SPREADING OF A BOUNDARY JET IN A COUNTER FLOW

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Counter jet flows may be used successfully as flame stabilizers in pulverized-coal and fuel oil burners [1], in order to increase heat exchange processes in gas suspensions [2], and in a number of other technical applications.

Results are given in [3-6] for experimental studies of free counter jet flows. An approximate integral method is described in [7] for calculation of these flows making it possible to obtain quite good agreement with most of the available experimental results.

Apart from specific progress in studying free counter jet flows there are almost no studies of boundary counter jets. As has been shown in experiments performed by us, boundary counter jets may markedly increase the process of heat transfer between a gas flow and the wall of a channel, and they may be used in order to control heat exchange [8]. The importance of developing methods for calculating these flows is connected with using them in order to organize thermal protection of production equipment from high-temperature gas flows [9].

The aim of the present work is to calculate spreading of a plane boundary counter jet in a restricted channel and to compare some of the most important calculated characteristics with experimental results obtained by us.

Given in Fig. 1 is a diagram of the flow of a boundary jet in a counter flow taken for the calculation. According to the diagram the air flow moves with a velocity of u_0 in a plane channel of height H. An air jet with velocity u_s is fed counter to it from a slot of height s in the lower part of the channel. The boundary jet velocity decreases gradually as it penetrates into the air flow and it becomes equal to zero, then the jet turns around and it is brought together with the flow. The most important characteristics of the flow are: ℓ is carry of the boundary jet, δ is thickness of the displacement layer in the zone of jet development, δ_1 and u_1 are thickness of the displacement layer and maximum velocity of the flow above the slot exit section. We determine these values in a similar way to that for an axisymmetrical free jet in [7].

We consider the contour bounded by transverse sections A and B (Fig. 1). We write for this contour equations for mass conservation and the amounts of movement ignoring friction resistance at the channel walls:

$$\rho u_s s + \rho u_0 H - \rho u_1 (H - \delta_1 - s) - \int_s^{s+\delta_1} \rho u dy = 0; \quad (1)$$

$$\rho u_s^2 s - \rho u_0^2 H + \rho u_1^2 (H - \delta_1 - s) + \int_s^{s+\delta_1} \rho u dy = \Delta p H \quad (2)$$

(Δp is difference between static pressures in sections A and B). Here it is assumed that static pressures are constant in the sections in question.

The air flow in a restricted channel, by going round the jet turning zone, increases its velocity from u_0 to u_1. Therefore the difference in static pressures is found from the Bernoulli equation $\Delta p = (\rho/2)(u_1^2 - u_0^2)$. We assume that the velocity profile in the displacement layer above the slot exit section is exponential:

$$\frac{u}{u_1} = \left(\frac{y - s}{\delta_1}\right)^n. \quad (3)$$

By substituting the expression for velocity (3) in Eqs. (1) and (2) and integrating we determine in dimensionless form layer displacement, layer velocity, and thickness above the exit section of the slot:

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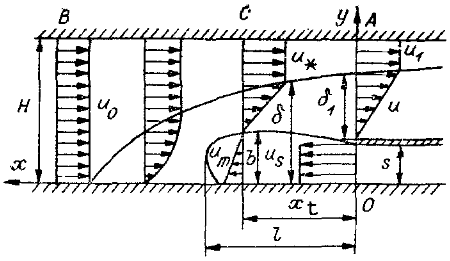

Fig. 1

$$\bar{u}_1 = \frac{m + \bar{H}}{\bar{H} - 1 - \frac{n}{n+1}\bar{\delta}_1}; \quad (4)$$

$$\bar{\delta}_1 = \frac{2n+1}{2n}\left[\frac{2m^2 + \bar{H}(\bar{u}_1^2 - 1)}{2\bar{u}_1^2} - 1\right]. \quad (5)$$

Here $m = \rho_s u_s/\rho_0 u_0 = u_s/u_0$ (with $\rho_s = \rho_0$) is injection parameter; $\bar{u}_1 = u_1/u_0$; $\bar{H} = H/s$, $\bar{\delta}_1 = \delta_1/s$. Expressions (4) and (5) make it possible to determine values of $\bar{u}_1$ and $\bar{\delta}_1$ for arbitrary smallness of the velocity profile above the slot exit section. Assuming for simplicity that the velocity profile is linear (n = 1), which is quite well confirmed by our experimental results for an adjacent shear displacement layer with counter injection, we find that

$$\bar{u}_1 = \frac{2(m + \bar{H})}{2(\bar{H} - 1) - \bar{\delta}_1}; \quad (6)$$

$$\bar{\delta}_1 = 0.75\,\frac{2m^2 + \bar{H}(\bar{u}_1^2 - 1)}{\bar{u}_1^2} - 1.5. \quad (7)$$

By solving (6) and (7) together we obtain a quadratic equation with respect to $\bar{u}_1$ one of whose roots has a physical meaning:

$$\bar{u}_1 = \frac{4(m + \bar{H}) + \sqrt{4m^2 + 30\bar{H}m^2 + 34m\bar{H} + \bar{H}^2 + 6\bar{H}}}{5\bar{H} - 2}. \quad (8)$$

Thus, expressions (7) and (8) make it possible to calculate for the given relation channel height $\bar{H}$ and injection parameter m the velocity above the slot exit section $\bar{u}_1$ and the thickness of the displacement layer $\bar{\delta}_1$.

Given in Fig. 2a are the results of calculating the flow rate above the slot exit section with counter boundary injection in relation to channel constraint $\bar{H}$ by Eq. (8). It follows from Fig. 2a that the smaller the relative channel height, the more marked is the increase in flow rate with the same injection rate. In channels with an identical relative height with an increase in injection parameter m an increase is observed in the velocity above the slot exit section.

Presented in Fig. 2b are the results of calculations by Eqs. (7) and (8) of the dependence of displacement zone thickness above the slot exit section on channel constraint; it can be seen that with an increase in relative channel height there is an increase in the displacement layer above the slot exit section and the relative height of the displacement layer with given $\bar{H}$ is greater, the higher the injection rate. The broken line relates to $\bar{\delta}_1 = \bar{H} - 1$ and it shows the maximum displacement layer height when it reaches the upper wall of the channel.

We determine the range $\bar{l}$ of a plane counter jet with m > 1. For this we write an equation for mass conservation and the amount of movement for the contour bounded by section B and one of the transverse sections which are in the jet expansion zone:

$$\rho u_0 H + \int_0^b \rho u dy - \int_b^\delta \rho u dy - \rho u_*(H - \delta) = 0; \quad (9)$$

$$\int_0^b u^2 dy - u_0^2 H + \int_b^\delta u^2 dy + u_*^2(H - \delta) = \frac{\Delta p}{\rho} H. \quad (10)$$

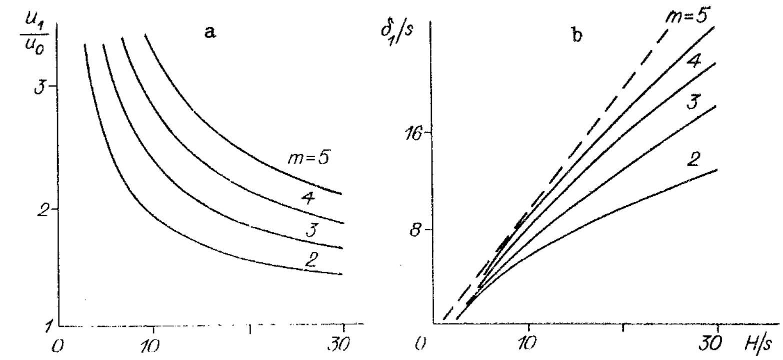

Fig. 2

We take velocity profiles as exponential:

$$\text{with } 0<y<b \qquad \frac{u}{u_m}=\left(\frac{b-y}{b}\right)^n,$$

$$\text{with } b<y<0 \qquad \frac{u}{u_*}=\left(\frac{y-b}{\delta-b}\right)^n$$

(b is expanding counter jet thickness).

By calculating integrals and moving to a dimensionless form for (9) and (10) we obtain

$$\frac{\bar b}{n+1}(\bar u_m+\bar u_*)+\bar u_*\bar\delta\,\frac{n}{n+1}-\bar H(\bar u_*-1)=0; \tag{11}$$

$$\frac{\bar b}{2n+1}(\bar u_m^2-\bar u_*^2)-\bar u_*^2\bar\delta\,\frac{2n}{2n+1}+\frac{1}{2}\bar H(\bar u_*^2-1)=0. \tag{12}$$

We consider transverse section C at distance x_t from the slot exit section in which the jet thickness reaches the maximum value. According to [7] we assume that in this section $u_m = u_*$, and $u_* \approx u_1$. Then for a linear velocity distribution (n = 1) Eqs. (11) and (12) take the form

$$\bar\delta_t=\frac{3}{4}\,\frac{\bar H(\bar u_1^2-1)}{\bar u_1^2}; \tag{13}$$

$$\bar b_t=\frac{\bar u_1(\bar H-0.5\bar\delta_t)-\bar H}{\bar u_1}. \tag{14}$$

It was noted in [10] that the opening angle for counter jets may with sufficient accuracy be taken as constant independent of injection rate: $b_t = cx_t \approx 0.3x_t$. As analysis of tests data in [7] showed, the range of the counter jet is greater than length x_t on average by a value of $1.5b_t$. Therefore,

$$l\approx x_t+1.5b_t=4.8b_t. \tag{15}$$

Relationships (13)-(15) make it possible to determine the range of a plane counter boundary jet with m > 1.

Results are given in Fig. 3 for calculations by Eqs. (13)-(15) of the change in range in relation to channel height. It can be seen that with an increase in injection rate or relative channel height an increase is observed in the range of the boundary counter jet. It should be noted that with an increase in relative channel height the range of channel constraint becomes weaker.

In order to check the calculation procedure described above for a plane boundary counter jet in a restricted channel an experimental study was performed. Tests were carried out in a subsonic aerodynamic tube with a working channel of rectangular cross section 145 × 150 mm (H = 145 mm) and length 1200 mm along which an air flow passed with velocity u_0. At a distance of 520 mm from the inlet to the channel in the lower wall a slot injection chamber was established with a slot height of s = 4.7 or 8 mm which created a counter boundary air jet with velocity u_s. The flow rate u_0 in the tests was 10, 12, 16, and 20 m/sec. The velocity of the counter jet u_s was varied from 12 to 120 m/sec. A study of the dynamic picture of flow was carried out by pneumatic probes and laser-doppler velocity meters.

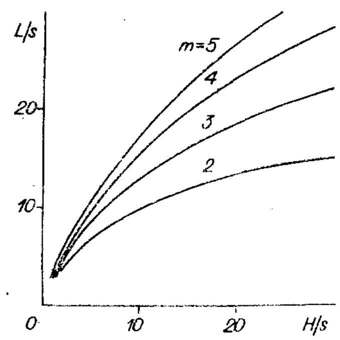

Fig. 3

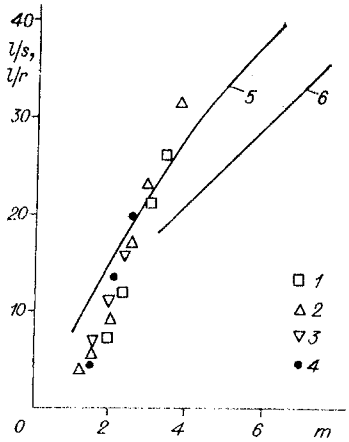

Fig. 4

Two different methods were used in order to determine range ℓ and the width of the displacement zone above the slot exit section δ_1. The first method is a "light knife" method. Here into the boundary jet powder or cigarette smoke particles were introduced with a size less than 1 μm which followed the air jet. Through a narrow slot in a transparent upper lid by a powerful pulsed light source illumination was carried out, and through the side wall photorecording of the reaction process of the jet with the flow was accomplished. From the photographic image obtained pictures were prepared of the range and thickness of the displacement layer. We nominally call experimental data found by this method during the analysis "diffusion." The second method involved prior heating of the boundary jet to a temperature T_s = 80°C (with a cold main flow T_0 = 15-20°C) and measurement by a temperature-sensitive element of the temperature profile at different transverse sections of the channel. In heat tests the distance from the wall at which the temperature in the displacement layer differed from the temperature in the undisturbed flow by 5% was taken for the thickness of the displacement layer. We call experimental results obtained by this method "thermal." More detailed information about the experimental unit and the procedure for performing tests may be found in [11].

Comparison of experimental and calculated data for range ℓ are presented in Fig. 4 in the form of the relationship ℓ = f(m) for H/s = 30. Here points 1-3 are the results of diffusion tests, respectively, with u_0 = 10, 16, 20 m/sec, 4 are thermal tests with u_0 = 12 m/sec. Curve 5 relates to calculation of the range of the plane boundary jet by relationships (13)-(15). It can be seen that the calculation reflects correctly the nature of the dependence of ℓ on injection parameter. With m > 2 poor qualitative agreement of the calculation and the experiment is observed. Given in Fig. 4 for comparison is calculation of the range for an axisymmetrical counter jet spreading over the center of a cylindrical chamber (line 6). The calculation was carried out by the procedure in [7] for the same axisymmetrical channel constraint as for plane constraint (R/r = H/s = 30, where R and r are radii of the cylindrical chamber and axisymmetrical jet. It can be seen from the curves that for the same injection parameters m the range of a plane jet (line 5) is higher than the range of an axisymmetrical jet (line 6).

Given in Fig. 5 is a comparison of calculated and experimental values of displacement layer thickness above the slot exit section δ_1 in relation to injection parameter m. Here points 1 and 2 are the results of diffusion tests with u_0 = 10 and 16 m/sec, and 3 is for thermal tests with u_0 = 12 m/sec. Comparison shows that the experimental results are described poorly by the suggested dependence (7) (curve 4). It should also be noted that with the same plane and axisymmetrical channel constraint (H/s = 30 and R/r = 30) the relative displacement layer thickness $\bar{\delta}_1 = \delta_1/r$ in an axisymmetric channel (line 5 is calculation by the procedure in [7]) is less than in a plane channel.

Experimental data for the change in velocity above the slot exit section due to waisting of the main flow by a counter jet are shown in Fig. 6 for H/s = 18 (points 1 and 2 for u_0 = 12 and 24 m/sec). It can be seen that with an increase in injection parameter m there is an increase in u_1; results of calculations of this velocity [line 3 is calculation of u_1 by Eq. (8)] are shown by lines. With m ≈ 6 the displacement layer above the slot exit section for this channel constraint (H/s = 18) according to (7) and (8) reaches the upper wall of the channel ($\bar{\delta}_1$ = H/s − 1) and $\bar{\delta}_1$ does not change with a further increase in m. Then for flow

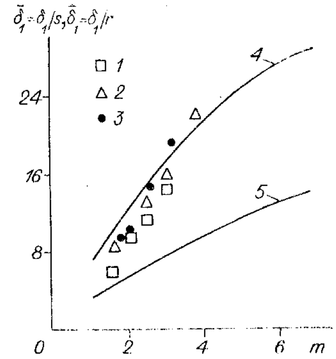

Fig. 5

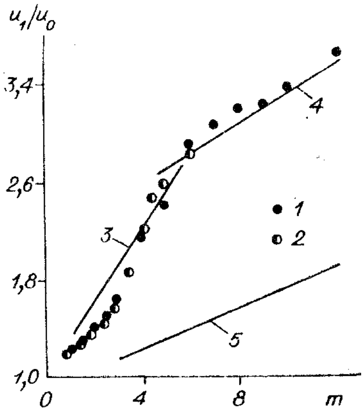

Fig. 6

regimes with which the displacement layer reaches the upper wall of the channel it is possible to determine the velocity above the slot exit section u_1 from relationship (6):

$$\bar{u}_1 = 2(m + \bar{\Pi})/(\bar{\Pi} - 1). \qquad (16)$$

Calculation by relationship (16) is represented by line 4 in Fig. 6. It can be seen that when the displacement layer reaches the upper channel wall there is a reduction in the rate of increase in velocity above the slot exit section with an increase in m. It follows from Fig. 6 that the calculation is in good agreement with experimental results. Line 5 shows the increase in velocity u_1 in an axisymmetrical channel with counter axial injection of a jet for R/r = 18 calculated by the procedure in [7]. It can be seen from the comparison that the increase in velocity in an axisymmetrical channel is less marked than in a plane channel.

In conclusion it is noted that the problem is solved in a simplified arrangement without taking account of nonuniformity of static pressure distribution across the channel, without analyzing boundary layers in a counter boundary jet and in an approach stream, and with a number of other simplifications. However, the correctness of the simple relationships obtained will make it possible to carry out calculation of some important parameters of boundary jet interaction with a counter flow in a restricted channel adequately confirmed by experimental results.

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