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FLOW AND HEAT TRANSFER IN COAXIAL JET FLOW AROUND AN OBSTACLE

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UDC 536.244:532.522

Results are presented of an experimental investigation of the gasdynamics and heat transfer in the reverse flow zone near an obstacle during coaxial jet flow on it along the normal.

In connection with the possibility of a directional influence on the nature of the flow and heat transfer at the surface of streamlined bodies, a considerable interest has recently been manifested in the problem of interaction between nonuniform flows of the "wake" type and blunt bodies placed across the stream [1-5]. It is experimentally shown in [2, 3] that a stable circulation flow with reverse currents to the central point of the body can be realized near the body for definite values of the ratio between the stream velocity at the circumference and the velocity in the central part (the coflow parameter is $m = U_2/U_1 > 1$).

The authors posed the problem of studying the effect of the origin of the return currents zone for jet flow around the obstacle and the possibility of its practical application for the intensification of heat transfer in the area of jet interaction with obstacles. The investigation, on the whole, is experimental in nature and is a continuation of [2], in which are presented preliminary results on the interaction between a subsonic axisymmetric jet with circumferential maximum velocity at the nozzle exit and a plane obstacle.

The experimental investigations were performed on an apparatus [6] consisting of a wind tunnel to whose stilling chamber an axisymmetric contractor representing a Vitoshinskii nozzle with waisting 9 and exit diameter $d_2 = 100$ mm is fastened, and a two-stage coordinating unit with measuring obstacles thereon. To obtain coaxial jets in the nozzle, an additional central contractor with exit diameter $d_1 = 25$, 50, 75 mm is inserted along its axis. Variation of the cojet parameter m assured the mounting of interchangeable grids with different clogging coefficients in the central contractor.

The flow and heat transfer were studied in the interaction domain by using "dynamic" and "thermal" plane obstacles permitting the measurement of the static pressure and the heat-transfer coefficient α on the obstacle surface, as well as the longitudinal component of the average velocity in the interaction domain near the obstacle. The static pressure on the obstacle was measured by drainage of the "dynamic" obstacle with a 1-mm-diameter collector hole. The transducer DD-6, operating in the range to 0.4 bar, was used as pressure sensor in conjunction with the measuring apparatus VI6-5MA and recording on an N-117 loop oscillograph during continuous pulling of the obstacle across the jet with the distance tied to markers in the path. The error in determining the pressure did not exceed 2%.

Leningrad Mechanics Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 38, No. 1, pp. 38-43, January, 1980. Original article submitted March 26, 1979.

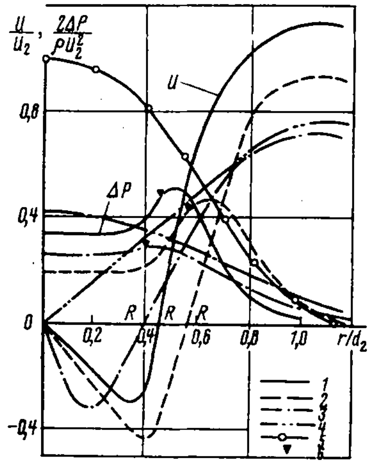

Fig. 1

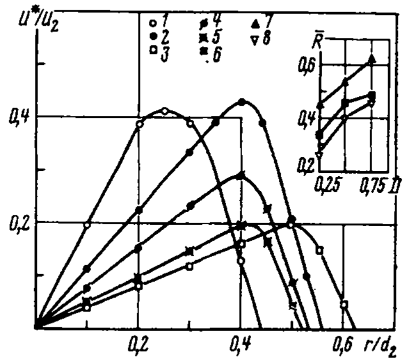

Fig. 2

Fig. 1. Velocity and static pressure distributions along the obstacle surface ($m = 4$, $U_2 = 20$ m/sec, $D = 0.5$): 1) $H = 0.5$; 2) 1; 3) 2; 4) 3; 5) single jet ($m = 0$, $H = 1$, $d_2 = 100$ mm).

Fig. 2. Influence of geometric and gasdynamic flow parameters on the change in the reverse flow velocity (U^*) and on the position of the circumferential stagnation point ($\bar{R}$) on the obstacle ($m = 4$, $U_2 = 20$ m/sec, $H = 1$): 1) $D = 0.25$; 2) 0.5; 3) 0.75; ($D = 0.5$, $U_2 = 20$ m/sec, $H = 1$): 4) $m = 2.13$; 5) 1.44; ($m = 1.44$-4): 6) $H = 0.5$; 7) 1; 8) 2.

The average stream velocities in the interaction domain were measured by a constant-temperature thermoanemometer in which a 5-μm-diameter, 1.5-mm-long tungsten wire was used as transducer sensor. It should be noted that a nonzero value of the velocity was determined near the central and circumferential stagnation points in measurements of the average reverse flow velocities because the transducer is not responsive to the stream direction and was superposed 1 mm above the obstacle surface. Hence, a correction was introduced in the readings to take into account that the velocity is zero at these points. The error in measuring the velocity did not exceed 5%.

The heat transfer was investigated on the basis of a study of the action of cold jets from a "thermal" obstacle heated by an electric current by discrete temperature measurements on the stationary mode of a tape heating element. The description of the latter, as well as the method of determining the heat-transfer coefficients, is elucidated in [6]. The total error in determining α did not exceed 6%.

An optical system permitting a light beam to be obtained by using cylindrical optics, whose thickness did not exceed 2 mm at the jet boundary, was used to visualize the gas flow in the interaction domain. The insertion of smoke particles in the stream permitted determination of the flow pattern in the plane of the "light knife edge" because of light scattering by the solid particles.

Results of the investigation are presented below for the following ranges of variation of the geometric and gasdynamic stream and apparatus parameters: $m = 1.3$-4; $U_2 = 5$-20 m/sec; $D = d_1/d_2 = 0.25$-0.75; $H = h/d_2 = 0.5$-5; $Re = d_2U_2/\nu = (0.33$-$1.33) \cdot 10^5$. Dependences of the static pressure ΔP and velocity distributions over the obstacle surface are constructed in Fig. 1 for different distances to the nozzle exit H. It follows from an analysis of the data presented that a circumferential maximum pressure whose magnitude significantly exceeds the pressure at the central point of the obstacle is realized during the flow of the coaxial jets on the obstacle. According to the data obtained, the circumferential static pressure maximum ΔP occurs for $m > 1.3$. It does not exist for lesser m and the distribution of ΔP corresponds to the typical pressure distribution on an obstacle with the maximum at the central point, as in the case of the flow of a single jet on an obstacle (curve 5) with a uniform velocity profile at the nozzle exit. As the cojet parameter increases, the magnitude of the static pressure maximum increases. The greatest value of the pressure drop between the circumferential and central points, noted in the experiment, is $\Delta P_{max}/\Delta P_m = 2.4$ for $m = 4$, $D = 0.5$ at a distance of $H = 1$ between the nozzle exit and the obstacle. The ratio is here $\Delta P_{max}/\Delta P_{02} = 0.47$, where ΔP_{02} is the excess stagnation pressure on the circumferential part of the jet. For $D = 0.75$ the circumferential maximum ΔP is implicit and the quantity $\Delta P_{max}/\Delta P_{02}$ is negligible.

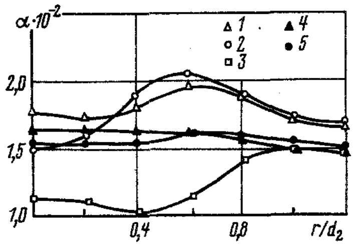

Fig. 3

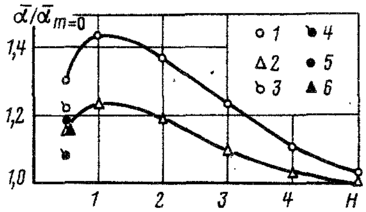

Fig. 4

Fig. 3. Distribution of the local heat-transfer coefficients over an obstacle surface ($m = 4$, $U_2 = 20$ m/sec, $H = 0.5$): 1) $D = 0.25$; 2) 0.5; 3) 0.75; 4) ($m = 4$, $U_2 = 20$ m/sec, $D = 0.5$, $H = 4$); 5) (single jet, $m = 0$, $U_2 = 20$ m/sec, $d_2 = 100$ mm; $H = 0.5$), $\alpha \cdot 10^{-2}$, W/m^2·deg K.

Fig. 4. Relative heat-transfer efficiency ($U_2 = 20$ m/sec, $D = 0.5$): 1) $m = 4$; 2) 2; ($U_2 = 20$ m/sec): 3) ($D = 0.25$ m, $m = 2$); 4) (0.75, 2); 5) (0.25, 4); 6) (0.75, 4).

The location of the maximum pressure depends on the geometry of the nozzles used D, the distance H, and is practically invariant with the change in m for D = const and H = const. Thus, for $D = 0.5$ and m = var the position of the coordinate of the maximum ΔP depends on H and is in the range $0.45 \leq r(\Delta P_{max})/d_2 = r(\Delta P_{max}) \leq 0.65$. For $m = 4$ and D = var, $\bar{r}(\Delta P_{max})$ is a function of H and is in the range $0.32 \leq \bar{r}(\Delta P_{max}) \leq 0.75$. Therefore, the greater the D the farther along the radius is the maximum ΔP displaced from the center of the obstacle for a constant distance between the nozzle exit and the obstacle.

The mentioned nature of the static pressure distribution is realized for $m > 1.3$ at distances $0.5 \leq H \leq 2$ between the nozzle exit and the obstacle. For $H > 2$ the pressure at the center of the obstacle is a maximum (curve 4 in Fig. 1), and the nature of its distribution is analogous to the nature of the pressure change, as in the case of interaction between an obstacle and a single jet with uniform velocity profile at the nozzle exit. The absence of a circumferential static pressure maximum at the ranges $H > 2$ is caused by the disappearance of the circumferential stagnation pressure maximum ΔP_0 in the cross section of a free coaxial jet because of viscous mixing and degeneration of the velocity profile into a typical profile for a single turbulent jet with maximum velocity on the axis.

As already mentioned above, the flow was visualized in addition to having the gasdynamic parameters measured to clarify the qualitative flow pattern during coaxial jet interaction with an obstacle. Results of the investigation showed that for $0.5 \leq H \leq 2$ a circulation zone characterized by reverse flow to the center of the obstacle occurred in the mode of realizing a circumferential maximum pressure at the central area of the obstacle. In this case, in addition to the central stagnation point, still another circumferential point R separating the reverse stream to the center from the radially spreading stream on the obstacle is determined on the obstacle surface. In addition to the stagnation points mentioned, the presence is noted of still another on the obstacle surface on the axis at a distance dependent on m (for D = const, H = const). The location of the point of separation on the axis shifts in the direction to the nozzle exit as m increases.

In order to determine the extent of the reverse flow zone on the obstacle, and the magnitude of the velocity there, the distribution of the velocity averaged over time was measured in direct proximity to the obstacle (Fig. 1). It follows from the data presented that the stream stagnation point R (6 on the pressure profile) is always in front of the circumferential maximum static pressure. Its position depends mainly on the geometry of the nozzle D and the distance H (Fig. 2). For m = var and D = const, H = const the coordinate $R = R/d_2$ varies negligibly.

As the parameter m increases, the intensity of the reverse flow increases. The maximum value of the reverse flow velocity U^* is achieved under the conditions of the experiment for $m = 4$, $D = 0.25$ and 0.5, and $H = 1$, and is a quantity on the order of $0.4U_2$ (Fig. 2, curves 1 and 2). For $D = 0.5$ the extent of the reverse flow zone is hence a maximum along the obstacle. The position of the maximum U^* depends on the nozzle geometry D and the distance H. Thus, for $m = 4$, $H = 1$, and m = var, the coordinate of maximum U^* is within the limits $0.25 \leq \bar{r}(U^*_{max}) \leq 0.5$. For $D = 0.5$, $H = 1$, and m = var, $\bar{r}(U^*_{max}) = 0.4$, i.e., as the cojet parameter changes while the other parameters remain unchanged, the position of the maximum U^* on the obstacle does not change (Fig. 2, curves 2, 4, and 5).

As the stagnation point R recedes, the gas velocity rises and reaches the maximum value (see Fig. 1) at the distance $\bar{r} \simeq 1-1.1$. The excess of the velocity on the obstacle over the maximum in the coaxial jets U_2 noted in the experiment for H = 0.5 is apparently associated with the influence of the obstacle on the gas flow in the nozzle at short distances of the nozzle exit. A pressure redistribution at the nozzle exit can hence occur for quantities m insignificantly greater than one so that the circumferential maximum ΔP_0 in the jet will practically vanish. For H > 2 there is no circulation flow, and the nature of the velocity distribution at the obstacle is typical for the case of the flow of a single jet with a uniform velocity profile at the nozzle exit over an obstacle for a linear velocity distribution law in the neighborhood of the stream stagnation point which agrees with the central point of the obstacle (Fig. 1, curve 4).

The results of an experimental investigation of the distribution of the heat-transfer coefficient α over the obstacle surface are represented in Fig. 3. As analysis of the data obtained shows, a circumferential maximum of the heat-transfer coefficient α_{max}, whose location is farther downstream than the location of the circumferential maximum static pressure, occurs in the α distribution. The quantity α_{max} exceeds the magnitude of the coefficient α_m considerably at the central point of the obstacle. Under the conditions of the experiment, the circumferential maximum heat-transfer coefficient is noted for $0.5 \leq H \leq 2$, while for H > 2 the α distribution (curve 4) is analogous to the distribution of the heat-transfer coefficient in the case of a single jet with a uniform velocity profile at the nozzle exit (curve 5) flowing on the obstacle.

The location of the maximum coefficient α relative to the coordinate r depends on the parameter D and depends slightly on m and H. The magnitude of the maximum α depends on the escape velocity U_2 in the circumferential part of the nozzle and on its distance H from the obstacle. As the results of an investigation for m = 2-4 and H = 0.5 show, for D = var the coordinate $\bar{r}(\alpha_{max})$ is in the range $0.6 \leq \bar{r}(\alpha_{max}) \leq 1$, where the greater the D the farther is the maximum α displaced from the center of the obstacle. The maximum value of the heat-transfer coefficient is determined at a distance of H = 1 for m = 4 and D = 0.5 (Fig. 3), which corresponds to the most developed reverse flow mode (the reversed flow velocity is a maximum). For this mode the ratio is hence $\alpha_{max}/\alpha_m = 1, 2$, and the ratio α_{max}/α_m diminishes (curve 4) as H increases.

The reverse flow to the center of the obstacle which is formed during the streaming of coaxial jets will result in a substantial increase in the integrated heat-transfer characteristics (relative to the obstacle surface) in addition to a rise in the local heat-transfer characteristics. Let us define the mean integral heat-transfer coefficient $\bar{\alpha}$ as

$$\bar{\alpha} = 2\pi \int_0^{\bar{r}} \alpha \bar{r} d\bar{r} / (\pi \bar{r}^2) = \Big[2 \sum_{\bar{r}=0}^{1.2} (\alpha \bar{r}) \Delta \bar{r} \Big] / (1.2)^2. \tag{1}$$

The values of $\bar{\alpha}$, found in conformity with (1), and referred to the mean-integrated heat-transfer coefficient $\alpha_{m=0}$ for a single jet with a uniform velocity profile at the nozzle exit (the same discharge) are represented in Fig. 4 as a function of the distance H. It follows from the graph that $\bar{\alpha}$ increases substantially as the parameter m grows and exceeds the quantity $\bar{\alpha}_{m=0}$ significantly (up to 1.4 times under the conditions of the experiment). The ratio $\bar{\alpha}/\bar{\alpha}_{m=0}$ has a maximum for m = 4, D = 0.5 at a distance H = 1. For H > 4 the value of $\bar{\alpha}$ approaches the quantity $\bar{\alpha}_{m=0}$.

The investigation performed indicates the efficiency of using coaxial jets with a circumferential maximum velocity at the nozzle exit to heat and cool surfaces because of the organization of a stable vertical flow near the obstacle surface. The method of shaping the flow with a circumferential maximum velocity far from the obstacle in order to achieve maximum heat transfer from the gas to the heated or cooled surface can be used in practice in the design of a different kind of heat-transfer apparatus. According to experiment, the operating mode of an apparatus for which the maximum value of the total heat flux to the obstacle is achieved is assured for the following parameters: m = 4, D = 0.5, $1 \leq H \leq 2$.

NOTATION

r is the radial distance from the central point of the obstacle;
h is the distance between the nozzle exit and the obstacle;
d is the diameter;
$\bar{r} = r/d_2$; $H = h/d_2$; $\bar{R} = R/d_2$;
$D = d_1/d_2$;
U is the velocity;

P	is the pressure;
$\Delta P_{02} = P_{02} - P_e$; $\Delta P = P - P_e$; $m = U_2/U_1$;	
ν	is the kinematic viscosity;
α	is the heat-transfer coefficient;
$\bar{\alpha}$	is the mean heat-transfer coefficient;
ρ	is the density.

Subscripts

1	parameters on the nozzle exit in the central part of the jet;
2	parameters of an annular jet;
m	axis;
e	external parameters;
o	stagnation parameters;
*	reverse flow to the center of the obstacle.

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EXTENT OF THE SUBSONIC DOMAIN IN A SUPERSONIC UNDEREXPANDED JET

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UDC 532.525:621.43.011

A method is proposed to determine the extent of the subsonic domain in a supersonic underexpanded jet. The method is based on representing the flow parameters in the form of series.

The qualitative flow pattern in a supersonic jet has been studied sufficiently well. It is known that a clear wave structure, conserved within the limits of several periods of the jet, is observed for $n < 5$. The flow parameters in such a jet are computed either by numerical methods [1] or by using approximate methods [2]. Computation of the stream parameters in the subsonic flow domain being formed during the nonregular reflection of a "hanging" compression shock from the jet axis (Fig. 1) is of definite difficulty. As computations have shown, the curvature of the contact surface being formed at the point C is sufficiently small. Hence, two flow schemes can be achieved which compare it to the flow of an inviscid gas in a channel with slightly cambered walls. In the first scheme, the contact surface forms a contracting channel, in whose minimal section the speed of sound is reached. This case corresponds to a negative slope of the velocity vector at the point C. In the second scheme the contact surface forms a channel of variable curvature in which the flow is first retarded somewhat and then accelerated to reach the speed of sound at the minimal section, as in the first case. This scheme corresponds to a positive angle θ_{6C}, characteristic for an underexpanded jet.

An approximate method is proposed for the analysis of the subsonic jet domain which is based on the assumption of one-dimensionality of the flow. We shall consider the flow parameters known up to the Mach

Leningrad Mechanics Institute. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 38, No. 1, pp. 44-48, January, 1980. Original article submitted March 13, 1979.