of the line AC [m], may be found from the right triangle ΔCAO_1 . The knowns are the hypotenuse $|O_1C| = r$ [m] and the leg $|AO_1| = |y - y_c|$ [m] for both cases: $y \geq y_c$ and $y < y_c$. Using the equations (3, 4):

$$\begin{aligned} |AC| &= \left(r^2 - (y - y_c)^2 \right)^{1/2} = \\ &= (y_b - y_d) \left(\frac{y - y_d}{y_b - y_d} \left(1 - \frac{y - y_d}{y_b - y_d} \right) \right)^{1/2}. \end{aligned} \quad (8)$$

Length [m] of the line BC can be found as difference between length [m] of the lines AB and AC :

$$\begin{aligned} |BC| &= \frac{1}{2} \frac{R - y}{\left(\frac{R - y_d}{y_b - y_d} \left(\frac{R - y_d}{y_b - y_d} - 1 \right) \right)^{1/2}} - \\ &- (y_b - y_d) \left(\frac{y - y_d}{y_b - y_d} \left(1 - \frac{y - y_d}{y_b - y_d} \right) \right)^{1/2}. \end{aligned} \quad (9)$$

To simplify calculations, the following formulas will be used, which can be checked by removing of parentheses:

$$a(1 - a) = (1 - (2a - 1)^2) / 4; \quad (10)$$

$$a(a - 1) = ((2a - 1)^2 - 1) / 4. \quad (11)$$

By the equations (7-11), both parts of AC and BC in AB are

$$\tilde{\varepsilon} = \frac{|AC|}{|AB|} = \frac{(1 - (2\tilde{y} - 1)^2)^{1/2} \left((2\tilde{R} - 1)^2 - 1 \right)^{1/2}}{2(\tilde{R} - \tilde{y})}; \quad (12)$$

$$\frac{|BC|}{|AB|} = 1 - \tilde{\varepsilon} = 1 - \frac{(1 - (2\tilde{y} - 1)^2)^{1/2} \left((2\tilde{R} - 1)^2 - 1 \right)^{1/2}}{2(\tilde{R} - \tilde{y})}, \quad (13)$$

where relative ordinate and radius:

$$\tilde{y} = (y - y_d) / (y_b - y_d); \quad (14)$$

$$\tilde{R} = (R - y_d) / (y_b - y_d). \quad (15)$$

At last, we need ordinate [m] of the touch point A_{12} . Let us draw perpendicular $A_{12}I$ from the touch point A_{12} to y . The point I is on the y -axis. To find length $|A_{12}I|$ [m] it is possible to use the right triangle ΔO_1IA_{12} . The angle O_1IA_{12} is right. The length $|A_{12}O_1| = r$ [m]. The angle $IA_{12}O_1 = \varphi$ because $A_{12}I \perp y$ and $A_{12}O_1 \perp t$. Thus length [m] of the line IO_1 ,

$$|IO_1| = r \cdot \sin(\varphi) = \frac{1}{2} \cdot \frac{(y_b - y_d)^2}{2R - y_b - y_d}. \quad (16)$$

The ordinate [m] is

$$y_t = |IO_1| + y_c. \quad (17)$$

By the equations (3, 14, 16, 17) after simple transformations, the relative ordinate of the touch point

$$\tilde{y}_t = (y - y_d) / (y_b - y_d) = \tilde{R} / (2\tilde{R} - 1). \quad (18)$$

4. KINEMATIC ANALYSIS

The puffs roll on the free boundary as wheels. X -velocity u_x [m/s] is linearly dependent on y [m] by the Euler formulas for rotation [14]. At the free boundary (point B_1) it is u_b [m/s]. Let us call the velocity at the division line (point A_1) u_d [m/s]. Let us accept the surplus x -velocity [m/s]

$$\Delta u_x = u_x - u_b. \quad (19)$$

The surplus x -velocity [m/s], using the equation (19), in the puff is

$$\Delta u_{x,p} = \Delta u_d (1 - \tilde{y}). \quad (20)$$

The x -velocity [m/s] in both parts of the interpuff layer can be found by the following equation

$$\Delta u_{x,i} = \Delta u_d P(\tilde{y}), \quad (21)$$

where P is a polynomial. For the external part the P is the simplest polynomial with all zero coefficients (identically equal to zero).

Both equations (20, 21) are independent on x [m] between the lines y and t . Therefore, difference between local and average velocity [m/s] is also independent on x [m]. Averaging by the line AB of any value a that is x -independent separately in the puff (a_p) and the interpuff layer (a_i) can be performed by the following equation:

$$\bar{a} = a_p (|AC|/|AB|) + a_i (|BC|/|AB|). \quad (22)$$

The straight over-line above an expression in this work means averaging of it.

Averaged surplus x -velocity [m/s] by the equations (15-18) after replacing a by Δu [m] and simple transformations is

$$\overline{\Delta u_x} = \Delta u_d \left((1 - \tilde{y} - P(\tilde{y})) \tilde{\varepsilon} + P(\tilde{y}) \right). \quad (23)$$

The pulsation velocity [m/s] can be found as root-mean-square of the velocity, using the equations (15, 16, 19):

$$u'_x = \left(\overline{(u_x - \bar{u}_x)^2} \right)^{1/2} = \left(\overline{(\Delta u_x - \bar{\Delta u}_x)^2} \right)^{1/2} = \Delta u_d |1 - \tilde{y} - P(\tilde{y}) \left(\tilde{\varepsilon} (1 - \tilde{\varepsilon}) \right)^{1/2}. \quad (24)$$

5. COMMON EQUATIONS FOR CONVEX AND CONCAVE WALL JETS

The same reasoning as for the equations (3-24), but for a convex wall, gives the similar equations as (18, 24), but with different signs. Therefore, the relative radius, the part of AC line, and the touch point ordinate are

$$\tilde{R} = (R \pm y_d) / (y_b - y_d); \quad (25)$$

$$\frac{|AC|}{|AB|} = \tilde{\varepsilon} = \frac{\left(1 - (2\tilde{y} - 1)^2 \right)^{1/2} \left((2\tilde{R} \pm 1)^2 - 1 \right)^{1/2}}{2(\tilde{R} \pm \tilde{y})}; \quad (26)$$

$$\tilde{y}_t = \tilde{R} / (2\tilde{R} \pm 1). \quad (27)$$

The top sign of the formulas (25-27) is for the convex jets. The bottom sign is for the concave jets. If there is no external flow, the convex jets does not produce an accompanying flow. By “old theory”, the boundary velocity u_b is zero. In this case $\Delta u = u$ [m/s]. By “modern theory”, the velocity profile is asymptotic and it is necessary to use Δu [m/s]. Both theories provide close results with acceptable deviation for ventilation.

The equation (24) may be used with formulas (25-27) after replacing the arc above the parameter ε by tilde. Turbulence intensity of jets is usually related to maximum velocity u_m , m/s, in a section:

$$\varepsilon = \frac{u'_x}{u_m} = \frac{\Delta u_p}{\Delta u_m} |1 - \tilde{y} - P(\tilde{y}) \left(\tilde{\varepsilon} (1 - \tilde{\varepsilon}) \right)^{1/2} \left[\frac{\Delta u_m}{u_m} \right]. \quad (28)$$

In the equation (28) the expression in the square brackets is only for the concave jets or convex jets by “modern theory”. For the convex jets by “old theory” it is equal to one. The maximum velocity u_m , m/s, may be found from the equation (23), using numerical optimization methods or bulky derivatives for convex or concave jets separately.

Let us accept I. Shepelev’s hypothesis [15] that it is possible to eliminate the wall boundary layer from consideration. Author’s refinement says that the puffs may be imaginary enlarged to the wall w . In this case, $y_b \approx 0$. The wall boundary layer stay thin and may be simulated by the A. Tkachuk’s theory as a very thin vortex film that act as a lubricant. Therefore, at the points A_1 , F and E velocity is near to u_p [m/s]. At the point A_{12} velocity is near to translational velocity of the puff $u_p/2$ [m/s]. The simplest polynomial P for the internal part 3 of the interpuff layer is a constant – average velocity by the points above:

$$P(\tilde{y}) = (3/4) - (u_b / u_p) \text{ at } \tilde{y} < \tilde{y}_t. \quad (29)$$

For the concave or flat wall jet, if using “old theory”, $u_b \approx 0$. Thus, the polynomial by the equation (29) is 3/4.

In the external part at $\tilde{y} \geq \tilde{y}_t$ the polynomial is zero.

6. ANALYSIS OF THE RESULTS

As only large-scale vorticity is considered, the results (figure 3) may be less than experimental data. For convex jets the intensity changes below 5 % ($\varepsilon = 0.1239 \dots 0.1304$) at $\tilde{R} \geq 2.14$.

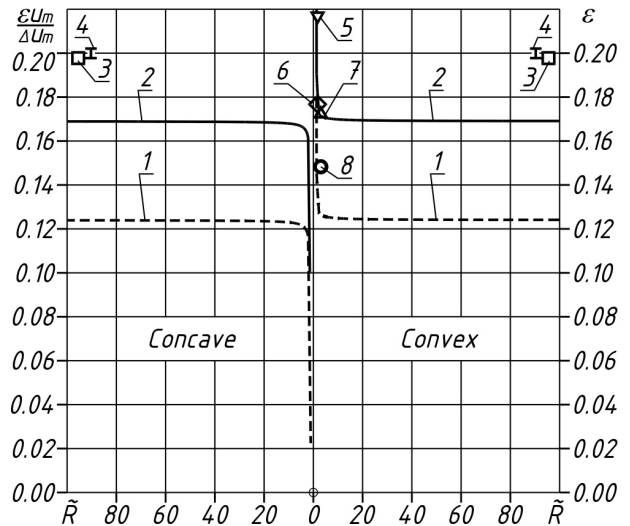


Figure 3: Maximum turbulence intensity in jets dependent on the relative wall radius: 1 – calculation results, 2 – corrected results using correction for turbulence intensity of inflow, 3 - experimental data for flat jets of J. G. Eriksson, R. I. Karlsson, and J. Persson [4]; 4 – DNS (direct numeric solution of Navier-Stokes equation) simulation results [4]; 5 – experimental data [16] at $\varphi = 65^\circ$ and initial Reynold's number 9340; 6 – the same at $\varphi = 65^\circ$ and initial Reynold's number 21040; 7 – the same at $\varphi = 35^\circ$ and initial Reynold's number 9340; 8 – the same at $\varphi = 35^\circ$ and initial Reynold's number 21040

For concave jets the intensity changes below 5 % ($\varepsilon [u_m / \Delta u_m] = 0.1180 \dots 0.1239$) at $\tilde{R} \leq 2.40$. This intensity change is equal to experimental errors, and it can be neglected.

Out of the ranges there is avalanche-like increase (convex jets) or decrease (concave jets) of turbulence intensity. It shows the jet detach (convex jets) or destroy due to geometric incompatibility between the wall and the puffs (concave jets).

The experimental data [16] for convex jets (figure 3) is differs up to 0.08. It is the influence of medium- and small-scale vorticity. It is possible to assume that the jet consumes the turbulent vorticity in injection flow to the jet. It can be assumed [17] as near to 0.055 (5.5 %), and it is possible to add it to the results and obtain the ideal difference – up to 0.025. For the concave jets (by experimental data of Tailand & Mathieu, Wilson & Goldstein and Spettel at al.) this value [18] is greater ($\varepsilon = 0.16 \dots 0.22$) due to additional Görtler’s medium-scale vortices. However, using plus 0.055 correction the deviation is up to 0.047, and it is enough for ventilation.

Thus, the geometric analysis of puffs gives a possibility of turbulence intensity prediction in wall jets because in most cases the large-scale turbulence gives a

greater part of the total turbulence intensity. In addition, this approach can predict the jet detach or destroy.

Future researches will be directed on jets interaction.

1. CONCLUSION

The approach to calculating turbulence intensity in jets, mixing layers between flows etc., caused by large-scale vorticity, without any fictitious values or experimental coefficients is proposed. The equations for the turbulence intensity calculation of the wall jets with different curvature are obtained. It is shown that the maximum turbulence intensity calculated by the large-scale vorticity only is lower than experimental values. This difference is caused by the small- and medium-scale vorticity. Deviation of results is very good after accepting the correction for injection flow turbulence. The approach is helpful for the developers of air distribution devices for ventilation and air conditioning.

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NOMENCLATURE

A	Area [m ²]
a	any value (intermediate result)
D	Diameter [m]
m	coefficient of axial velocity change $m = 2 / (\pi^{1/2} m')$
m'	coefficient of mixing of jet and ambient air
P	polynomial
R	radius of the wall [m]

r	radius of the selected puff [m]
u	velocity in jet [m/s]
u'	pulsation velocity [m/s]
v	velocity of injection flow to the jet [m/s]
x, y	coordinates [m]

Greek symbols

Δu	surplus velocity [m/s]
ε	turbulence intensity in jet $\varepsilon = u' / u_m$
Ξ	relation between length of legs AC and AB in convex wall jets $\Xi = AC / AB $
ξ	local resistance coefficient of nozzle
π	pi constant $\pi = 3.14159\dots$
φ	angle of tangent of the selected puff in radians

Subscripts

0	jet output (initial)
b	free jet boundary
c	puff centre
d	division line between boundary layers
i	interpuff layer
m	locus of maximum velocity
p	puff
t	touch point of puffs
x	projection on x -axis

Overlines

\frown	relative value for concave jets
\sim	puff centre
—	averaging

УПРОШЋЕНА АНАЛИЗА ИНТЕНЗИТЕТА ТУРБУЛЕНЦИЈЕ КОД ЗАКРИВЉЕНИХ ЗИДНИХ МЛАЗЕВА

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Циубенко

Приказан је упрошћени приступ процени интензитета турбуленције код турбулентних потоњених зидних млазева на цилиндричним површинама различите закривљености. Рад представља наставак истраживања Андреја Ткачука, професора Националног грађевинског и архитектонског факултета у Кијеву. Геометријском и кинематичком анализом турбулентне макроструктуре предлаже се успостављање не само карактеристика просечног струјања већ и турбулентних пулсација. Анализа визуелних истраживања потоњених млазева допушта да се претпостави да постоји такво струјање јер се додирује са великим кружним вртлозима (вировима), који се крећу уз зидове слободних граница струјања.

Извршена је геометријска и кинематичка анализа дијаграма макроструктуре код конкавних потоњених зидних млазева и утврђен је интензитет турбуленције. Резултати исте анализе спроведене код потоњених конвексних зидних млазева омогућили су да добијемо заједничке зависности за различита закривљења. Резултати су потврђени упоређивањем са познатим експерименталним подацима.