STRUCTURE OF TURBULENT UNDEREXPANDED JETS
ISSUING INTO AN IMMERSED SPACE AND A COFLOW

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Results of an experimental investigation of the geometric structure of the initial section of underexpanded jets are presented, and the fundamental singularities of the flow in the mixing layer on the boundary of a strongly underexpanded jet in a turbulent flow mode are examined on the whole length of the initial portion of the jet.

A supersonic coflow exerts a substantial qualitative and quantitative influence on the geometry of the initial section of underexpanded jets. The most essential singularity of a jet in a coflow is the "degeneration" of the central compression shock at the coflow Mach numbers $M_{\infty} > 2$. The transverse and longitudinal dimensions of the initial section of an underexpanded jet in a coflow with $M_{\infty} > 1.5-2$ diminish as $M_{\infty}$ grows. The singularities established for the co-current jet structure make replacement of the co-current jet by an equivalent submerged jet impossible. Approximate relations are presented which permit taking account of the influence of the coflow on the fundamental characteristic dimensions of the initial section of the jet.

The characteristic flow domains in a compressed viscous underexpanded jet layer are extracted. Self-similarity of the fields of gas-dynamic parameters is established. Data are presented on the location of the mixing layer in space, on the total head and statistical pressure profiles, and on the dimensionless excess stagnation temperature in strongly underexpanded jets.

The fields of gas-dynamic parameters have been investigated experimentally for the nozzle Mach number range $M_a = 1-4$, the external flow Mach number $M_\infty = 0-10$, the degree of jet off-design $n = p_a/p_\infty = 1-10^4$, and the Reynolds number $R_a = 10^5-10^6$. The ratio between the jet stagnation and the external flow temperatures $T_1 = T_{0a}/T_{0\infty}$ varied in the 0.5-2 range. The number $R$ defined by means of the free-stream parameters and the characteristic jet dimension was hence greater than $10^6$.

The turbulent flow mode was determined by means of shadowgraphs obtained by the condensed spark method. Models with cylindrical root section and the ratio $D_a/D_m = 0.2-1.0$ ($D_m$ is the diameter of the middle of the model) were investigated.

Here $p_a$ is the static pressure at the nozzle exit, $p_\infty$ is the static pressure in the submerged space or in the external stream ahead of the jet, $R_a$ is the Reynolds number defined by means of the parameters at the nozzle exit, and $T_{0\infty}$ is the stagnation temperature of the external stream.

I. Influence of a Coflow on the Dimensions of the Initial Section of a Supersonic Underexpanded Turbulent Jet

1. Let us consider the qualitative picture of the escape of an underexpanded jet into a coflow. Shown in Fig. 1 are diagrams of the...
initial section of an underexpanded jet discharging into a submerged space (Fig. 1a) and the supersonic co-
flow (Fig. 1b), and shadowgraphs of the initial section of a jet discharging into a submerged space (Fig. 2a;
$M_a = 2$, $n = 22.6$) and subsonic (Fig. 2b, $M_\infty = 0.7$, $M_a = 2$, $n = 20.75$), transonic (Fig. 2c, $M_\infty = 0.93$, $M_a = 2$, $n = 20.7$), and supersonic (Fig. 2d, $M_\infty = 1.2$, $M_a = 2$, $n = 17.82$) coflows are shown in Fig. 2.

As an underexpanded jet escapes into a coflow, the pressure along the boundary of the initial section
of the jet is variable. The pressure along the jet boundary varies monotonically in the $0 < M_\infty < 0.7$ number
range, decreases in the direction from the nozzle exit, and the flow picture is outwardly analogous to the
flow picture for a submerged jet (Fig. 2b). A local supersonic zone enclosing the compression shock (Fig.
2c) originates in the $M_\infty = 0.7-0.95$ number range in the neighborhood of the maximum of the visible jet
boundary. An increase in the number $M_\infty$ in this range or an increase in the degree of the jet off-design
for a constant value of $M_\infty$ results in a downstream displacement of the compression shock in the external
flow to a section in which the reflected compression shock 4 (Fig. 1) interacts with the jet boundary.

A compression shock 5 (Fig. 1b) originates in the supersonic coflow ahead of the jet. The pressure
along the jet boundary is substantially variable, and its drop in the flow direction (with the exception of the
separation domain ahead of the jet) results in a diminution in the curvature of the jet boundary and of the
hanging compression shock.

The pressure rise in the compression shock 5 can cause boundary layer separation on the model sur-
face ahead of the expanding jet. For a given external flow the magnitude of the degree of jet off-design at
which separation 8 (Fig. 1) starts to originate at the side surface as well as the jet structure in the neigh-
borhood of the nozzle exit depend on the shape of the model root section, characterized by the dimension-
less parameters $D_a/D_m$, $D_k/D_m$, $\theta_k$, etc. (Here $D_k$ is the diameter of the model root exit, $\theta_k$ is the cone
half-angle for the case of a conical model root section.) Without considering the flow picture in the neigh-
borhood of the nozzle exit in detail, let us just say that boundary layer separation for models with a sharp
edge ($D_m = D_k = D_a$, $\theta_k = 0$) occurs on the side surface at essentially lower values of $n$ than those which cor-
respond to the formation of a detached compression shock in the inviscid gas flow approximation.

2. The dimensionless parameters determining the flow in a submerged supersonic jet are $n$, $M_a$,
the ratio of the specific heats $\gamma_a$, the ratio of the total temperatures $T_T$, and the Reynolds number $R_e$. The
geometric flow parameter is the nozzle cone angle $\theta_a$ (or the parameter governing the velocity profile at
the nozzle exit in the general case).