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Impact of Frictional Resistance of End Plates on Flat Jet Attenuation

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Abstract: During this study impact of frictional resistance of end plates on flat jet attenuating was experimentally investigated. It was established that laminar, turbulent and transition layer may exist on end surfaces depending on particular conditions. Empiric expressions to change maximum jet velocity have been acquired.

Key words: Jet, friction, impact, turbulent, laminar

INTRODUCTION

As a result of experimental studies held during recent years (Faghani *et al*., 2010) it has been established that at jet out flowing from a rectangular nozzle various types of velocity profiles of mean flow develop in between flat plates limiting from the ends depending on the structure of coherent vortexes within the jet initial study.

Development types of large scale vortexes in the initial section of flat jet limited by end walls and their impact on profiles of the jet mean flow are analyzed in the study (Abramovich *et al*., 1984).

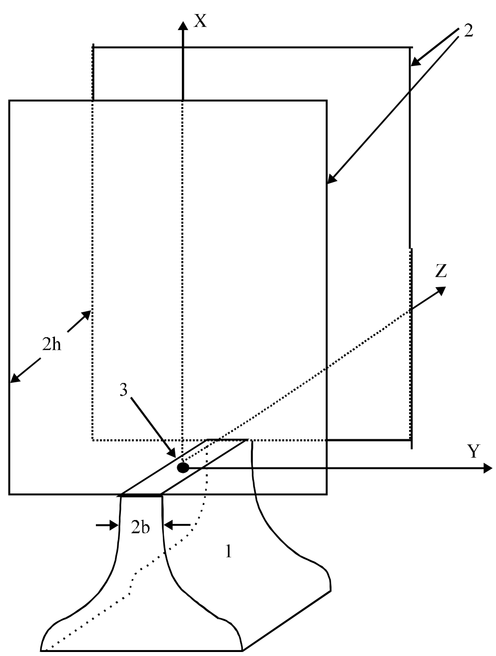

Fig. 1: Test unit layout; 1: nozzle; 2: limiting plates; 3: origin of coordinates

In recent times study of coherent structures of flow of wall jets is given great attention (Namgyal and Hall, 2013). This area is an important subject for study. Going forward to study flow dynamic characteristics is also important. In this research impact of frictional resistance of end plates on flat jet development regularities was experimentally investigated.

Layout of test unit and directions of axes of coordinates are shown in Fig. 1. Jet flows out from rectangular nozzle with 2b wide and 2h high corresponding also to the distance between the end plates limiting the jet.

MAIN BODY

Geometrical parameter $\lambda = 2h/2b$ characterizes relative elongation of nozzle exit section. Jets with changing λ value in the range from 3-25 were studied in tests.

To estimate impact of frictional resistance of end plates on attenuating intensity of flat free turbulent jet one should first of all experimentally define regularities of changing resistance at the wall. Up to now regularities of changing frictional resistance at the surface of the plates at flowing around with turbulent wall jet have been studied (for instance in the study (Sigalla, 1958)). With the values $\lambda>10$ and relatively small thickness of transition layer at the surface of end wall $\delta<<2b$ one may assume similarity of wall transition layer to the transition layer on the plate with homogenous current flowing around. Changes in friction stress and resistance factor on the end surface along and across jet direction for certain λ values are shown in Fig. 2-6.

As well known free jet turns to turbulent beginning from Re>50 and within major jet section along the axis turbulence level $\varepsilon_{U_m} = \sqrt{U'^2_m}/U_m$ goes up to values 20÷30%, where U_m is jet axis velocity, $\sqrt{U'^2_m}$ is axial root mean square pulsation.

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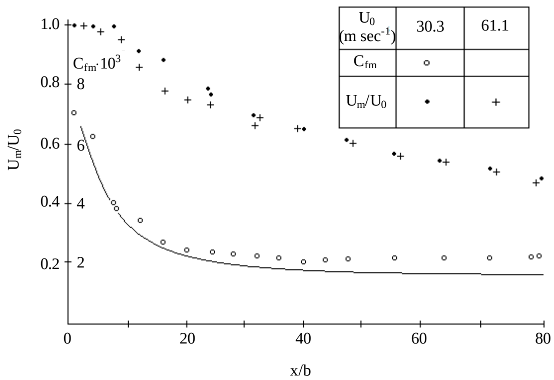

Fig. 2: Changing of axial velocity and friction factor with λ = 16 and $Re_0 = U_0 2b/v$ = 4518

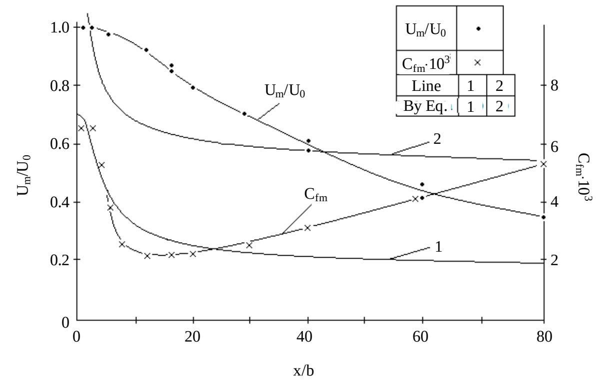

Fig. 4: Changing of friction factor at the end wall at value λ = 4, U_0 = 30 m sec^{-1}

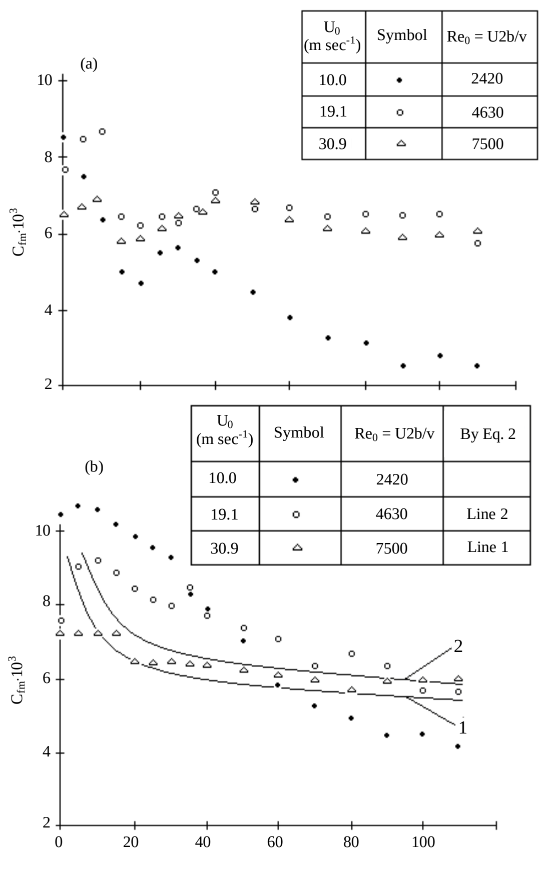

Fig. 3: a) Changing of friction factor at the end wall with smooth coherence of the plate with the nozzle edge for value λ = 25 and b) changing of friction factor at the end wall with availability of turbulator at the nozzle edge for value λ = 25

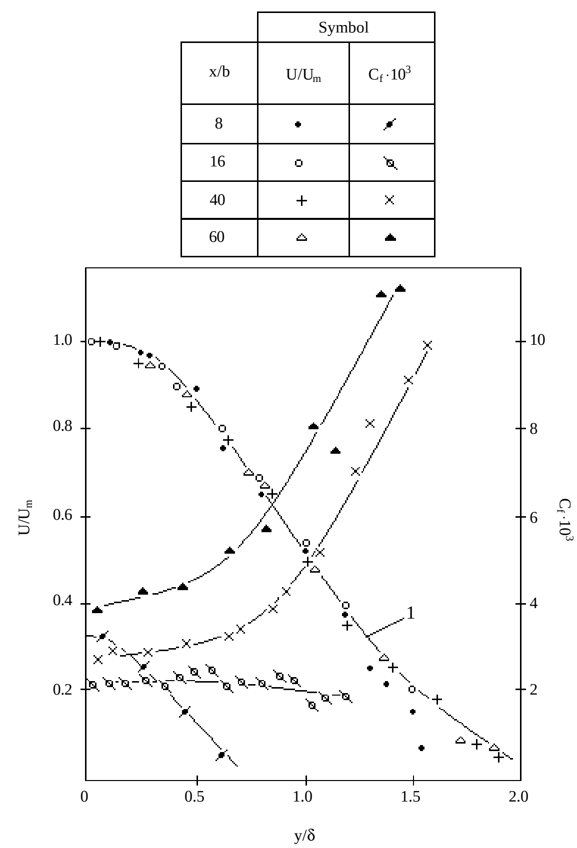

Fig. 5: Velocity distribution in plane of symmetry (z = 0) and friction coefficient at the end walls at λ = 4, U_0 = 30 m sec^{-1}

When a flat surface is longitudinally flowed by homogeneous flow laminar transition layer may exist up to values $R_{e_x} = U_0 x/v \le 5 \cdot 10^5$, where x-longitudinal distance, U_0-velocity at the nozzle edge. However, due to high jet turbulence level it could have been expected that transition layer at the end walls should be turbulent practically across the entire surface of end plates.

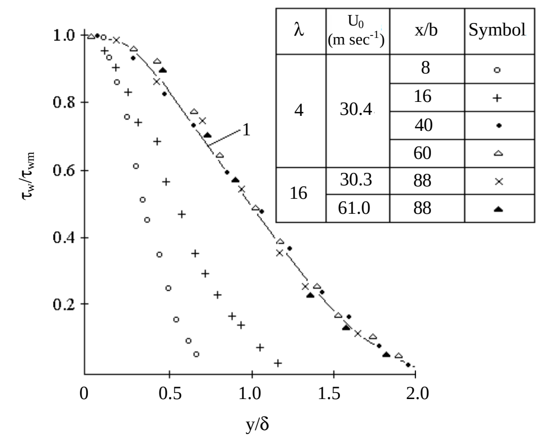

Fig. 6: Distribution of friction stress at the end walls

RESULTS

Tests showed that in fact laminar, turbulent layer and transition layer may exist on end surfaces depending on particular conditions. For instance on the jet end surface with $\lambda = 16$ and initial velocity $U_0 = 30.3$ m sec^{-1} (Fig. 2) throughout, the jet entire length up to 100 calibers changing rate of friction resistance coefficient coincides with theoretical dependency for a plate flowed by a homogenous current with a laminar transition layer:

$$C_f = \frac{0.664}{\sqrt{Re_{mx}}} \quad (1)$$

where, $Re_{mx} = (U_m x)/\nu$. Line in the Fig. 2 corresponds to calculation by Eq. 1. Figure 3a and b show results of changing friction resistance coefficient along end plate alongside the current axis for $\lambda = 25$ at various values of initial velocity. As you can see from Fig. 3a that at smooth coherence of the end plate with the nozzle walls originally a laminar transition layer develops which then turns in turbulent at the end of the initial section. However, at the initial jet velocity $U_0 = 10$ m sec^{-1} friction coefficient at the wall gradually decreases as distance from the nozzle grows approaching to its value at laminar transition layer.

At having turbulized peak with height ~0.4 mm at the boundary of nozzle exit section and the end wall a turbulent transition layer appears from the very beginning just like when flowed by a homogenous current. In Fig. 3b, lines 1 and 2 are built by the following theoretical dependency:

$$C_f = \frac{0.0576}{\left(\frac{U_m x}{\nu}\right)^{0.2}} \quad (2)$$

for initial jet velocities 30.9 and 19.0 m sec^{-1}. Test results with Eq. 2 coincide to a satisfactory degree with at $U_0 = 19.1$ and 30.9 m sec^{-1}. However, values of test data at $U_0 = 10$ do not correspond to this dependency.

Figure 4 shows results of measuring friction resistance coefficient at the end wall with value $\lambda = 4$. $U_0 = 30$ m sec^{-1}. Here, you can see that a laminar transition layer appears in the initial friction section which gradually turns into a well developed turbulent transition layer to a large length extent. This figure also shows lines 1 and 2 calculated by Eq. 1 and 2.

Thereby as you can see that both laminar and turbulent transition layers may develop at the end walls with resistances described by Eq. 1 and 2. It's interesting to notice that a high level of turbulence of jet flow does not affect intensity of frictional resistance to a significant extent. Figure 5 shows velocity profiles along the axis y at z = 0 in coordinates $U/U_m = f(y/\delta)$ and friction resistance coefficient $C_f = \tau_w/\rho U^2/2$ at the end wall at various proximities from the nozzle for value $\lambda = 4$, $U_0 = 30$ m sec^{-1}. As you can see velocity profiles have affine similarity though distribution of friction coefficient has no such regularity. However, friction stress distribution profiles in various sections of the major length at x/b>30 in coordinates $\tau_w/\tau_{wm} = f(y/\delta)$, where δ-conditional jet width at $U = U_m/2$ have affine similarity (Fig. 6). As one can see size-less profile of friction stress coincides with size-less velocity profile.

Lines 1 in Fig. 5 and 6 correspond to velocity profile first offered by Schlichting in the polynomial form:

$$\frac{U}{U_m} = 1 - 6\eta^2 + 8\eta^3 - 3\eta^4 \quad (3)$$

where, $\eta = y/\delta_c$, δ_c-full half-width of the jet equal to the distance from the axis to the external boundary at U = 0 and related to the conditional width $\delta_c = 2.59\delta$.

In connection with the above matter it's required to compute impact of frictional resistance of end plates on jet attenuating at both laminar and turbulent transition layers.

Based on these data computation of impact of resistance of turbulent transition layer of end surfaces on change in maximum velocity was carried out and as a result the following formula was acquired:

$$\frac{U_m}{U_0} = \frac{N}{\sqrt{\frac{x}{b}+\frac{x_0}{b}}} \exp\left\{-\frac{0.1481}{A}\left(\frac{x}{b}\right)^{0.9} + \frac{0.01372}{A^2}\left(\frac{x}{b}\right)^{1.8} - \frac{0.00288}{A^3}\left(\frac{x}{b}\right)^{0.27}\right\} \quad (4)$$

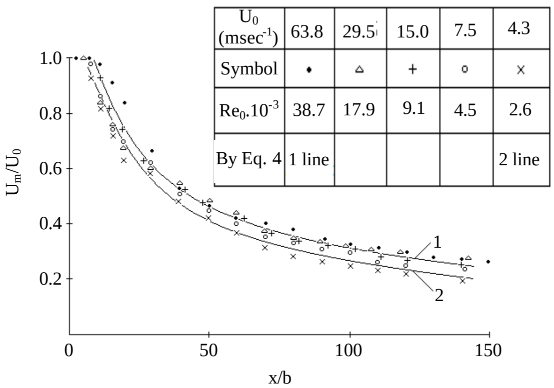

Fig. 7: Change in jet axial velocity $\lambda = 3$

where, $A = \lambda Re_0^{0.2} N^{0.2}$, $\lambda 2h/2b$, $Re_0 = U_0 2b/v$, x_0-polar distance. Calculations by this formula show that correction for velocity decrement makes up to 35% for $\lambda<10$.

Comparison of computation results by Eq. 4 in shown in Fig. 7 at $\lambda = 3$ and $U_0 = 4.3$ and 63.8 m sec^{-1}. Herewith, it should be taken into account that in Fig. 7 value of measured maximum velocity corresponds to the jet axial line. Maximum velocity values were computed in theoretical calculations averaged by axis z throughout the entire jet height. Therefore, test values of maximum velocity must be a little more than theoretically specified values.

CONCLUSION

It is found that there can exist three types of a large-scale vortex. In case of sufficient compression of the nozzle, the jet of current is as a rule, laminar at the output from nozzle. Owing to unstable current in vacant frontier layer discontinuous vortexes are formed, axis of which are parallel to the nozzle edge. These vortexes either set against end plate or circled on themselves, forming vortex ring.

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